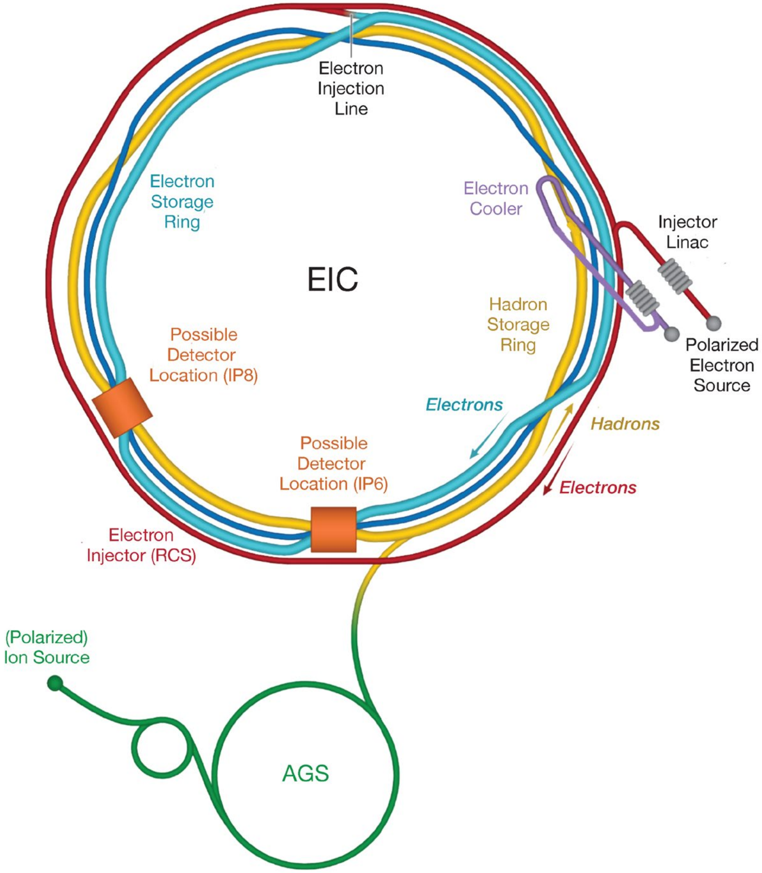
On the possibility of measuring the polarization of the ^{3}He beam at EIC by the HJET

A.A. Poblaguev

Brookhaven National Laboratory

Hadronic polarimetry at the EIC



High energy, 40-275 GeV polarized proton and helion ($^3He^{\uparrow}$) beams are planned at the future Electron Ion Collider.

The requirement for the EIC beam polarimetry:

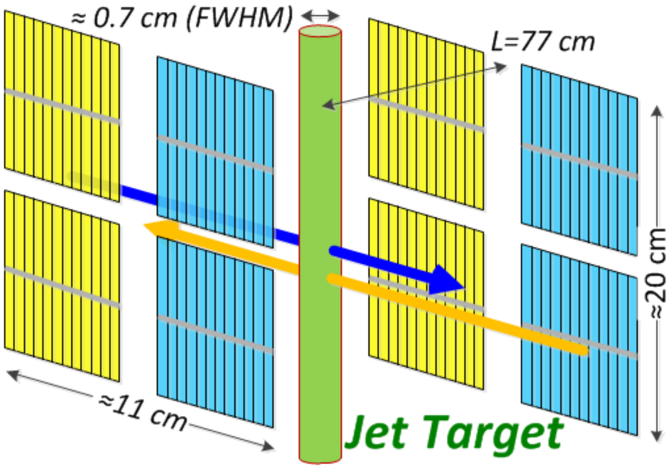
$$\sigma_P^{syst}/P \lesssim 1\%$$

Compared to RHIC, there are new challenges for the hadronic beam polarimetry at EIC

- Much shorter, 10 ns bunch spacing (107 ns at RHIC)
- $^3He^{\uparrow}$ beam

- **A complete analysis of the beam polarization includes measurement of the polarization profile, polarization decay time, …**
- **The main goal of this presentation is to discuss the RHIC Hydrogen Jet Target (HJET) feasibility to measure the $^3He^{\uparrow}$ beam averaged absolute polarization at EIC.**

The Atomic Polarized Hydrogen Gas Jet Target (HJET)



- Vertically polarized gas jet target, $P_{jet} \approx 96 \pm 0.1\ \%$
- 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.

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)

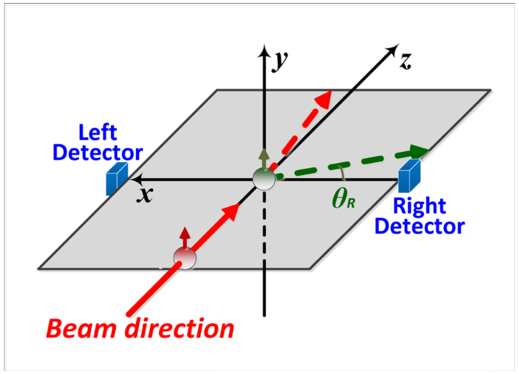
$\frac{z_R - z_{jet}}{L} = \sqrt{\frac{T_R}{2m_p}\frac{E_{beam}+m_p}{E_{beam}-m_p+T_R}} \approx \sqrt{\frac{T_R}{2m_p}} \times \left(1 + \frac{m_p}{E_{beam}}\right)$ (for elastic scattering)

- The HJET geometry predetermine measurements in the CNI region

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

$t = -2m_pT_R$ **!**

Polarization measurement of proton beams at HJET



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

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

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

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

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

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

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

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

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

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

Elastic single spin proton-proton analyzing power $A_{\mathrm{N}}(s,t)$

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:

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

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

$$A_N(t) = \frac{2\mathrm{Im}\left[\phi_5^{\mathrm{em}}\phi_+^{\mathrm{h}\,*} + \phi_5^{h}\phi_+^{em\,*} + \phi_5^{h}\phi_+^{h\,*}\right]}{\left|\phi_+^{\mathrm{h}} + \phi_+^{\mathrm{em}} e^{i\delta_C}\right|^2}$$

$$= \frac{\sqrt{-t}}{m_p}\,\frac{\kappa_p t_c/t - 2I_5 t_c/t - 2R_5}{(t_c/t)^2 - 2(\rho+\delta_C)t_c/t + 1}$$

$\kappa_p = \mu_p - 1 = 1.793$
$t_c = -8\pi\alpha/\sigma_{\mathrm{tot}} = -1.86\times 10^{-3}\ \mathrm{GeV}^2$
$\rho = -0.079$
$\delta_C = 0.024 + \alpha\ln t_c/t$

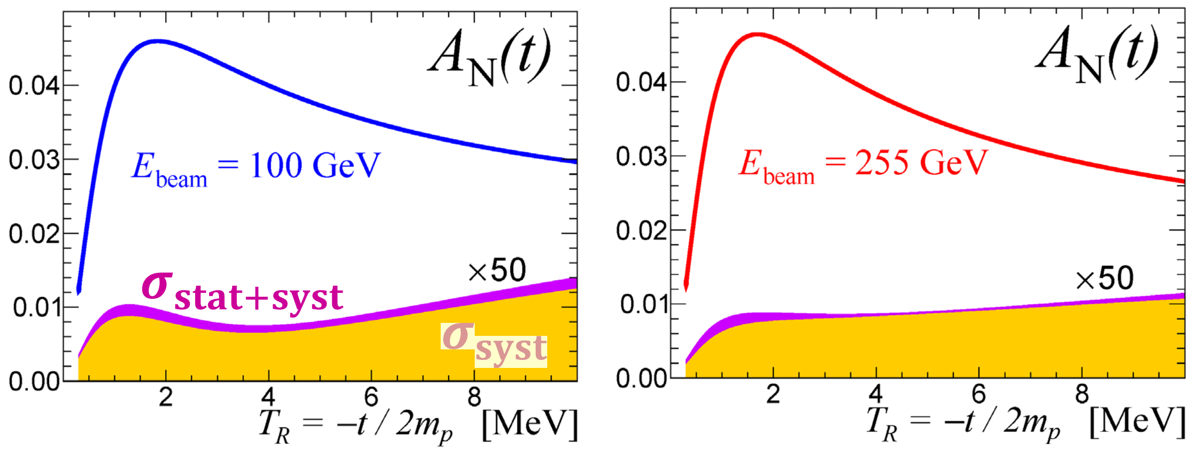
(for 100 GeV beam)

The primary goal of the experimental study of the elastic pp analyzing power in the CNI region is an evaluation of the hadronic spin-flip amplitude, parameterized by

$$r_5 = \frac{m_p\,\phi_5^{\mathrm{had}}(s,t)}{\sqrt{-t}\,\mathrm{Im}\phi_+^{\mathrm{had}}(s,t)} = R_5 + iI_5, \qquad |r_5| \sim 2\%$$

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

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



- The filled areas specify 1σ experimental uncertainties, stat.+syst., scaled by x50.
- Hadronic spin-flip amplitude parameter

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

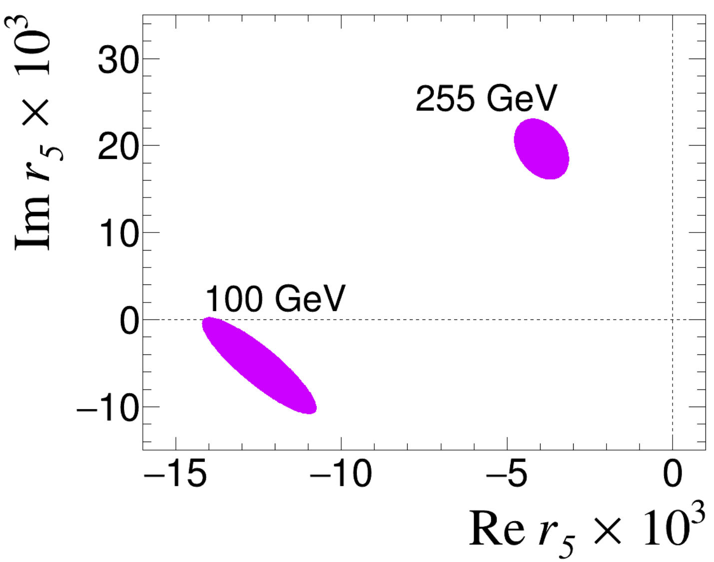
The measured hadronic spin flip amplitudes:

$\sqrt{s} = 13.76$ GeV
$$R_5 = (-12.5 \pm 0.8_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-3}$$
$$I_5 = (-5.3 \pm 2.9_{\text{stat}} \pm 4.7_{\text{syst}}) \times 10^{-3}$$

$\sqrt{s} = 21.92$ GeV
$$R_5 = (-3.9 \pm 0.5_{\text{stat}} \pm 0.8_{\text{syst}}) \times 10^{-3}$$
$$I_5 = (19.4 \pm 2.5_{\text{stat}} \pm 2.5_{\text{syst}}) \times 10^{-3}$$

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

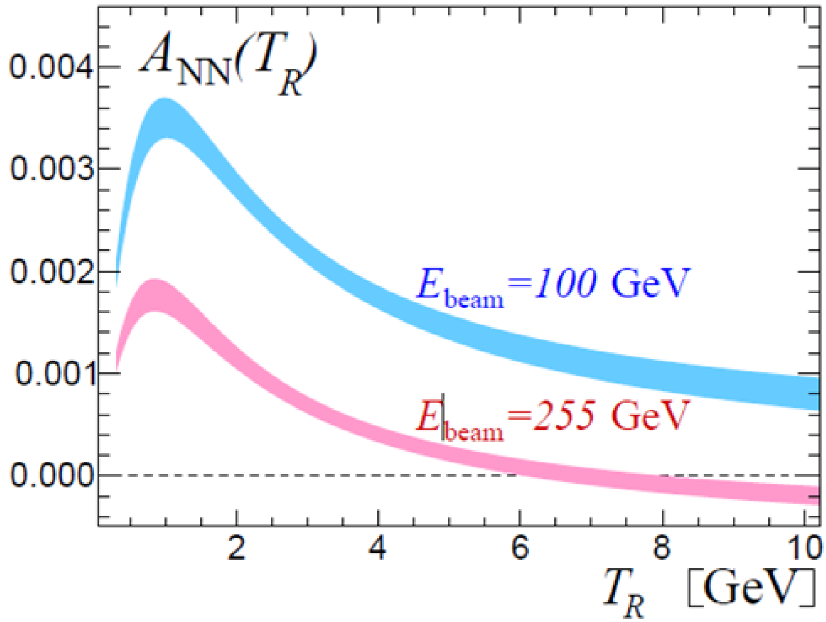
$$R_5 = R_5^{\text{PRL}} + \left(3.1_{\text{abs.}} + 0.8_{r_p}\right) \times 10^{-3}$$



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

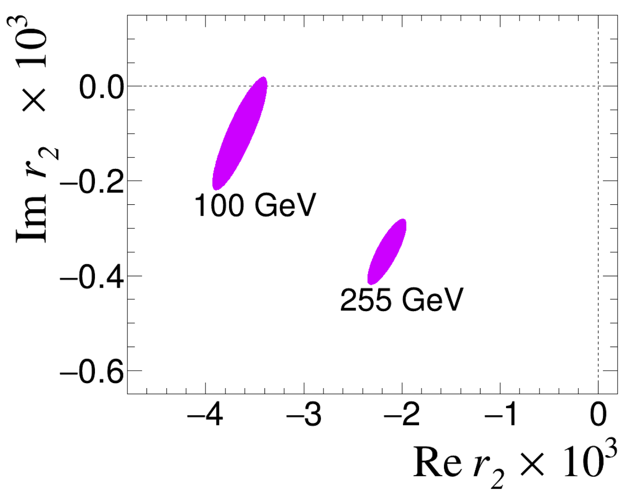
A.A. Poblaguev *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)

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



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

$\sqrt{s} = 13.76$ GeV	$R_2 = (-3.65 \pm 0.28_{stat}) \times 10^{-3}$ $I_2 = (-0.10 \pm 0.12_{stat}) \times 10^{-3}$
$\sqrt{s} = 21.92$ GeV	$R_2 = (-2.15 \pm 0.20_{stat}) \times 10^{-3}$ $I_2 = (-0.35 \pm 0.07_{stat}) \times 10^{-3}$



How to measure the EIC ^{3}He beam polarization with HJET

AP, Phys. Rev. 106, 065202 (2022)

$$P^h_{\text{meas}}(T_R) = P_{\text{jet}} \frac{a_{\text{beam}}(T_R)}{a_{\text{jet}}(T_R)} \times \frac{A_N^{p^\uparrow h}(T_R)}{A_N^{h^\uparrow p}(T_R)}$$

$$= \frac{a_{\text{beam}}}{a_{\text{jet}}} P_{\text{jet}} \times \frac{\kappa_p - 2I_5^{ph} - 2R_5^{ph} T_R/T_c + \omega^{ph}(r_5, T_R)}{\kappa_h - 2I_5^{hp} - 2R_5^{hp} T_R/T_c + \omega^{hp}(r_5, T_R)}$$

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

$\kappa_p = \mu_p - 1 = 1.793$
$\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$
$T_c \approx 0.7$ MeV
$\omega(r_5, T_R)$ are the breakup,
$h \to pd$ and $h \to ppn$, 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 $P^h_{\text{meas}}(T_R)$ to $P^h_{\text{meas}}(0)$ may result in non-zero value of $\delta\omega$.

- r_5^{ph} and r_5^{ph} can be related to the proton-proton r_5 (predetermined for the same beam energy per nucleon). 10—20% theoretical accuracy of such calculation is sufficient to satisfy EIC requirement $\sigma_P^{\text{syst}}/P \leq 1\%$.
- Since no breakup is possible for $t = 0$, the breakup corrections are expected to be small in the HJET measurements

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

$$\phi_{\rm sf}^{pA}(t)/\phi_{\rm nf}^{pA}(t) = \phi_{\rm sf}^{pp}(t)/\phi_{\rm nf}^{pp}(t) \quad \Rightarrow \quad r_5^{pA} = r_5^{pp}\,\frac{i+\rho^{pA}}{i+\rho^{pp}} \approx r_5^{pp}$$

The result can be easily reproduced in the Glauber theory. For example, elastic proton-deuteron (pd) scattering can be approximated by the proton-nucleon collisions (pN):

$$F_{ii}(\boldsymbol{q}) = S\left(\frac{\boldsymbol{q}}{2}\right) f_n(\boldsymbol{q}) + S\left(\frac{\boldsymbol{q}}{2}\right) f_p(\boldsymbol{q}) + \frac{i}{2\pi k}\int S(\boldsymbol{q}')f_n\left(\frac{\boldsymbol{q}}{2}+\boldsymbol{q}'\right) f_p\left(\frac{\boldsymbol{q}}{2}-\boldsymbol{q}'\right) d^2\boldsymbol{q}'$$

Since the pN spin-flip amplitude is small (at HJET),

$$f_N^{\rm sf}(\boldsymbol{q}) = \frac{\boldsymbol{qn}}{m_p}\frac{r_5}{i+\rho} f_N(\boldsymbol{q}), \qquad \left|f_N^{\rm sf}(\boldsymbol{q})/f_N(\boldsymbol{q})\right| \le 0.003,$$

to calculate the spin-flip pd amplitude, one should replace in the right-hand side

$$f_n \to f_n^{\rm sf}, \qquad f_p \to f_p^{\rm sf}, \qquad \text{and} \quad f_n f_p \to f_n^{\rm sf} f_p + f_n f_p^{\rm sf}$$

$$F_{ii}^{\rm sf}(\boldsymbol{q}) \equiv \frac{\boldsymbol{qn}}{m_p}\frac{r_5^{pA}}{i+\rho^{pA}} F_{ii}(\boldsymbol{q}) = \frac{\boldsymbol{qn}}{m_p}\frac{r_5}{i+\rho} F_{ii}(\boldsymbol{q})$$

More general consideration of the elastic $p^{\uparrow}A$ scattering

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

$$F_{fi}(\boldsymbol{q_T}) = \frac{ik}{2\pi}\int e^{ib\boldsymbol{q}_T}\,\Psi_f^*(\{\boldsymbol{r}_j\})\,\Gamma(\boldsymbol{b},\boldsymbol{s}_1\ldots\boldsymbol{s}_A)\Psi_i(\{\boldsymbol{r}_j\})\prod_{j=1}^{A} d^3r_j\,d^2b$$

and can be calculated if initial $\Psi_i(\{\boldsymbol{r}_j\})$ and final $\Psi_f\;(\{\boldsymbol{r}_j\})$ state wave functions are known.

In Glauber theory, elastic pA amplitude can be expressed via the proton nucleon ones

$$F_{ii}(q) = \sum_a \{S_a f_a\} + \sum_{a,b}\{S_{ab} f_a f_b\} + \sum_{a,b,c}\{S_{abc} f_a f_b f_c\} + \ldots$$

$$\sum_{a,b,c}\{S_{abc} f_a f_b f_c\} = \int S_{abc}(\boldsymbol{q}'_a,\boldsymbol{q}'_b,\boldsymbol{q}'_c) f_a(\boldsymbol{q}'_a) f_b(\boldsymbol{q}'_b) f_c(\boldsymbol{q}'_c)\delta(\boldsymbol{q}-\boldsymbol{q}'_a-\boldsymbol{q}'_b-\boldsymbol{q}'_c)d^2\boldsymbol{q}'_a d^2\boldsymbol{q}'_b d^2\boldsymbol{q}'_c$$

No knowledge of form factors $S_a, S_{ab}, \ldots$ is needed to calculate the elastic spin flip amplitude

$$F_{ii}^{\mathrm{sf}}(\boldsymbol{q}) = \frac{\boldsymbol{qn}}{m_p}\frac{r_5}{i+\rho}F_{ii}(q) \quad \Rightarrow \quad \boldsymbol{r}_5^{pA} = \boldsymbol{r}_5\,\frac{\boldsymbol{i}+\boldsymbol{\rho}^{pA}}{\boldsymbol{i}+\boldsymbol{\rho}^{pp}}$$

Elastic $p + h^{\uparrow} \to p + h$ *hadronic spin-flip amplitude*

- The spin-flip proton-nucleon amplitude depends on the nucleon's polarization

$$pN^{\uparrow} \quad \Rightarrow \quad f^{sf}(q) = \frac{qn}{m_p}\frac{r_5 P_N}{i+\rho} f(q)$$

- If all nucleons in a nuclei have the same spatial distributions, i.e., if $S_{a,b,\dots} = S_{b,a,\dots} = S_{b,c,\dots}$, then for unpolarized proton scattering off the polarized nuclei

$$r_5^{Ap} = r_5 \frac{i+\rho^{pA}}{i+\rho^{pp}} \frac{\sum P_i}{A}$$

where P_i are nucleon polarizations in the nuclei.

Since in a fully polarized helion in the ground S state, $P_n = 1$ and $P_p = 0$,

$$r_5^{hp} = r_5/3$$

Considering also S'- and D-wave components , it was found $P_n \approx 0.88,\ P_p \approx -0.02$
[J.L. Friar *et al*., Phys. Rev. C **42**, 2310 (1990)]

$$r_5^{hp} = (0.27 \pm 0.06) r_5$$

r_5 *related uncertainties in the* ^{3}He *beam polarization measurement*

$$P^h_{\mathrm{meas}}(T_R) = \frac{a_{\mathrm{beam}}}{a_{\mathrm{jet}}} P_{\mathrm{jet}} \times \frac{\kappa_p - 2\,I_5 - 2\,R_5\,T_R/T_c}{\kappa_h - 0.54\,I_5 - 0.54\,R_5\,T_R/T_c}$$

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

$r_5 = R_5 + iI_5$, is the proton-proton hadronic spin-flip amplitude parameter

$$\frac{\delta^{r_5}_{\mathrm{syst}} P^h_{\mathrm{beam}}}{P^h_{\mathrm{beam}}} = \xi_0 = \underbrace{\frac{2}{\kappa_p}\delta I_5^{ph} \oplus \frac{-2}{\kappa_h}\delta I_5^{hp}}_{\lesssim 0.2\%} \oplus \underbrace{\left(\frac{2}{\kappa_p} - \frac{0.54}{\kappa_h}\right)\delta I_5}_{\lesssim 0.5\%} \oplus \underbrace{\left(\frac{2}{\kappa_p} - \frac{2}{\kappa_h}\right)\frac{I_5^{pn} - I_5^{pp}}{3}}_{\lesssim 0.2\%} \lesssim 0.6\%$$

Calculation of r_5^{ph} and r_5^{hp}

Measurement of r_5 (pp)

Possible difference between pn and pp amplitudes

For 100 GeV/nucleon ^{3}He beam, the expectation for the r_5 related systematic uncertainties in measured polarization is in agreement with the EIC requirement

$p^{\uparrow} + A \to p + (A_1 + A_2 \ldots)$ *hadronic spin-flip amplitude*

For a breakup scattering $p^{\uparrow}A \to pX$ (e.g., $\boldsymbol{ph \to ppd}$), the amplitude can be a function of $\Delta = M_X - M_A$ (and other the breakup internal variables).
It may be convenient to define ratio of the breakup and elastic amplitude,

$$\psi_{fi}(\boldsymbol{q},\Delta) = F_{fi}(\boldsymbol{q},\Delta)/F_{ii}(\boldsymbol{q}) = \left|\psi_{fi}(\boldsymbol{q},\Delta)\right| e^{i\varphi_{fi}(\boldsymbol{q},\Delta)},$$

Generally, $\boldsymbol{\varphi \neq 0}$

and (redefine) the spin-flip parameter $\tilde{r}_5$

$$F_{fi}^{\mathrm{sf}}(\boldsymbol{q}) = \frac{\boldsymbol{qn}}{m_p}\frac{\tilde{r}_5}{i+\rho}F_{fi}(\boldsymbol{q})$$

A breakup pA amplitude can be expresses via proton-nucleon amplitudes in the same way as elastic one, but with some different set of formfactors

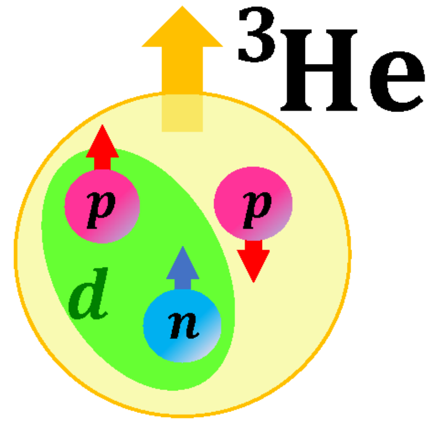
$$F_{fi}(q) = \sum_{a}\{\tilde{S}_a f_a\} + \sum_{a,b}\{\tilde{S}_{ab} f_a f_b\} + \sum_{a,b,c}\{\tilde{S}_{abc} f_a f_b f_c\} + \ldots$$

$\boldsymbol{p^{\uparrow}A \to pA_1A_2 \ldots}$

$$\tilde{\boldsymbol{r}}_{\boldsymbol{5}}^{\boldsymbol{p^{\uparrow}A}} = \boldsymbol{r_5}$$

Inelastic $p + h^{\uparrow} \rightarrow p + (p+d)_h$ *hadr. spin-flip amplitude*

$$\tilde{r}_5^{hp} = \tilde{r}_5^{h\rightarrow pd} = (0.27 + \delta_{pd})r_5$$



In the ground S state of a polarized ^{3}He, protons $p^{\uparrow}$and $p^{\downarrow}$ are spin singlet, $p^{\uparrow}$ and $n^{\uparrow}$bound state may be interpreted as deuteron.

Considering single scattering amplitude with large q (to knock-out the nucleon), one finds that the $h \rightarrow pd$ breakup can be associated with $pp^{\downarrow}$ scattering, that is

$$\tilde{r}_5^{hp\rightarrow pdp} = -r_5 \quad \Rightarrow \quad \delta_{pd} = -1.27$$

In the same approach,

$$\tilde{r}_5^{h\rightarrow ppn} = +r_5$$

Anticipating that for low q the result may be different,

$$-1.27 < \delta_{pd} < 0$$

will be considered for estimates

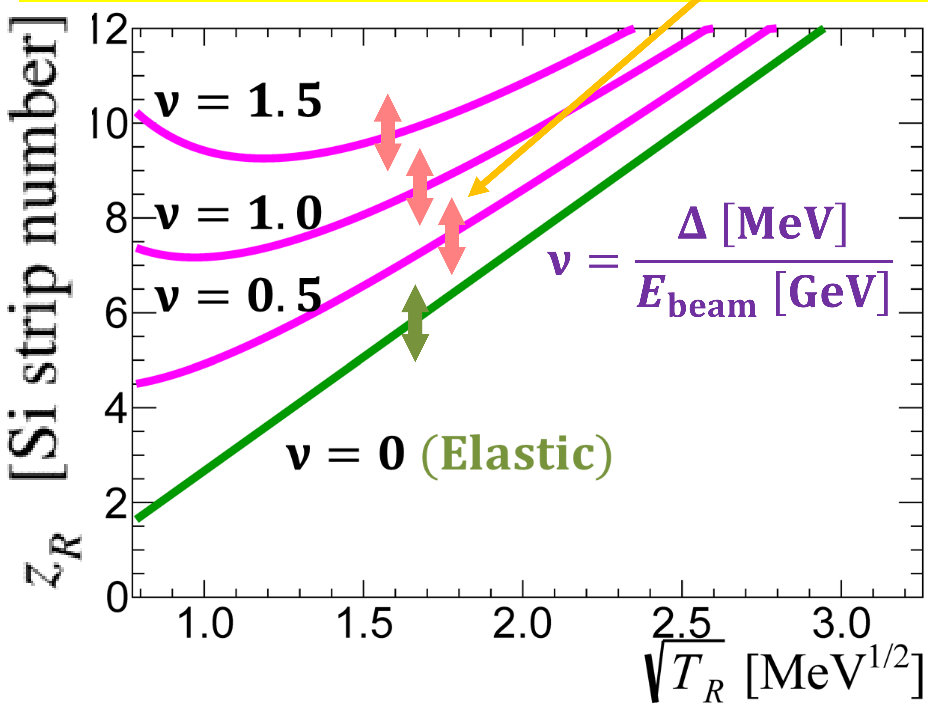
Inelastic scattering in HJET

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

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

$\Delta = M_X - m_p > m_\pi$
E_{beam} is the beam energy per nucleon

At HJET, z_R is discriminated by the Si strip width, $3.75\ \text{mm}$
the dependence is smeared due to $\sigma_{\text{jet}} \approx 2.5\ \text{mm}$



- 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 $\nu \gtrsim 2.5$ $(E_p < 55\ \text{GeV})$.

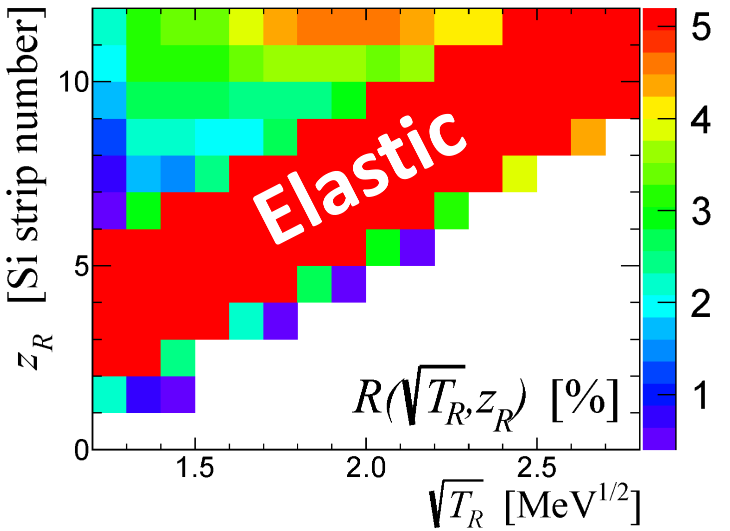
$$p^{\uparrow}_{\text{beam}} + p^{\uparrow}_{\text{jet}} \rightarrow X_{\text{beam}} + p_{\text{jet}}$$

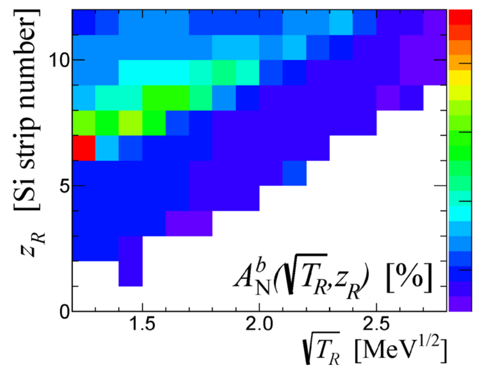
$R(T_R, z_R) = N_{\text{bin}}(T_R, z_R)/N^{el}_{\text{max}}$

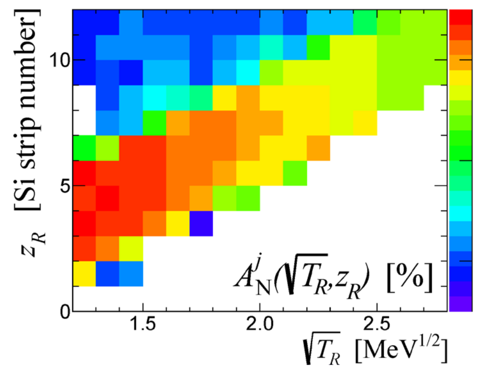
For the inelastic scattering

$\Delta > m_\pi$

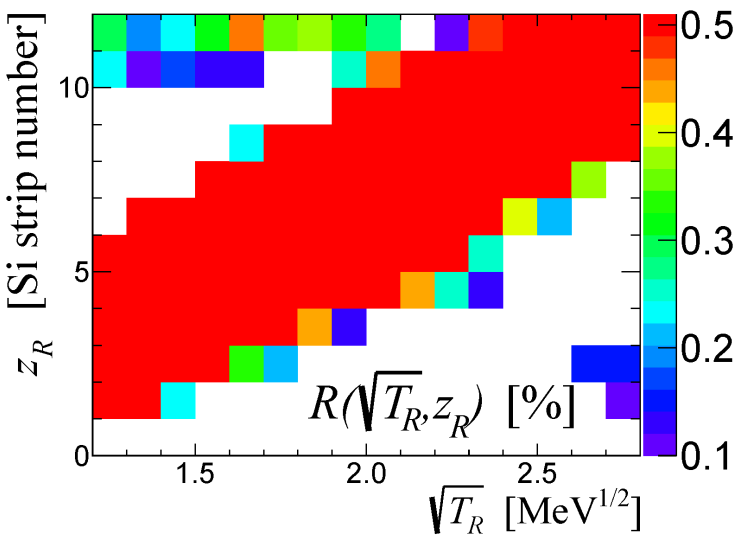
255 GeV

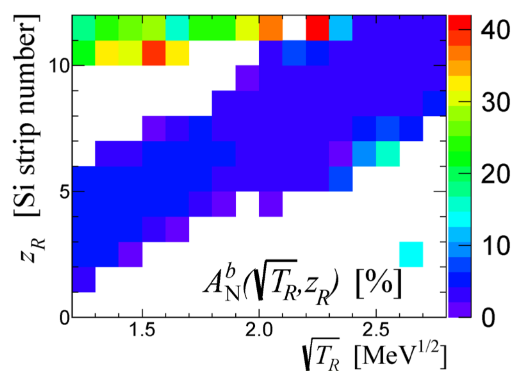


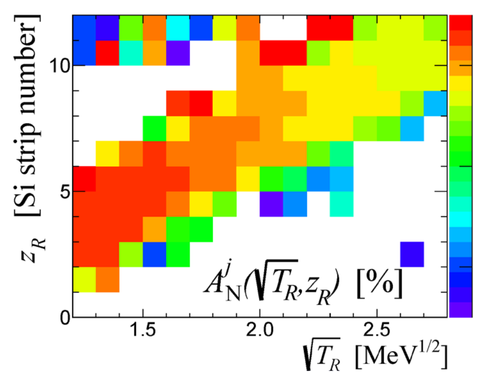




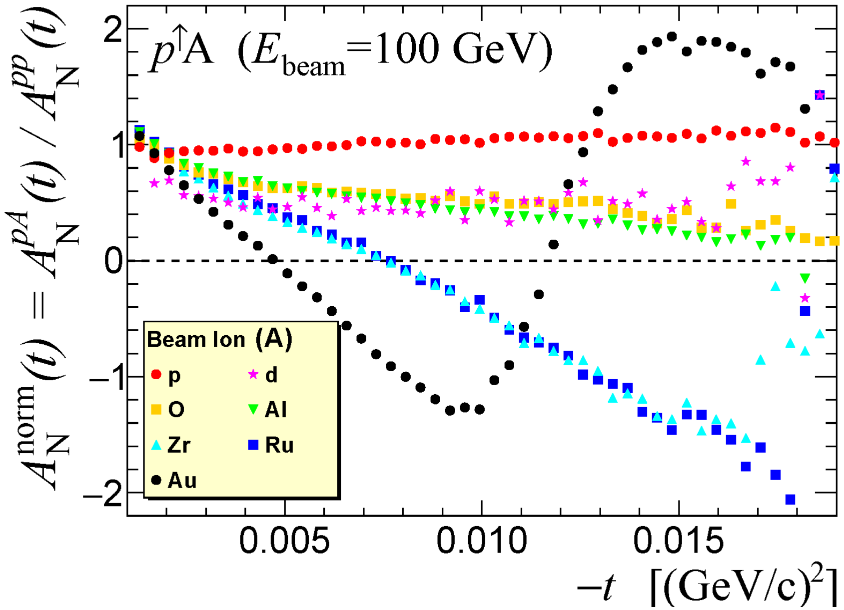
100 GeV

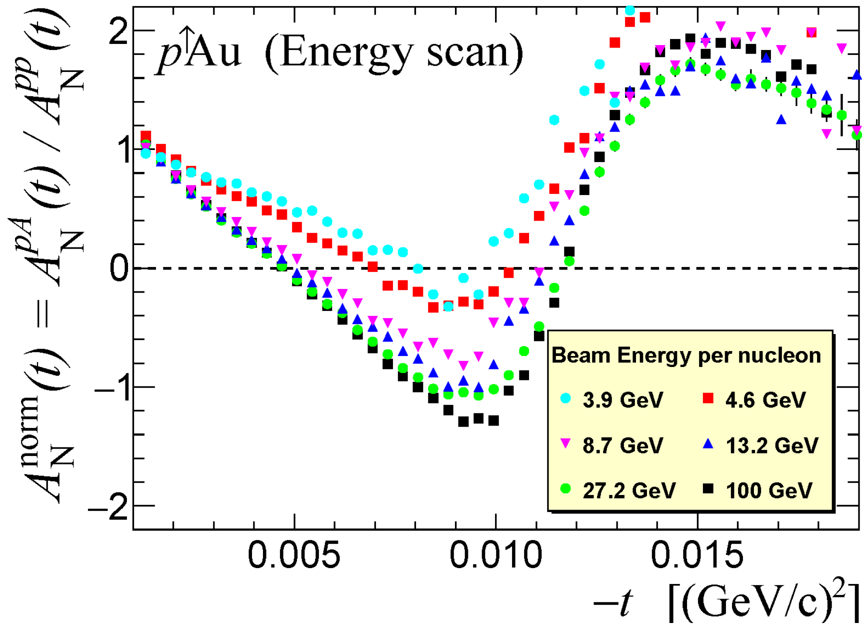






Proton-nucleus Scattering at HJET





In the Au beam measurements at HJET ($\Delta \gtrsim 4$ MeV, $3.8 < E_{\text{beam}} < 100$ GeV/n), no evidence of the breakup fraction in the elastic data was found.

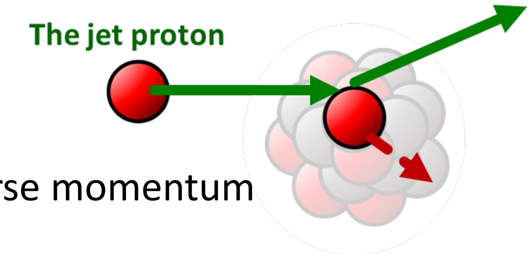
$$\left\langle \frac{d\sigma_{\text{brk}}^{p\text{Au}}(T_R,\Delta)}{d\sigma_{\text{el}}^{p\text{Au}}(T_R)} \right\rangle_{\mathbf{1.7 < T_R < 4.4\ MeV}}$$

3.85 GeV/n: $0.20 \pm 0.12\%$ $[3.6 < \Delta < 8.5 \text{ MeV}]$

26.5 GeV/n: $-0.08 \pm 0.06\%$ $[\ 20 < \Delta < 60 \text{ MeV}]$

A model used to search for the $d \to pn$ breakup events at HJET

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



$$\Delta = \left(1 - \frac{m_p}{M_A}\right) T_R + p_x \sqrt{\frac{2T_R}{m_p}},$$ where p_x is the target nucleon transverse momentum

Assuming the following p_x distribution, $f_{\text{BW}}(p_x, \sigma_p) = \frac{\pi^{-1}\sqrt{2}\sigma_p}{p_x^2 + 2\sigma_p^2}$, $\int f_{\text{BW}}(p_x, \sigma_p) dp_x = 1$,

one finds for a two-body breakup (for given T_R)

$$dN/d\Delta \propto f_{\text{BW}}(\Delta - \Delta_0, \sigma_\Delta)\Phi_2(\Delta), \qquad \Delta_0 = (1 - m_p/M_A)T_R, \ \sigma_\Delta = \sigma_p \sqrt{2T_R/m_p}$$

$$\frac{d^2\sigma_{h\to pd}(T_R,\Delta)}{d\sigma_{h\to h}(T_R)\, d\Delta} = |\psi(T_R,\Delta)|^2 \omega(T_R,\Delta) = |\psi|^2 f_{BW}(\Delta - \Delta_0, \sigma_\Delta) \frac{\sqrt{2m_p m_d}}{4\pi m_h} \sqrt{\frac{\Delta - \Delta_{\text{thr}}^h}{m_h}}$$

- The breakup fraction $\omega(T_R,\Delta)$ dependence is pre-defined by the nucleon momentum distribution in a nuclei.
- In the HJET measurements, $\Delta < 50$ MeV is small.
- The breakup to elastic amplitude ratio, $\psi(T_R,\Delta)$, is about independent of the T_R and Δ.
- The $h \to pd$ breakup is strongly suppressed by the phase space factor $\omega(T_R,\Delta) \propto \sqrt{\Delta - \Delta_{\text{thr}}^h}$.
- For the $h \to ppn$ breakup the suppression is much stronger $\omega(T_R,\Delta) \propto \left(\Delta - \Delta_{\text{thr}}^h\right)^2$.
- The electromagnetic ph amplitudes are nearly the same for elastic and breakup scattering.

Deuteron beam measurements at HJET

AP, Phys. Rev. 106, 065203 (2022)

- 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.
- The breakup was evaluated for $2.8 < T_R < 4.2\ \text{MeV}$
- In the data fit, the $d \to pd$ breakup fraction $\omega(T_R, \Delta)$ was parameterized,

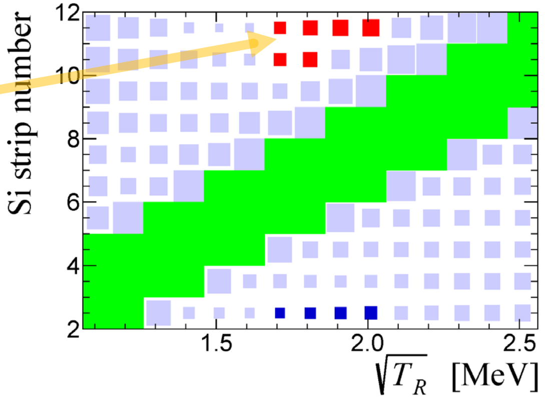
$$|\psi| \approx 5.6, \quad \sigma_p \approx 35\ \text{MeV}$$

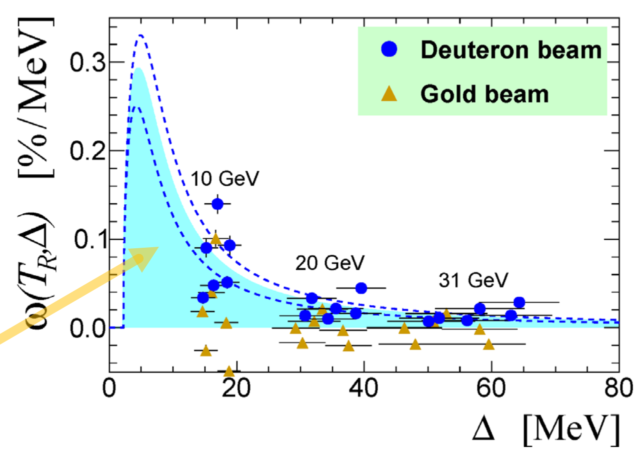
- For $T_R \sim 3.5\ \text{MeV}$, the breakup fraction was evaluated to be

$$\frac{d\sigma_{d\to pn}(T_R)}{d\sigma_{d\to d}(T_R)} = \omega_{d\to pn}(T_R)$$

$$= |\psi|^2 \int d\Delta\, \omega_{d\to pn}(T_R, \Delta) \approx 5.0 \pm 1.4\%$$

- The result obtained strongly depends on the used parametrization and, thus, a verification is needed.



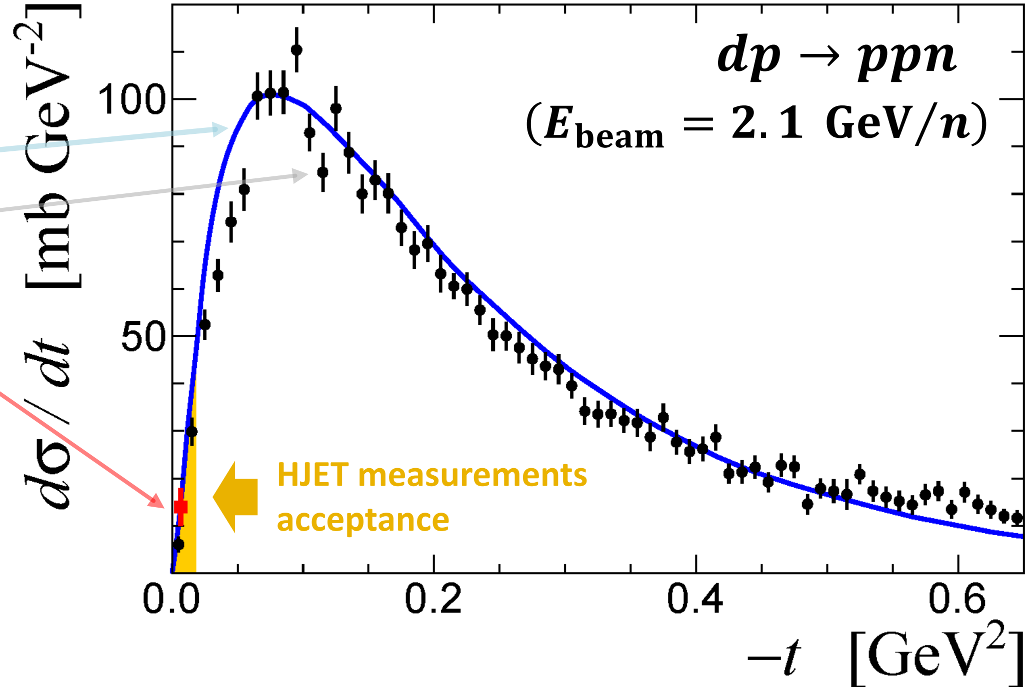


$d \to pn$ breakup in the hydrogen bubble chamber

B. S. Aladashvili *et al.*, J. Phys. G **3**, 1225 (1977).

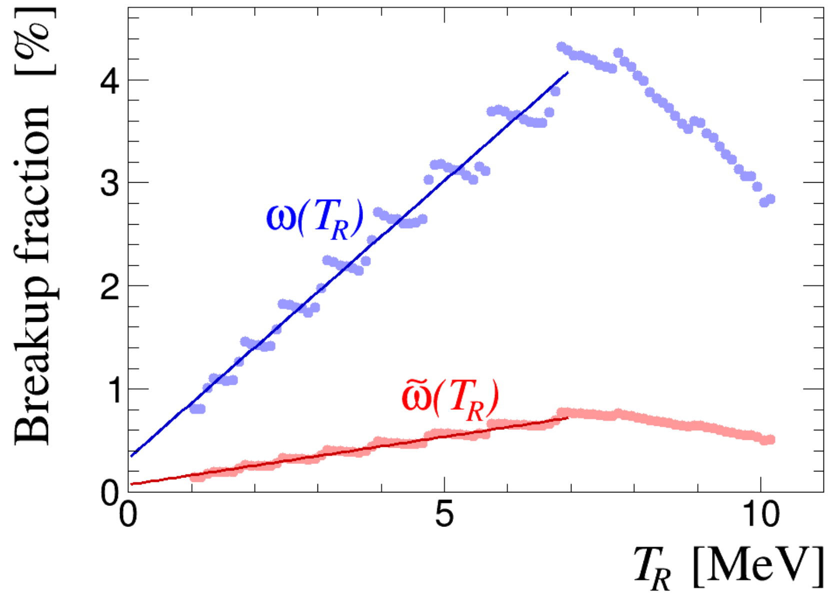
$d\sigma/dt$ @ $-t = 0.0066\ \mathrm{GeV}^2$
($T_R = 3.5\ \mathrm{MeV}$)

$15 \pm ?$	$\mathrm{mb/GeV^2}$	Theory
8 ± 2	$\mathrm{mb/GeV^2}$	Experiment
14 ± 4	$\mathrm{mb/GeV^2}$	From the HJET deuteron beam measurements



- The HJET measurement of the deuteron beam breakup is in reasonable agreement with the bubble chamber measurements
- The model used satisfactory describes the HJET measurements (within the experimental accuracy.
- Only a small fraction, $\sim 1.5\%$, of $d \to pn$ breakups can be detected at HJET.

Extrapolation to the ^{3}He *beam breakup at HJET*



- Using the model parametrization, $|\psi| \approx 5.6$, $\sigma_p \approx 35$ MeV, evaluated with the deuteron beam, the breakup rate for the 100 GeV/n helion beam was evaluated.
- For $\mathbf{1 < T_R < 10}$ **MeV**, the following $\boldsymbol{h \to pd}$ breakup fraction was calculated

$$\langle d\sigma_{h\to pd}/d\sigma_{\rm el}\rangle = 2.4 \pm 0.4\%$$

- Considering event selection cuts at HJET, the breakup fraction as a function of T_R was found

$$\frac{d\sigma_{h\to pd}(T_R)}{d\sigma_{h\to h}(T_R)} = \omega(T_R) = |\psi|^2 \int d\Delta\, \omega(T_R,\Delta)$$

$$\tilde{\omega}(T_R) = |\psi| \int d\Delta\, \omega(T_R,\Delta) = \omega(T_R)/|\psi|$$

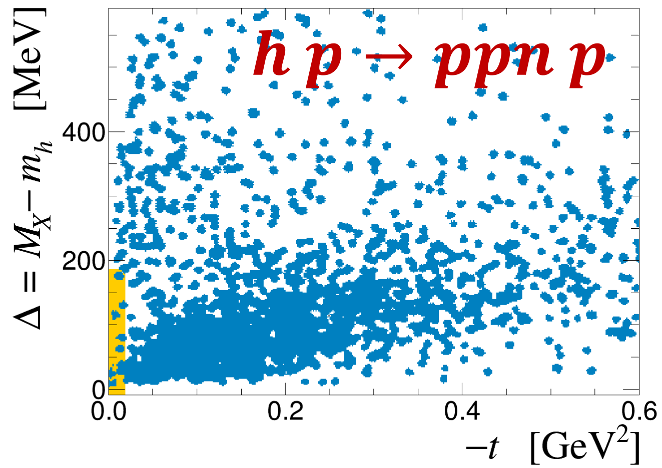
^{3}He *breakup measurements in the hydrogen bubble chamber*

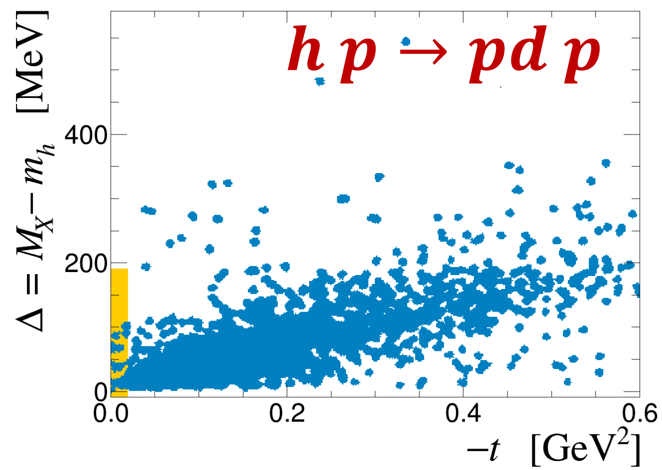
V.V. Glagolev et al., C **60**, 421 (1993)

$$\sigma_{el} = 24.2 \pm 1.0 \text{ mb}$$
$$\sigma_{h\to pd} = 7.29 \pm 0.14 \text{ mb}$$
$$\sigma_{h\to ppn} = 6.90 \pm 0.14 \text{ mb}$$

J. Stepaniak , Acta Phys. Polon. B **27**, 2971 (1996)

$E_{beam} = 4.6$ GeV/n





The effective cross sections in HJET measurements:

$\sigma^{HJET}_{elastic} \approx 11$ mb

$\sigma^{HJET}_{h\to ppn} < 0.02$ mb (bubble chamber)

$\sigma^{HJET}_{h\to pd} \sim 0.15$ mb (bubble chamber)

$\sigma^{HJET}_{h\to pd} \approx 0.25$ mb (*deuteron beam in HJET*)

The ^{3}He breakup rates $\omega(T_R)$ and $\tilde{\omega}(T_R)$ derived from the deuteron beam measurements at HJET can be interpreted as upper limits.

The breakup corrections in the ^{3}He beam polarization measurements with HJET

$$P^h_{\text{meas}}(T_R) = \frac{a_{\text{beam}}}{a_{\text{jet}}} P_{\text{jet}} \times \frac{\kappa_p - 2\, I_5 - 2\, R_5\, T_R/T_c}{\kappa_h - 0.54\, I_5 - 0.54\, R_5\, T_R/T_c}$$

The corrections:

$\kappa \to \kappa \times [1 + \widetilde{\omega}(T_R) \cos\varphi]$

$I_5 \to I_5 + \widetilde{\omega}(T_R) \times [\tilde{I}_5 \cos\varphi + \tilde{R}_5 \sin\varphi]$

$R_5 \to R_5 + \omega(T_R) \times \tilde{R}_5$

For the kinetic energy range $2 < T_R < 10$ MeV,

$$\widetilde{\omega}(T_R) \approx 0.23\% + 0.05\%\, T_R/T_c$$

$$\omega(T_R)\, T_R/T_c \approx \omega_0 + \omega_1\, T_R/T_c = -6.7\% + 4.5\%\, T_R/T_c$$

$$\left|\frac{\delta^{\text{brk}}_{\text{syst}} P^h_{\text{beam}}}{P^h_{\text{beam}}}\right| \lesssim \left|\left(\frac{2(0.27+\delta_{pd})}{\kappa_h} - \frac{2}{\kappa_p}\right)\omega_0 R_5\right| \leq \left|\left(\frac{0.54}{\kappa_h} - \frac{2}{\kappa_p}\right)\omega_0 R_5\right| \lesssim 0.2\%$$

A better result can be obtained in non-linear fit of the measured polarization:

$$P^h_{\text{meas}}(T_R) = P^h_{\text{beam}} \times \left[1 + \xi_1\, T_R/T_c + \xi_\omega \omega^{\text{calc}}(T_R)\, T_R/T_c\right]$$

Summary

- Feasibility for precisely measuring the EIC 100 GeV $^3\mathrm{He}$ beam polarization with the RHIC Polarized Atomic Hydrogen Gas Jet Target polarimeter was considered.
- Knowledge of the $p^{\uparrow}h$ and $h^{\uparrow}p$ analyzing power ratio is needed for such a measurement.
- Although the ratio is well defined by values of the proton and helion magnetic moments with accuracy of a few percent, the correction due to the proton-helion hadronic spin-flip amplitudes and due to the possible beam $^3\mathrm{He}$ breakup should be considered.
- The hadronic spin-flip amplitudes for $p^{\uparrow}h$ and $h^{\uparrow}p$ scattering can be derived, with sufficient accuracy, from proton-proton value of r_5 measured at HJET.
- The breakup corrections were found to be small and can be neglected in the polarization measurements.
- **It was found that the EIC $^3\mathrm{He}$ beam polarization can be measured with HJET with low systematic uncertainties satisfying the EIC requirement**

$$\boldsymbol{\sigma_P^{syst}/P \lesssim 1\%}$$