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The $p^{\uparrow}$ and $^{3}\mathrm{He}^{\uparrow}$ beam polarization measurements at the RHIC and future EIC using the Polarized Hydrogen Gas Jet Target

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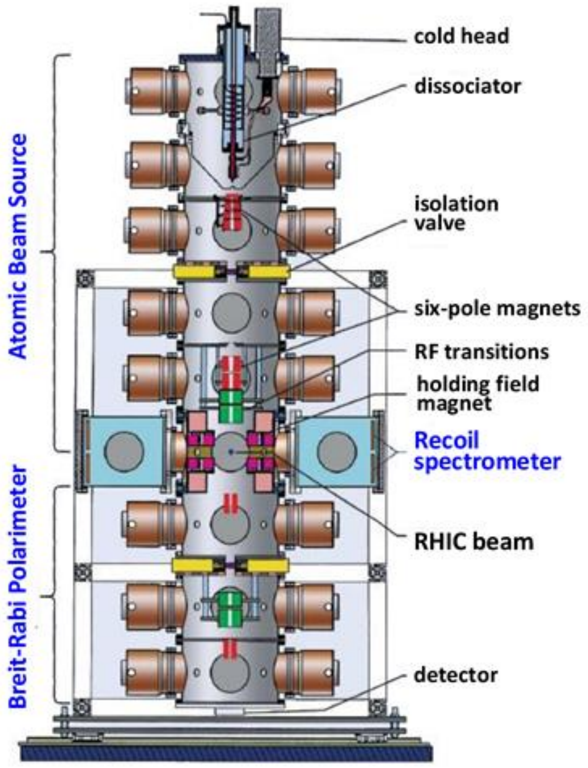
The Atomic Polarized Hydrogen Gas Jet Target (HJET)

- At RHIC, HJET is utilized to measure absolute polarization of the proton beams.
- For the future EIC, HJET is planned for the proton beam polarimetry with low systematic uncertainties of $\sigma_P/P \lesssim 1\%$.
- HJET is also considered for $^3\mathrm{He}$ beam polarimetry at EIC.

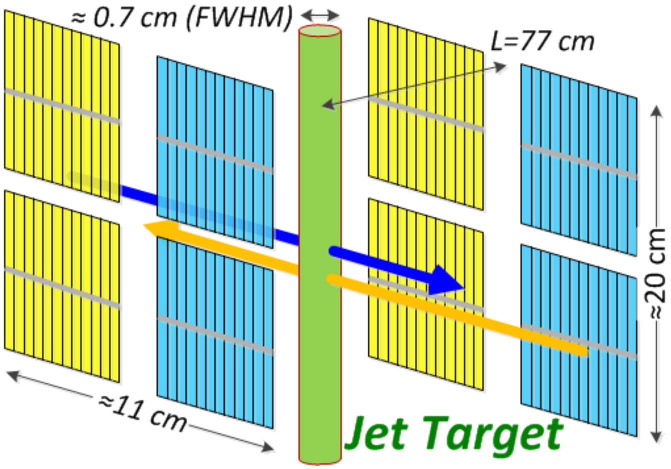
- The jet target polarization is $\boldsymbol{P}_{\mathbf{jet}} \approx \mathbf{96 \pm 0.1}\ \%$.
- The hydrogen gas target allows us to measure spin asymmetry in CNI region $\mathbf{0.0013 < -t < 0.018\ GeV^2}$ (where analyzing power is well predictable) with low background and low systematic uncertainties.

- Actually, HJET is a standalone fixed target experiment to measure $p^{\uparrow}p$ and $p^{\uparrow}A$ transverse analyzing powers $A_{\mathrm{N}}(t)$. The measurements are carried out in parasitic mode during RHIC operations with proton p or ion A beams.

A. Zelenski et al., Nucl. Instrum. Meth. A **536**, 248 (2005)



The Atomic Polarized Hydrogen Gas Jet Target (HJET)



A. P. et al., Nucl. Instrum. Meth. A **976**, 164261 (2020)

- The vertically polarized proton beams are scattered from the vertically polarized gas jet target.
- The recoil protons are detected in the vertically oriented Si strip detectors.
- For elastic events $\frac{z_R - z_{jet}}{L} \approx \sqrt{\frac{T_R}{2m_p}} \times \left(1 + \frac{m_p}{E_{beam}}\right)$
- $T_R = -t/2m_p$ is (measured) kinetic energy of the recoil proton

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

$$a_{beam}(T_R) = \frac{N_R^{\uparrow} - N_R^{\downarrow}}{N_R^{\uparrow} + N_R^{\downarrow}} = A_N(t) P_{beam}$$

$$a_{jet}(T_R) = \frac{N_R^{+} - N_R^{-}}{N_R^{+} + N_R^{-}} = A_N(t) P_{jet}$$

$$P_{beam} = \frac{\langle a_{beam}(T_R) \rangle}{\langle a_{jet}(T_R) \rangle} P_{jet}$$

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

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

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

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

B. Kopeliovich and L. Lapidus, Yad. Fiz. 19, 218 (1974)
N. Buttimore et al., Phys. Rev. D 18, 694 (1978)
N. Buttimore et al., Phys. Rev. D 59, 114010 (1999)

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:

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

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

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

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

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

(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

$$r_5 = \frac{m_p\,\phi_5^{\mathrm{had}}(s,t)}{\sqrt{-t}\,\mathrm{Im}\phi_+^{\mathrm{had}}(s,0)} = R_5 + iI_5, \qquad |r_5| \sim 2\%$$

$$\phi_5^{\mathrm{had}}(s,t) = \frac{\sqrt{-t}}{m_p}\,\frac{r_5}{i+\rho}\,\phi_+^{\mathrm{had}}(s,0)$$

Some important corrections to $A_N(t)$

- The following parametrization of $A_N(t)$ [N. Buttimore et al., Phys. Rev. D 59, 114010 (1999)] was standardly used in experimental data analysis's]

$$A_N(t) = \frac{\sqrt{-t}}{m_p} \frac{\left[\kappa_p(1-\rho\delta_C)-2(I_5-R_5\delta_C)\right]t_c/t - 2(R_5-\rho I_5)}{(t_c/t)^2-2(\rho+\delta_C)t_c/t+1+\rho^2}$$

- However, it was pointed out [B. Kopeliovich and M. Krelina (2017)] that
  - ✓ The difference between hadronic $B = 11.2\ \mathrm{GeV}^{-2}$ $(p_{Lab} = 100\ \mathrm{GeV})$ and electromagnetic $B_{\mathrm{em}} = \frac{2}{3}\langle r_p^2\rangle = 12.1\ \mathrm{GeV}^{-2}$ slopes was neglected. The following correction may be needed

$$\boldsymbol{t_c/t} \rightarrow \boldsymbol{t_c/t} + (B_{\mathrm{em}} - B)/2$$

  - ✓ The electromagnetic form factor was determined in ep scattering. For pp scattering it is modified by the absorption effect $B_{\mathrm{em}} \rightarrow B_{\mathrm{em}} + \mathrm{a}$, which results in

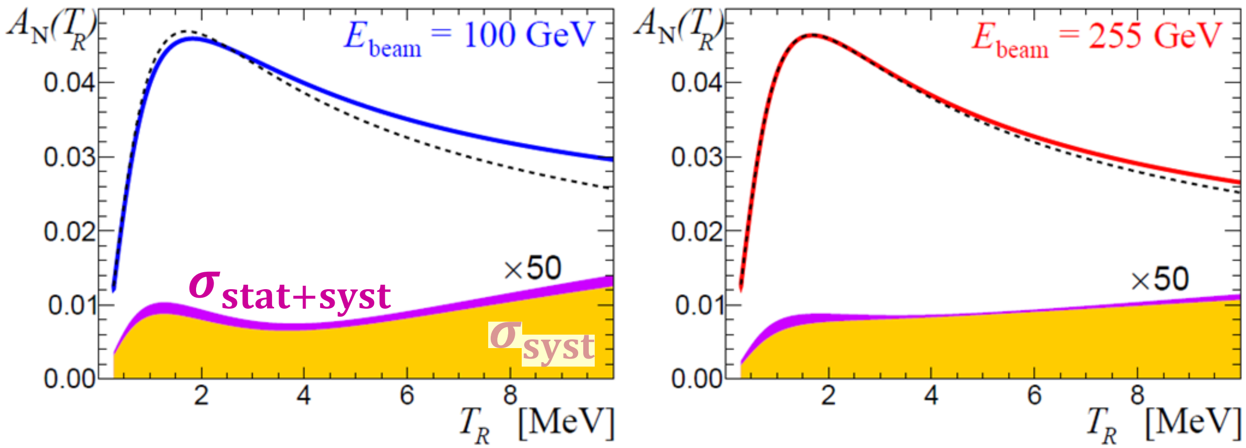
$$\boldsymbol{R_5} \rightarrow \boldsymbol{R_5} - \frac{\alpha\,\kappa_p}{2}\,\frac{B}{B+B_{\mathrm{em}}^{\mathrm{sf}}} \approx \boldsymbol{R_5} - 0.003$$

The corrections

- are essential for the HJET experimental accuracy.
- may alter interpretation of the STAR results for elastic pp $A_N(t)$ at $\sqrt{s} = 200\ \mathrm{GeV}$.
- are critically important for understanding $p^{\uparrow}\mathrm{Au}$ analyzing power.

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

A.P. *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 the leading order approximation predicted in 1974.

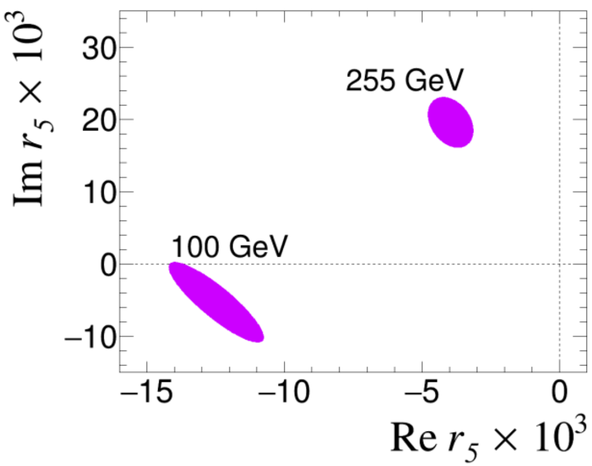
The measured hadronic spin flip amplitudes:

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

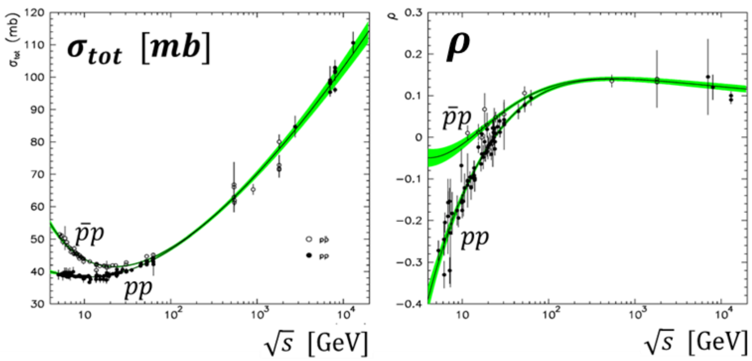
$I_5 = (-5.3 \pm 2.9_{stat} \pm 4.7_{syst}) \times 10^{-3}$

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

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



Incorporating spin dependence in a Regge pole analysis



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

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

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

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

$$\boldsymbol{\sigma_{tot}(s) \times [i + \rho(s)] = P(s, \alpha_F) + R^+(s, \alpha_{R^+}) + R^-(s, \alpha_{R^-})}$$

$$\boldsymbol{\sigma_{tot}(s) \times r_5(s) = f_5^P P(s, f_F) + f_5^+ R^+(s, \alpha_{R^+}) + f_5^- R^-(s, \alpha_{R^-})}$$

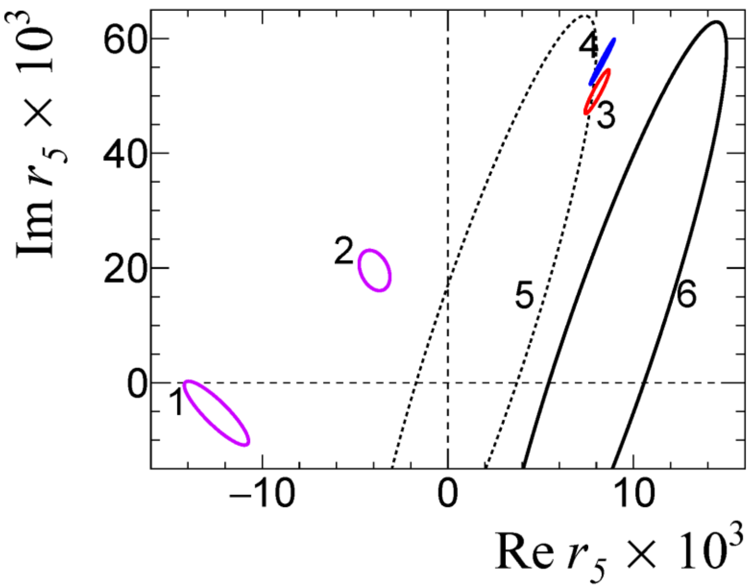
The HJET $r_5(s)$ data fit:

$$\chi^2/\mathrm{ndf} = 0.7/1$$
$$f_5^P = 0.054 \pm 0.002_{stat} \pm 0.003_{syst}$$

Pomeron single spin-flip coupling is well determined and found to be significantly different from zero.

- Although, the model used to fit $r_5(s)$ is oversimplified, it is in good consistent with the HJET measurements.
- Any improvements cannot be statistically significant if only HJET data is used.
- The HJET results cannot be explained by Regge poles $R^{\pm}(s)$ only.

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** $(\alpha_{R^+} = 0.65,\ \alpha_{R^-} = 0.45,\ \alpha_F = 0.009)$

  $\chi^2/\mathrm{ndf} = 0.7/1$ **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**

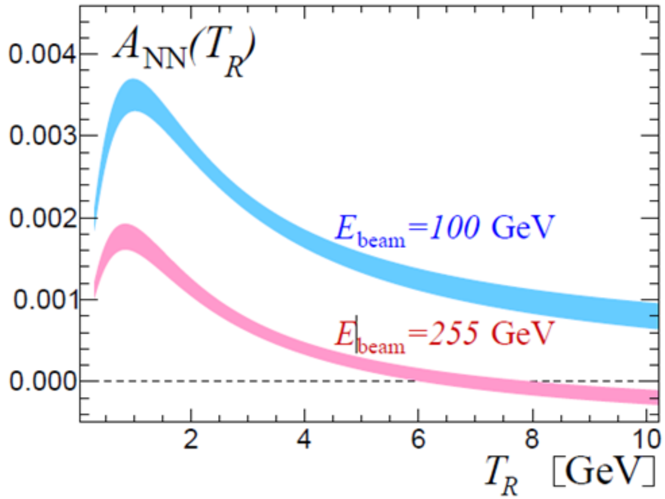
  $\alpha_P^{\mathrm{nf}} = 1.096^{+0.012}_{-0.009}$ (global fit of the unpolarized data)

- Some discrepancy between HJET (extrapolated) and STAR (corrected) values of r_5 is statistically equivalent to *1.8 standard deviations*.
- The correction applied to the STAR value of r_5 is mainly due to the difference between $B_{\mathrm{em}}^{\mathrm{eff}}$ (including absorption) and hadronic slope B. There was **no revision of the measured** $A_N(t)$.
- Theoretical estimates of Pomeron contribution to r_5 at $\sqrt{s} = 200$ GeV should be compared with the corrected STAR value rather than with the published one.

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

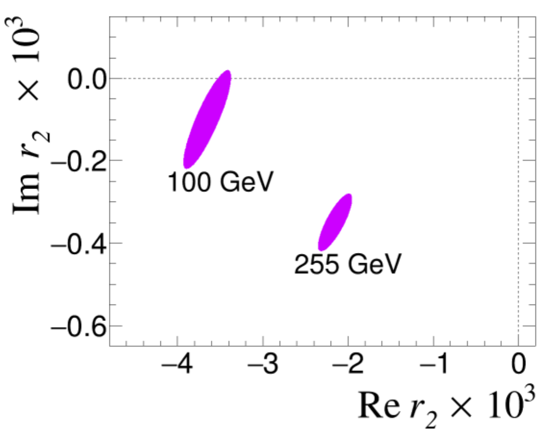
A.P. *et al.*, Phys. Rev. Lett. **123**, 162001 (2019)

$$\frac{d^2\sigma}{dtd\varphi} \propto \left[1 + A_N(t)\sin\varphi\,(P_b + P_j) + A_{NN}(t)\sin^2\varphi\,P_b\,P_j\right]$$ (at HJET, $\sin\varphi = \pm1$)



Double spin-flip amplitude parameter $r_2 = \frac{\phi_2^{had}(s,t)}{2\,\mathrm{Im}\,\phi_+^{had}(s,0)} = R_2 + iI_2$

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



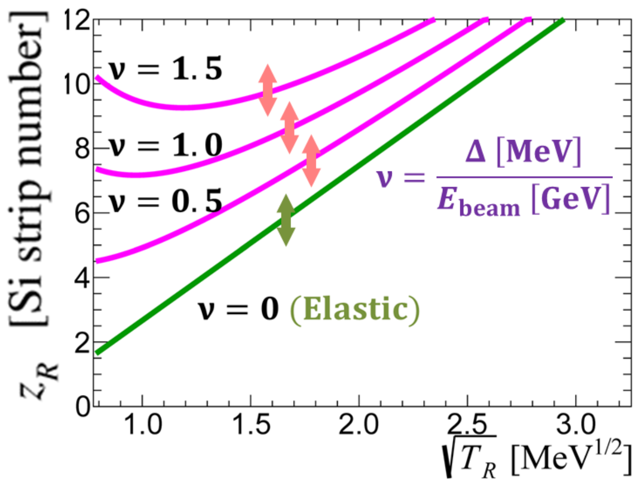
- The hadronic double spin-flip amplitudes are well isolated
- The Regge fit suggests non-zero double spin-flip Pomeron coupling
  $\chi^2/\mathrm{ndf} = 1.6/1$
  $f_2^P = -0.0020 \pm 0.0002_{stat}$
- The sensitivity of $A_{NN}(t)$ to the Odderon was discussed in E Leader and T. Trueman, Phys. Rev. D 61, 077504 (2000). The measured $A_{NN}(t)$ noticeably disagrees with the theoretical estimate without Odderon contribution.

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 $A + p \rightarrow X + p$ scattering:

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

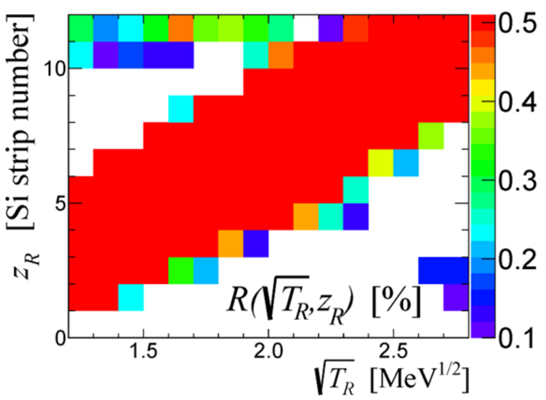
$\Delta = M_X - m_p > m_\pi$
E_{beam} is the beam energy per nucleon



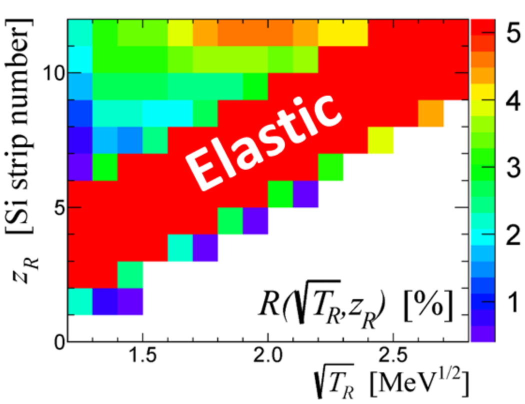
- The inelastic events occupy the area above the elastic line.
- For the 100 GeV beam, the inelastic event detection in HJET is strongly suppressed.
- For 255 GeV elastic events are well detected (but not overlapped with the elastic ones)

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

100 GeV

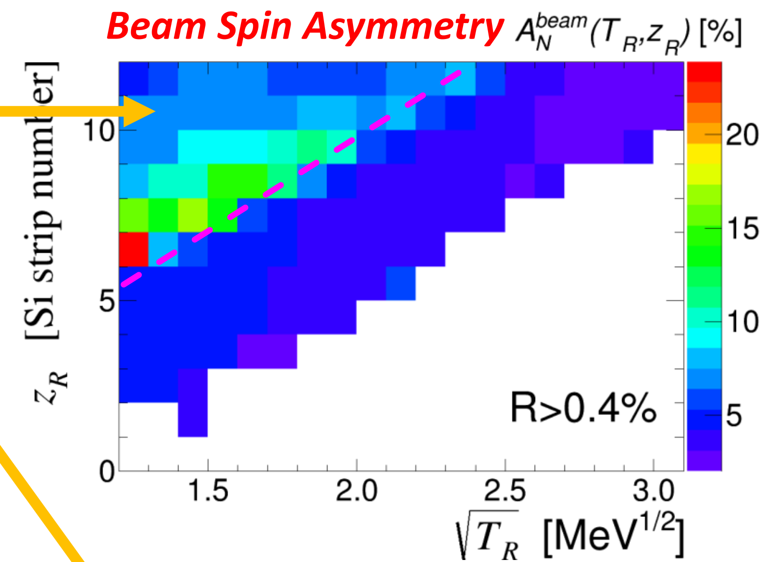


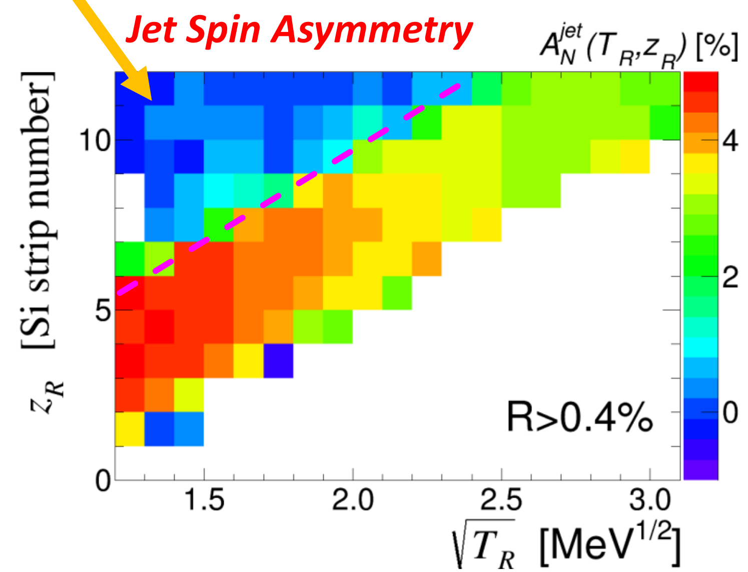
255 GeV



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

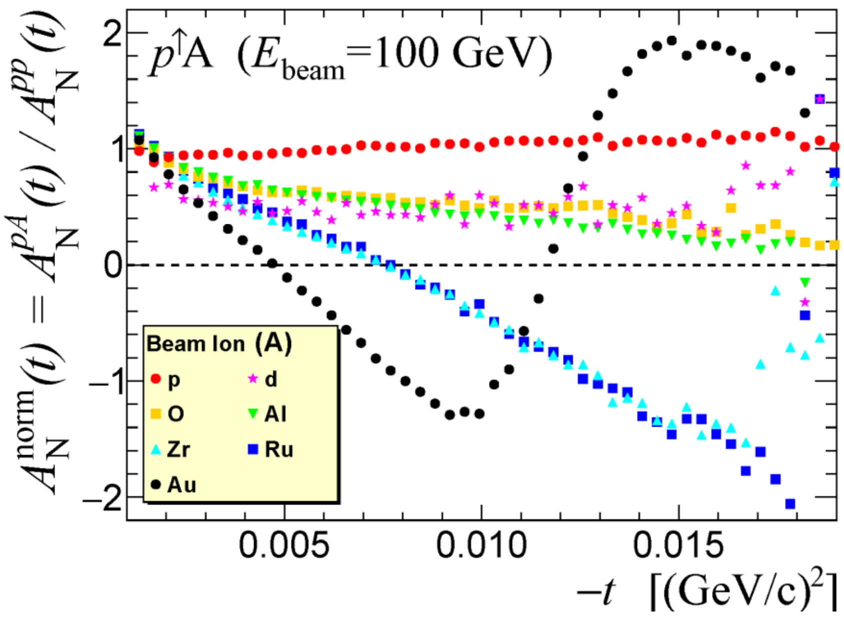
- The inelastic events can be isolated.
- $A_{\mathrm{N}}^{\mathrm{jet}\,(in.)} < A_{\mathrm{N}}^{\mathrm{elastic}} < A_{\mathrm{N}}^{\mathrm{beam}\,(in.)}$
- $A_{\mathrm{N}}^{(in.)}(t,\Delta)$ grows with decreasing Δ.
- $A_{\mathrm{N}}^{\mathrm{beam}\,(in.)}(t,\Delta) \sim 20\%$ is observed in the data.

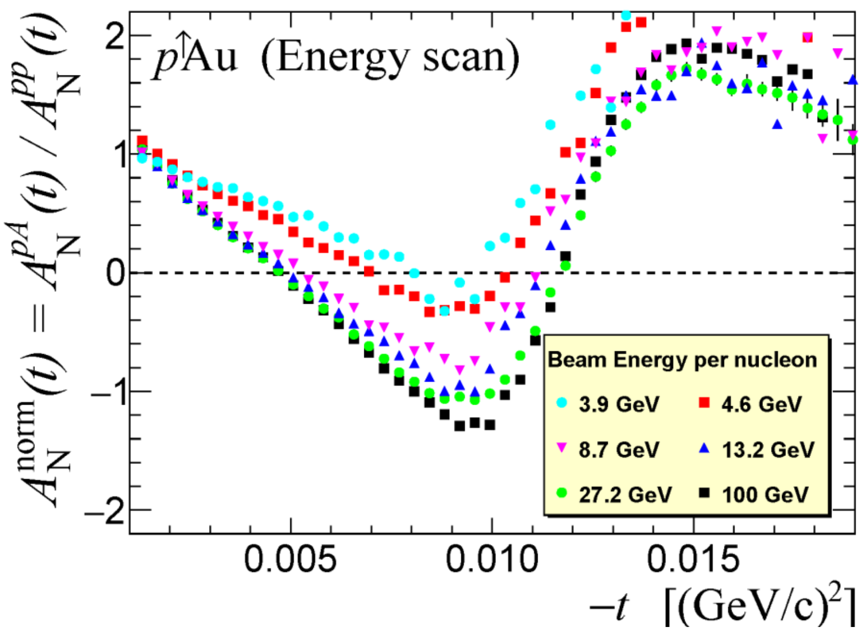




Similar result (qualitatively) was also observed for 100 GeV beam, but the statistics was much lower.

Proton-nucleus Scattering at HJET





- Since $r_5^{pA} \approx r_5^{pp}$, proton-nucleus A_N for 100 GeV may allow us to study nonflip pA amplitudes for wide range of A.
- If the result can be extrapolated to the 4-30 GeV/nucleon Au beam, r_5^{pp} can be evaluated in this energy range.

In HJET measurements, the breakup contamination of the elastic data is strongly suppressed.

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

3.85 GeV/n:	$0.20 \pm 0.12\%$	$[3.6 < \Delta < 8.5\ \rm MeV]$
26.5 GeV/n:	$-0.08 \pm 0.06\%$	$[\ 20 < \Delta < 60\ \rm MeV]$

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

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

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

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

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

$\kappa_p = \mu_p - 1 = 1.793$
$\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$
$T_c \approx 0.7$ MeV

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

Since $r_5^{pA} = r_5^{pp}\frac{i+\rho^{pA}}{i+\rho^{pp}} \approx r_5^{pp}$ [B. Kopeliovich and T. Trueman, Phys. Rev. **D 64**, 034004 (2001)],

$$r_5^{ph} \approx r_5^{pp}$$

$$r_5^{hp} \approx r_5^{pp}\langle P_{p,n}\rangle \approx r_5^{pp}/3$$

Systematic error in the ^{3}He beam polarization measurements due to possible uncertainties in values of r_5^{ph} and r_5^{hp} is expected to be small

$$\frac{\sigma_P^{\text{syst}}\left(r_5^{ph}/r_5^{pp}, r_5^{hp}/r_5^{pp}\right)}{P} \ll 1\%$$

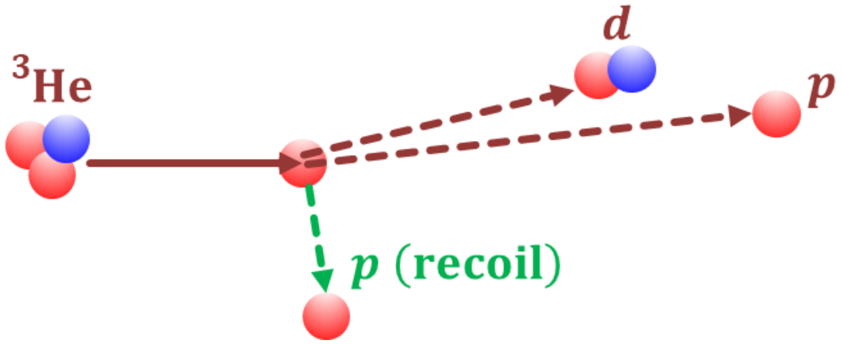
^{3}He breakup

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

$$d\sigma_{el}(T_R) \rightarrow d\sigma_{el}(T_R) + \int d\Delta \, \frac{d\sigma_{\text{brk}}(T_R,\Delta)}{d\Delta} \, \varepsilon_{\text{acc.}}(T_R,\Delta)$$

$$= d\sigma_{el}(T_R) \times [1 + \omega(T_R)]$$

$\boldsymbol{T_R = -t/2m_p}$, $\boldsymbol{\Delta = M_X - m_h}$



Similar corrections,

$$1 + \omega_{\text{int}}(T_R), \qquad \omega_{\text{int}} \in \{\omega_\kappa^p, \omega_I^p, \omega_R^p, \omega_\kappa^h, \omega_I^h, \omega_R^h\}$$

modify the interference terms in the analyzing power ratio

$$\frac{\kappa_p - 2I_5^{ph} - 2R_5^{ph}\, T_R/T_c}{\kappa_h - 2I_5^{hp} - 2R_5^{hp}\, T_R/T_c} \Longrightarrow \frac{\kappa_p[1+\omega_\kappa^p] - 2I_5^{ph}[1+\omega_I^p] - 2R_5^{ph}[1+\omega_R^p]\, T_R/T_c}{\kappa_h[1+\omega_\kappa^h] - 2I_5^{hp}[1+\omega_I^h] - 2R_5^{hp}[1+\omega_R^h]\, T_R/T_c}$$

Since for all $\omega(T_R)$ and $\omega_{\text{int}}(T_R)$,

$\omega(T_R \rightarrow 0) = 0$,

The breakup corrections cancel in the extrapolation of the measured ^{3}He beam polarization

$P^h_{\text{meas}}(T_R \rightarrow 0)$.

The breakup corrections

AP, Phys. Rev. C **108**, 025202 (2023)

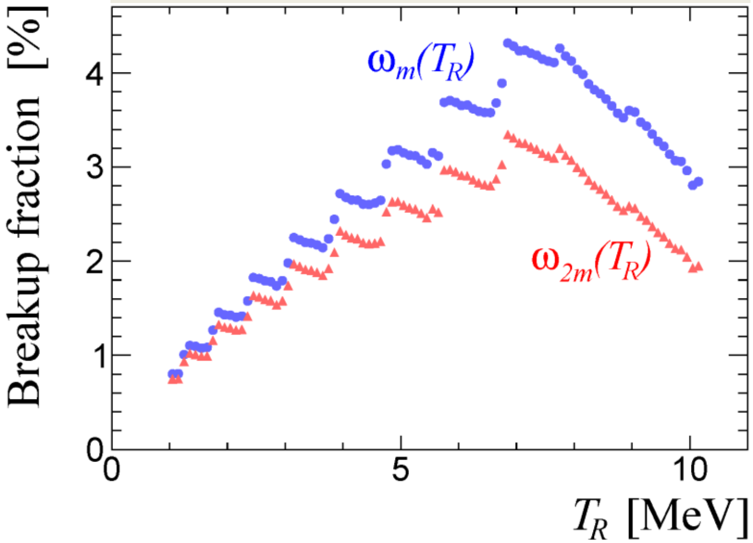
An incoherent scattering of proton from ^{3}He can be approximated by scattering off a nucleon $(m^* = m_p)$ or di-nucleon $(m^* = 2m_p)$. Thus, the breakup corrections (to the interference terms) are limited by:

$$\omega_{2m}(T_R) \le \omega_{\rm int}(T_R) \le \omega_m(T_R)$$

Assuming linear fit of the measured polarization $P^h_{meas}(T_R)$, the following estimate can be done :

$$\left|P^h_{\rm meas}(T_R)/P^h_{\rm beam} - 1\right| \;<\; |\omega_m(T_R) - \omega_{2m}(T_R)|/2 \approx -0.11\% + 0.13\% \frac{T_R}{T_c}$$

The ^{3}He breakup fraction estimate followed from the experimental study of the deuteron beam breakup at HJET:



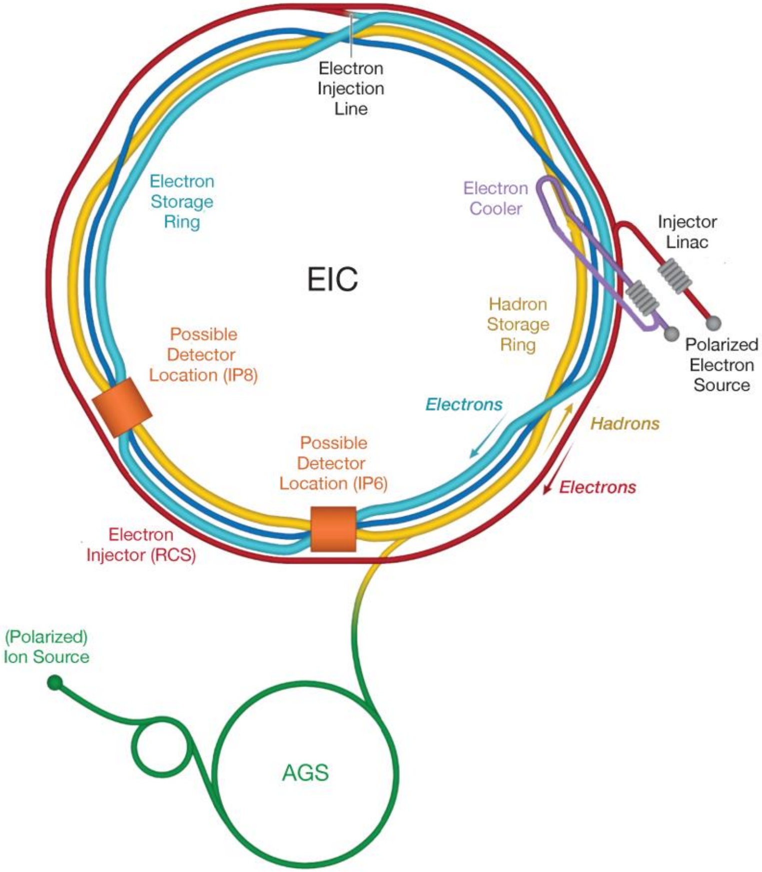
Effect of the helion breakup is negligible in the EIC ^{3}He beam polarization measurement using HJET.

Summary

- HJET, which was designed to measure absolute proton beam polarization at RHIC, can also be used for the proton and $^3\mathrm{He}$ beam polarimetry in the future EIC.
- The HJET performance allows us to study $p^\uparrow p^\uparrow$ and $p^\uparrow A$ transverse analyzing powers in the Coulomb-nuclear interference scattering, $0.0013 < -t < 0.018\ \mathrm{GeV}^2$.
- To complete the HJET experimental data analysis, the following theoretical calculations (studies) are important:
  - ✓ Regge pole, including Pomeron/Froissaron $P(t,s)$ and Odderon $O(t,s)$ functions, which can be used to study single $r_5(s)$ double $r_2(s)$ spin-flip elastic pp amplitude at low t.
  - ✓ The beam and target analyzing power parametrization for the inelastic pp scattering $p^\uparrow_{\mathrm{beam}} + p^\uparrow_{\mathrm{target}} \to X + p_{\mathrm{recoil}}$.
  - ✓ Parametrization (ready to use in the HJET data) for the forward $p^\uparrow A$ analyzing power $A_N(t,s,A)$ for $|t| < 0.02\ \mathrm{GeV}$, $2 < A < 200$, and the proton beam energy $4 < E_p < 100\ \mathrm{GeV}$.
  - ✓ More accurate calculation of the breakup effects in the $^3\mathrm{He}$ beam scattering of the HJET protons is needed.

Backup

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

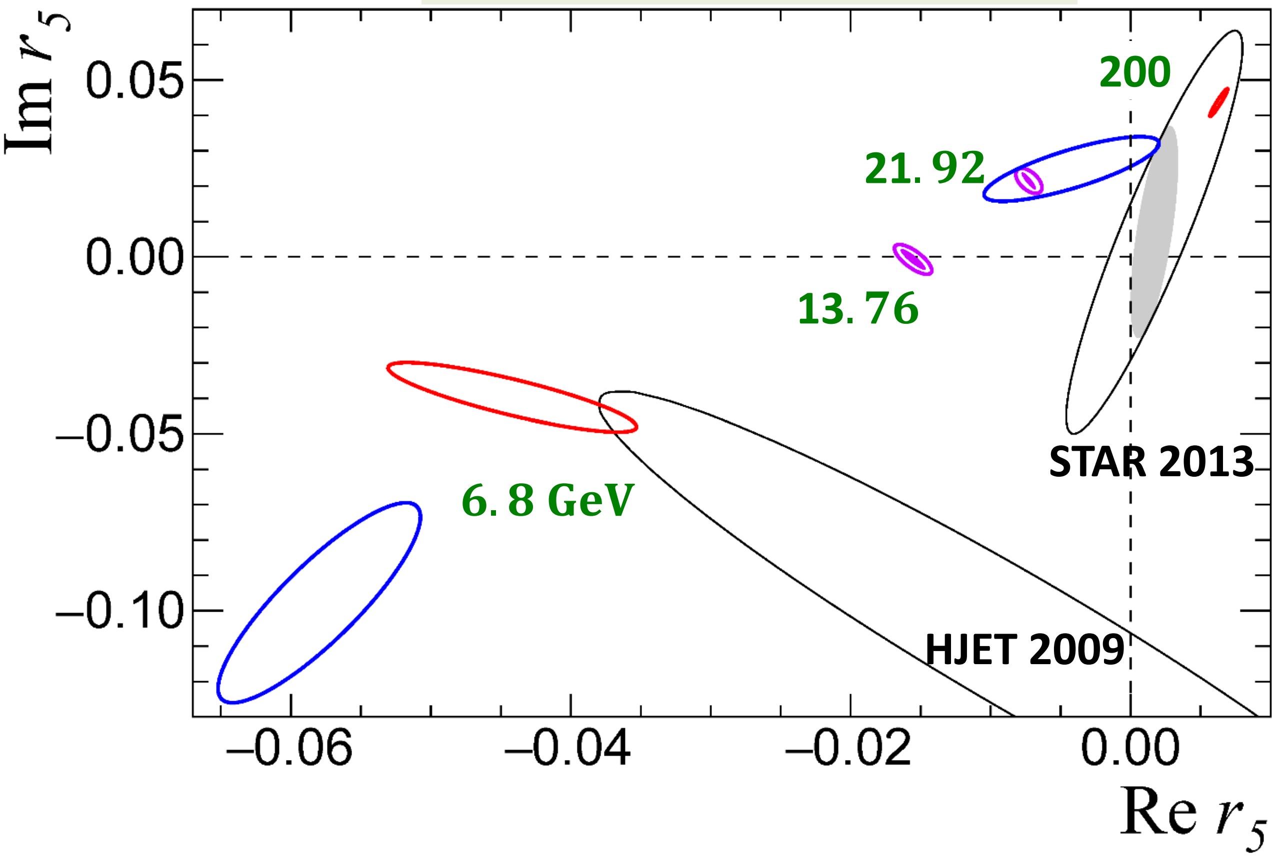
- **A complete analysis of the beam polarization includes measurement of the polarization profile, polarization decay time, …**
- **The main goal of this presentation is to discuss the RHIC Hydrogen Jet Target (HJET) feasibility to measure the $^3He^{\uparrow}$ beam averaged absolute polarization at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

Hadronic Single Spin-Flip Amplitude $r_5(\sqrt{s})$

Color Legend:

- This work (13.76 and 21.92 GeV)
- R±P extrapolation to 6.8 and 200 GeV
- R±PO extrapolation to 6.8 and 200 GeV
- Other measurements (6.8 and 200 GeV)

Very-very preliminary
(shown at SPIN 18)



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)

$\chi^2 = 2.2/5$

$R^{\pm}\ P\ O$

$f_5^+ = 0.057 \pm 0.034$

$f_5^- = 1.141 \pm 0.239$

$f_5^P = 0.032 \pm 0.009$

$f_5^O = -0.107 \pm 0.252$

$\chi^2 = 7.7/4$

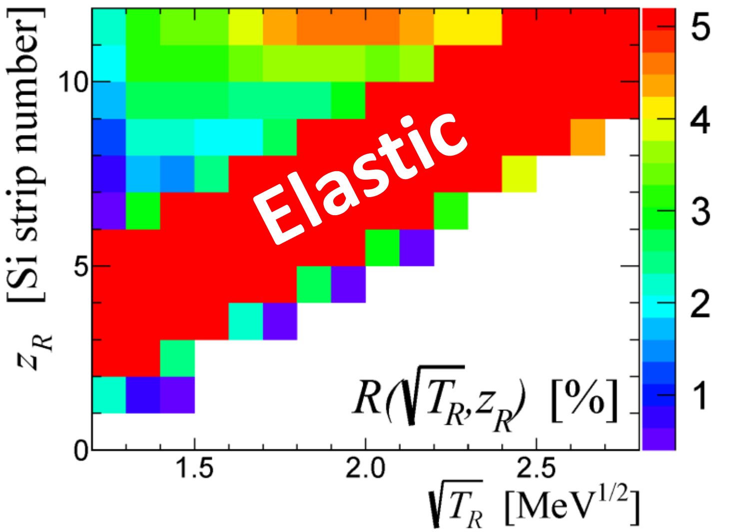
STAR 2013: ($\sqrt{s} = \mathbf{200\ GeV}$), L. Adamczyk et al, Phys. Lett. B **719** (2013) 62.
HJET 2009: ($\sqrt{s} = \mathbf{6.8\ GeV}$), I.G. Alekseev et. al., Phys. Rev. D **79**, 094014 (2009)

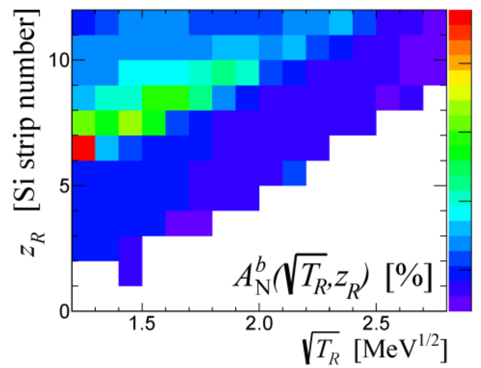
$p^{\uparrow}_{\text{beam}} + p^{\uparrow}_{\text{jet}} \rightarrow X_{\text{beam}} + p_{\text{jet}}$

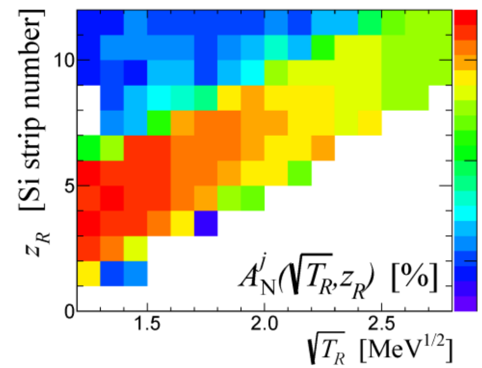
$R(T_R, z_R) = N_{\text{bin}}(T_R, z_R)/N^{el}_{\text{max}}$

For the inelastic scattering
$\Delta > m_\pi$

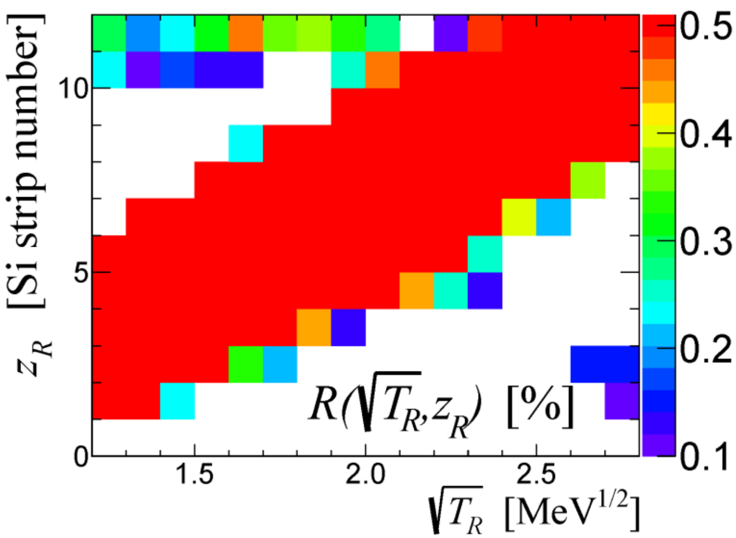
255 GeV

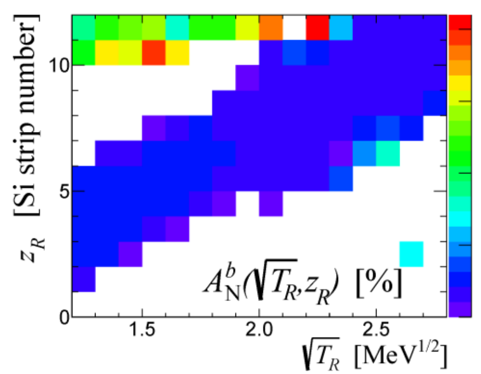


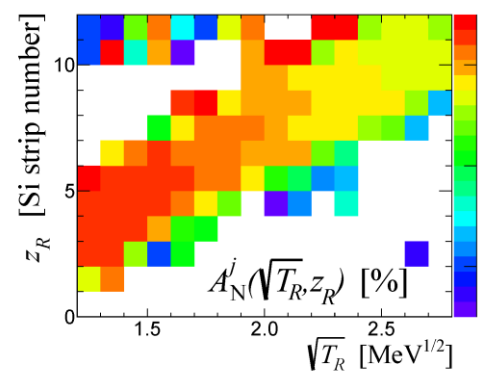




100 GeV







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

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

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),

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

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

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

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

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 $\mathbf{p} + h^{\uparrow} \rightarrow p + h$ *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 $S_{a,b,\ldots} = S_{b,a,\ldots} = S_{b,c,\ldots}$, 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)]

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

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

For a breakup scattering $p^{\uparrow}A \rightarrow pX$ (e.g., $\boldsymbol{ph \rightarrow ppd}$), 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,

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

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

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

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

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

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

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

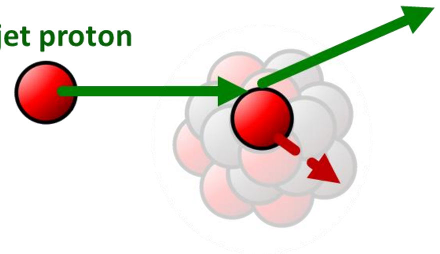
$$\tilde{\boldsymbol{r}}_{\boldsymbol{5}}^{\boldsymbol{p^{\uparrow}A}} = \boldsymbol{r_5}$$

A model used to search for the h→ pd breakup events at HJET

For incoherent proton-nucleus scattering,

a simple kinematical consideration gives:

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



where $m^* = m_p$ and p_x is the target nucleon transverse momentum

Assuming the following p_x distribution,

$$f_{\mathrm{BW}}(p_x, \sigma_p) = \frac{\pi^{-1}\sqrt{2}\sigma_p}{p_x^2 + 2\sigma_p^2}, \qquad \int f_{\mathrm{BW}}(p_x, \sigma_p)\, dp_x = 1,$$

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

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

phase space factor

$$\frac{d^2\sigma_{h\to pd}(T_R, \Delta)}{d\sigma_{h\to h}(T_R)\, d\Delta} = |(\psi_0 T_R, \Delta)|^2 \omega(T_R, \Delta) = |\psi_0|^2 f_{BW}(\Delta - \Delta_0, \sigma_\Delta) \frac{\sqrt{2m_p m_d}}{4\pi m_h} \sqrt{\frac{\Delta - \Delta_{\mathrm{thr}}^h}{m_h}}$$

$p^{\uparrow}A \to p + A_1A_2$ *scattering*

	nonflip amplitudes	spin-flip amplitudes
Elastic:	$f_{\text{el}}(T_R)$	$f_{\text{el}}^{\text{sf}}(T_R) \quad = f_{\text{el}}(T_R)\,\frac{\boldsymbol{k}_p\boldsymbol{n}}{m_p}\,\frac{r_5^{pA}}{i+\rho^{pA}}$
Breakup:	$f_{\text{brk}}(T_R,\Delta) = f_{\text{el}}(T_R)\;\tilde{f}_{\text{brk}}(T_R,\Delta)$	$f_{\text{brk}}^{\text{sf}}(T_R,\Delta) = f_{\text{el}}(T_R)\;\tilde{f}_{\text{brk}}(T_R,\Delta)\,\frac{\boldsymbol{k}_p\boldsymbol{n}}{m_p}\,\frac{\tilde{r}_5^{pA}}{i+\rho^{pA}}$

$T_R \;= -t/2m_p$
$\Delta \;\; = M_X - M_A \approx (M_X^2 - M_A^2)/2M_A$
$\boldsymbol{k}_p$ is the recoil proton momentum
$\boldsymbol{n}$ is unit vector perpendicular the beam spin an momentum

Similarly to the elastic pA scattering:

$$\tilde{r}_5^{pA} = r_5^{pp}\,\frac{i+\rho^{pA}}{i+\rho^{pp}} = r_5^{pA}$$

Using the previous page notations:

$$f_{\text{brk}}(T_R,\Delta) = f_{el}(T_R)\;\psi_0(T_R,\Delta)\;\psi_{\text{BW}}(T_R,\Delta) \qquad |\psi_{BW}(T_R,\Delta)|^2 = f_{BW}(\Delta - \Delta_0, \sigma_\Delta)$$

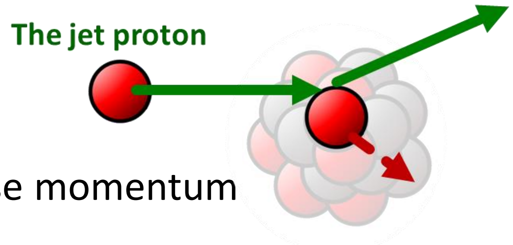
- $f_{el}(T_R)$: Explains dependence on T_R
- $\psi_{\text{BW}}(T_R,\Delta)$: Explains dependence on Δ
- $\psi_0(T_R,\Delta)$: For the low $t \to 0$ scattering,

$$\psi_0\,(T_R,\Delta) \approx \psi_0\,(0{,}0),$$

should be **the same for all, nonflip/spin-flip and hadronic/electromagnetic**, amplitudes of the considered breakup $A \to A_1 + A_2$

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, $\Delta < 50\text{ MeV}$ 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)

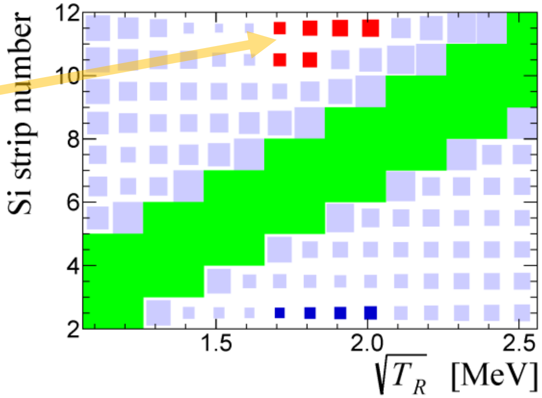
- In RHIC Run 16, deuteron-gold scattering was studied at beam energies 10, 20, 31, and 100 GeV/n.
- In the HJET analysis, the breakup events $d \to p + n$ $\left(\Delta^{d}_{\text{thr}} = 2.2\ \text{MeV}\right)$ were isolated for 10, 20, and 31 GeV data.
- The breakup was evaluated for $2.8 < T_R < 4.2\ \text{MeV}$
- In the data fit, the $d \to pd$ breakup fraction $\omega(T_R, \Delta)$ was parameterized,

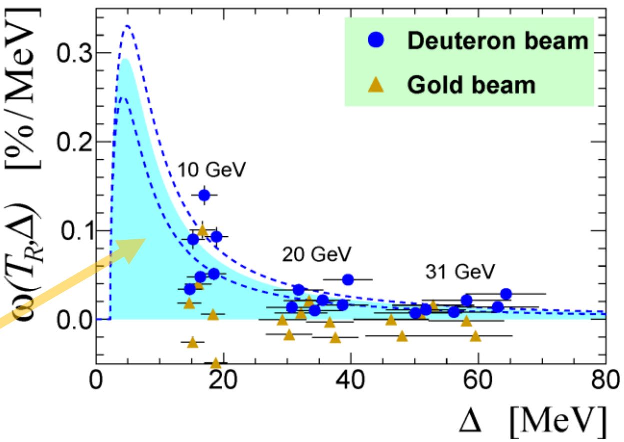
$$|\psi| \approx 5.6, \quad \sigma_p \approx 35\ \text{MeV}$$

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

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

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





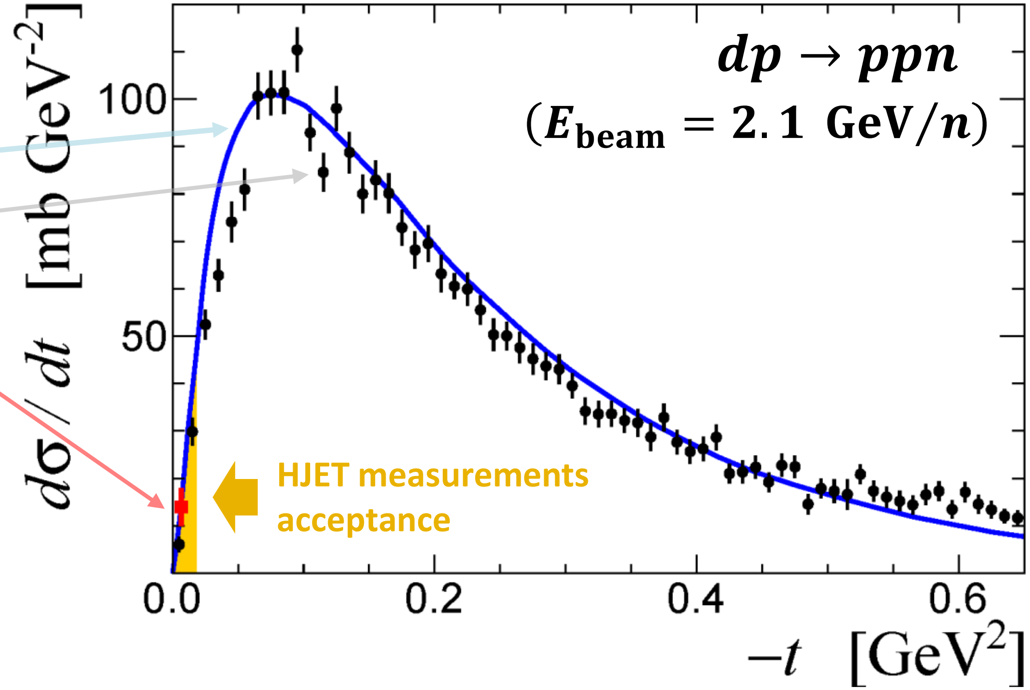
- The result obtained strongly depends on the used parametrization and, thus, a verification is needed.

$d \to pn$ 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.

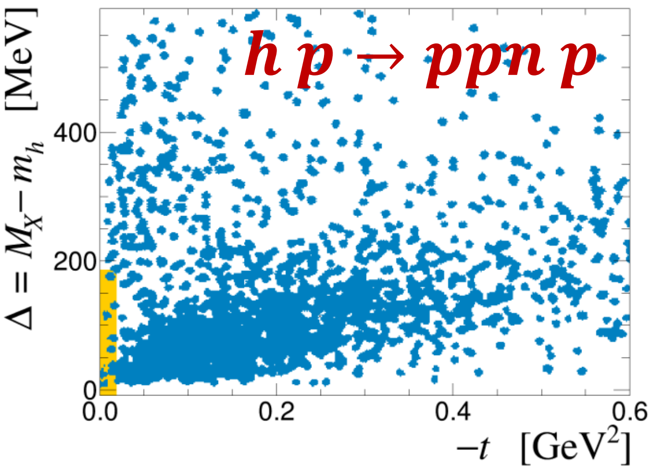
^{3}He *breakup measurements in the hydrogen bubble chamber*

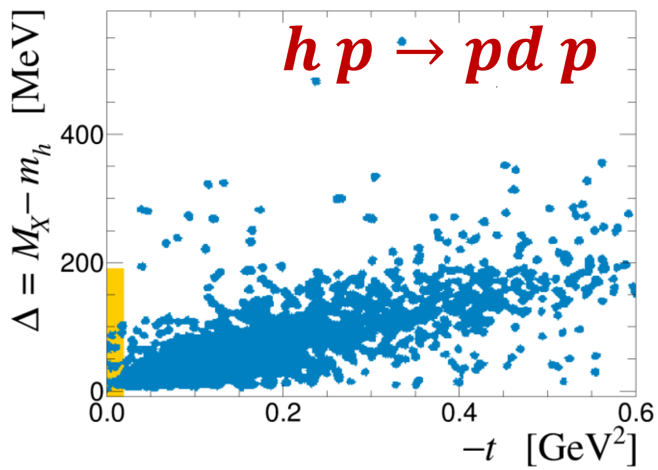
V.V. Glagolev et al., C **60**, 421 (1993)

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

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

$E_{\text{beam}} = 4.6\ \text{GeV/n}$





The effective cross sections in HJET measurements:

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

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

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

$\sigma^{\text{HJET}}_{h\to pd} \approx 0.25$ 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.