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The Polarized Hydrogen Gas Jet Target. From RHIC to EIC.

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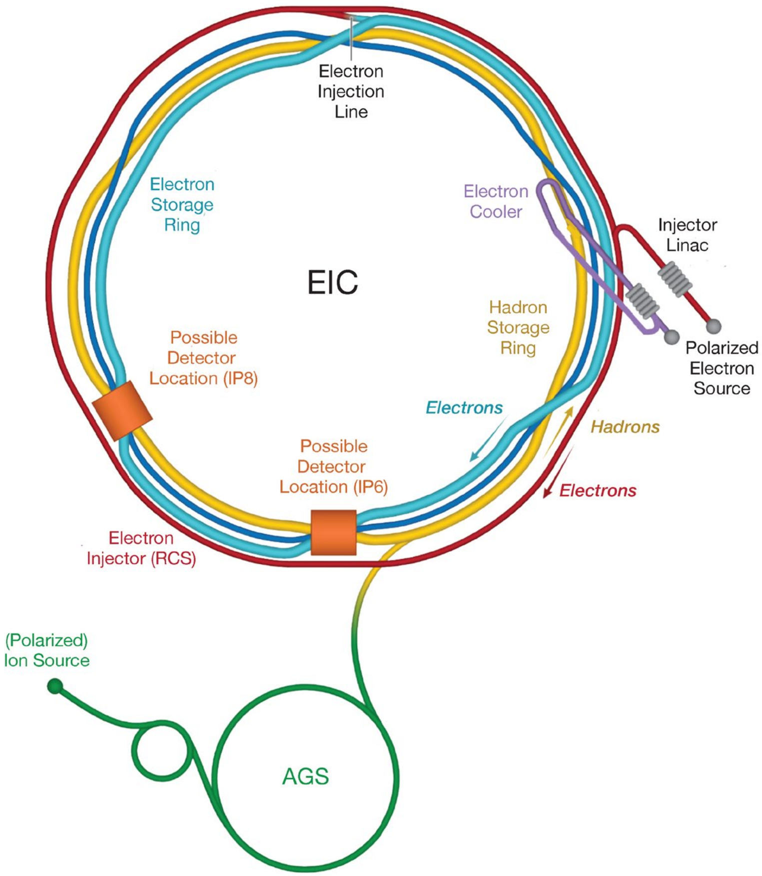
Hadronic polarimetry at the EIC



High energy, 41-275 GeV polarized proton and helion (^{3}He$^\uparrow$) 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

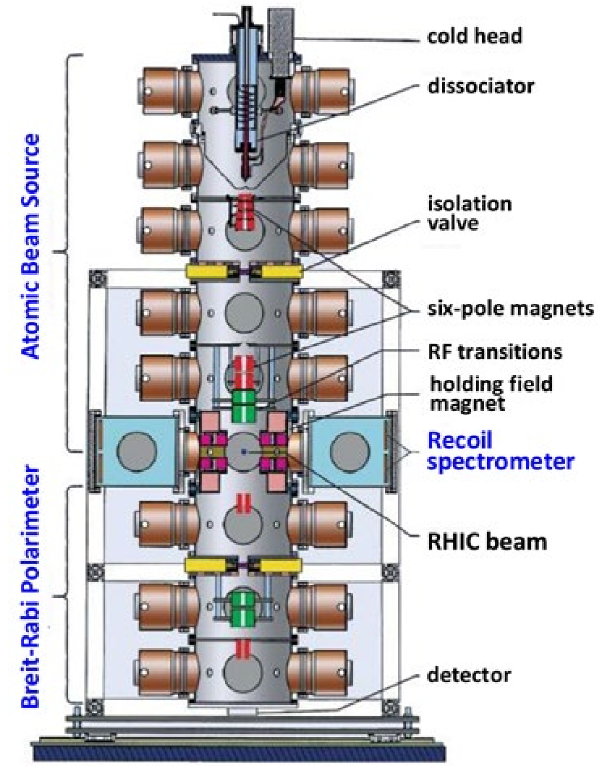
- Much shorter, 10 ns bunch spacing (107 ns at RHIC)
- ^{3}He$^\uparrow$ beam

- **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 provide absolute calibration of the *p*$^\uparrow$ and ^{3}He$^\uparrow$ beam polarization at EIC.**

The Atomic Polarized Hydrogen Gas Jet Target (HJET)

- HJET was designed to measure absolute polarization of the proton beams with accuracy <5% in RHIC Spin Program.
- It was commissioned in 2005.
- The actual performance of HJET significantly surpassed the design requirements.

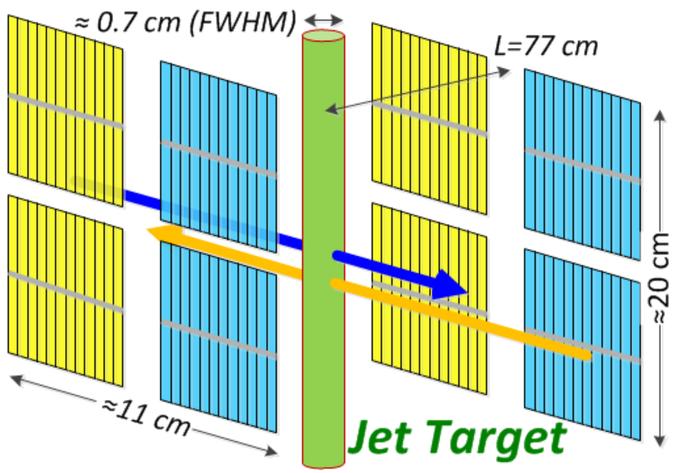
A. Zelenski et al., Nucl. Instrum. Meth. A **536**, 248 (2005)



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

- During RHIC Runs, HJET can operate continuously in parasitic mode (i.e., without disturbing RHIC beams).
- In numerous measurements (for 20 years) with proton $p^\uparrow$ and ion $(d, \mathrm{O}, \mathrm{Al}, \mathrm{Ru}, \mathrm{Zr}, \mathrm{Au})$ beams
    - transverse analyzing powers $A_{\mathrm{N}}(t)$ for $p^\uparrow p$ and $p^\uparrow A$ scattering was measured
    - HJET performance was well studied

The HJET recoil spectrometer



AP 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

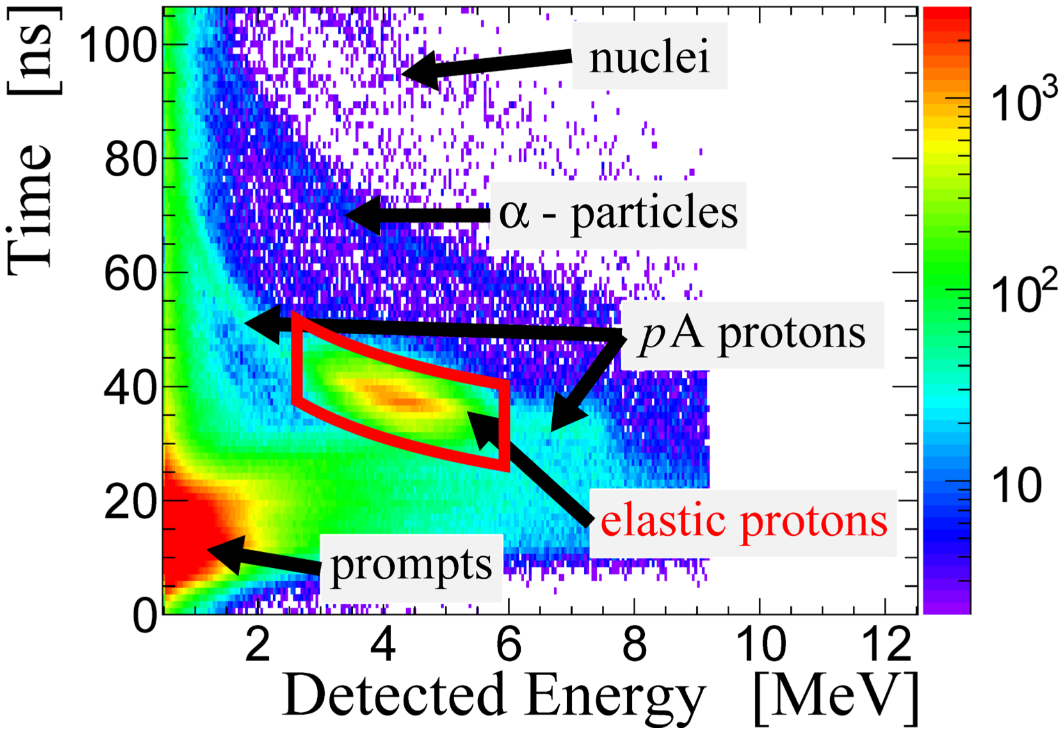
$$\left.\begin{aligned} a_{\text{beam}}(T_R) &= \frac{N_R^{\uparrow} - N_R^{\downarrow}}{N_R^{\uparrow} + N_R^{\downarrow}} = A_N(t) P_{\text{beam}} \\ a_{\text{jet}}(T_R) &= \frac{N_R^{+} - N_R^{-}}{N_R^{+} + N_R^{-}} = A_N(t) P_{\text{jet}} \end{aligned}\right\} \quad P_{\text{beam}} = \frac{\langle a_{\text{beam}}(T_R)\rangle}{\langle a_{\text{jet}}(T_R)\rangle} P_{\text{jet}}$$

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

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

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

Isolation of the elastic pp events

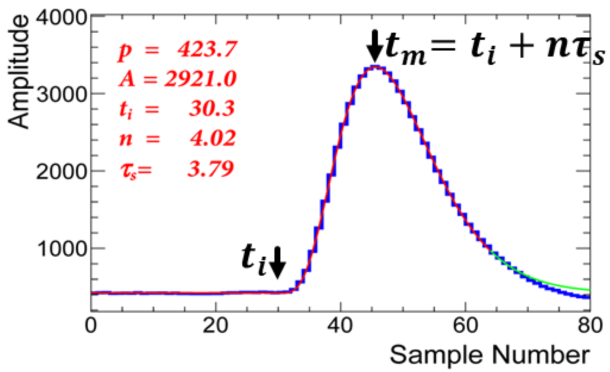


The detected signal time-amplitude distribution in a Si strip.

The recoil protons with kinetic energy above 7.8 MeV punch through the Si detector and only part of the energy is detected.

- Only few percent of all detected events are elastic recoil protons.
- Nonetheless, for 107 ns bunch spacing at RHIC, the elastic events can be easily isolated, and background can be properly subtracted.
- However, to validate the method 10 ns bunch spacing at EIC, a special study is needed.

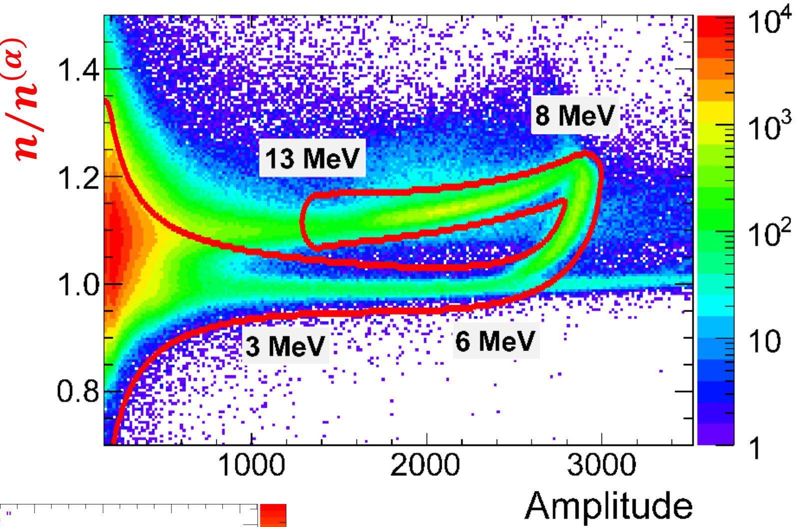
Reconstruction of the punch-through proton kinetic energy

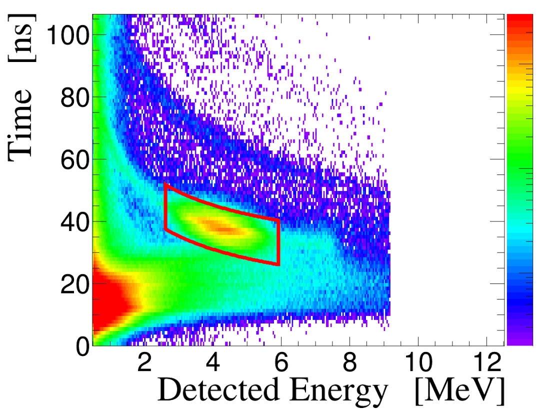


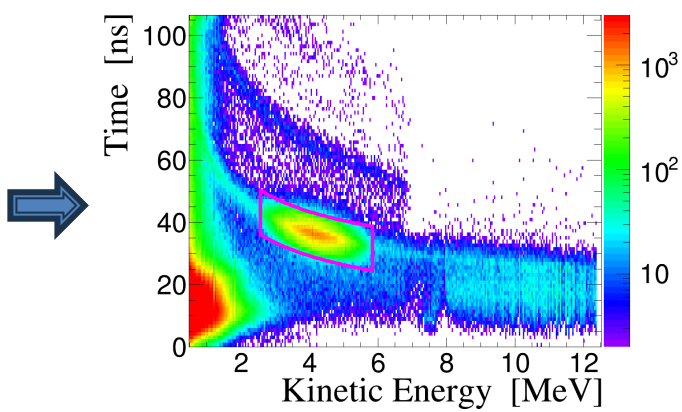
Signal parametrization:

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

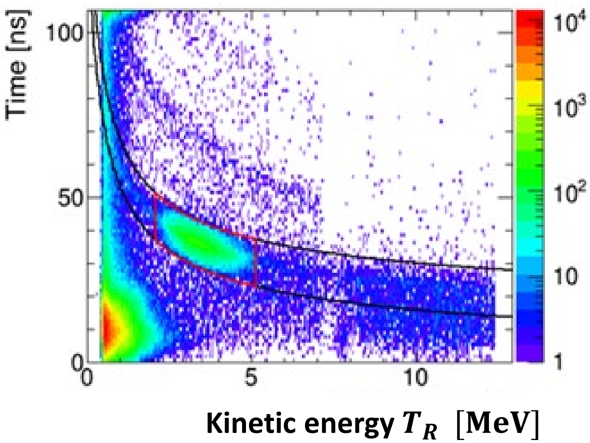
- The signal wave form shape depends on the recoil proton energy.
- It allows us to reconstruct kinetic energy of the punch-through recoil protons.





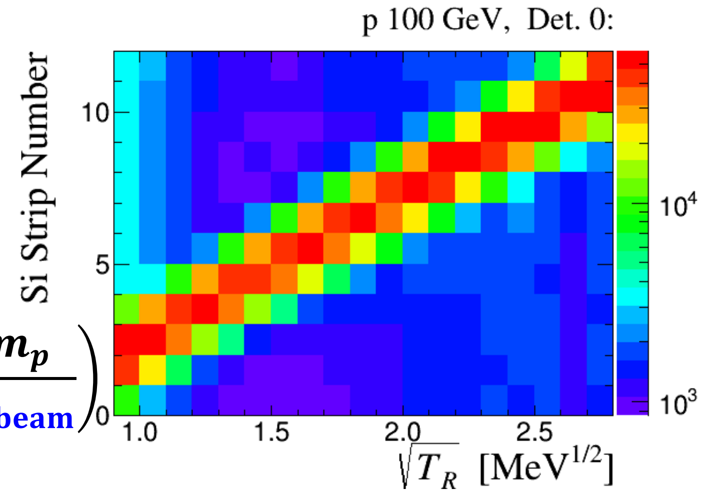


Isolation of the elastic pp events



$$t = t_0 + \frac{T_R}{2m_p}\frac{L}{c}$$

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



- To isolate elastic events:
  - The measured time-of-flight is compared with ToF corresponding measured T_R (**the detected particle is proton**)
  - The measured $\sqrt{T_R}$ is compared with $\sqrt{T_R}$ corresponding to the Si strip
  - (**the scattered particle is proton**)
- Since, for fixed T_R, the background rate is **<u>about</u>** the same in all strips of the Si detector, background events can be subtracted (separately for each combination of the beam and jet spins) from the elastic data. However, the results of the background suppression may be affected by
  - Inelastic events
  - Tracking of the recoil protons in the Holding Field magnet.

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

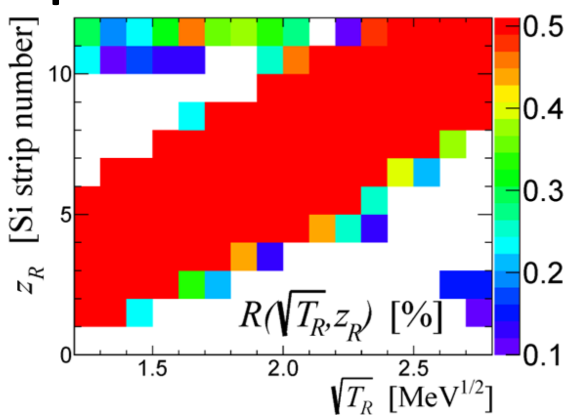
$$\frac{z_R - z_{\text{jet}}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_{\text{beam}}} + \frac{m_p \Delta}{T_R E_{\text{beam}}}\right]$$

$\Delta = M_X - M_A$
E_{beam} is the beam energy per nucleon

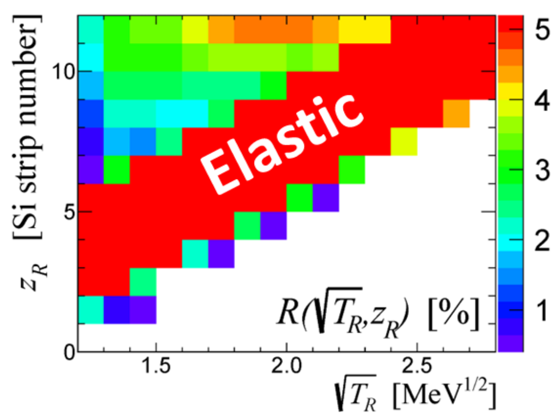
- The inelastic events occupy the area above the elastic line.
- For the 100 GeV beam, the inelastic event detection in HJET is strongly suppressed.
- For 255 GeV elastic events are well detected (but not overlapped with the elastic ones)

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

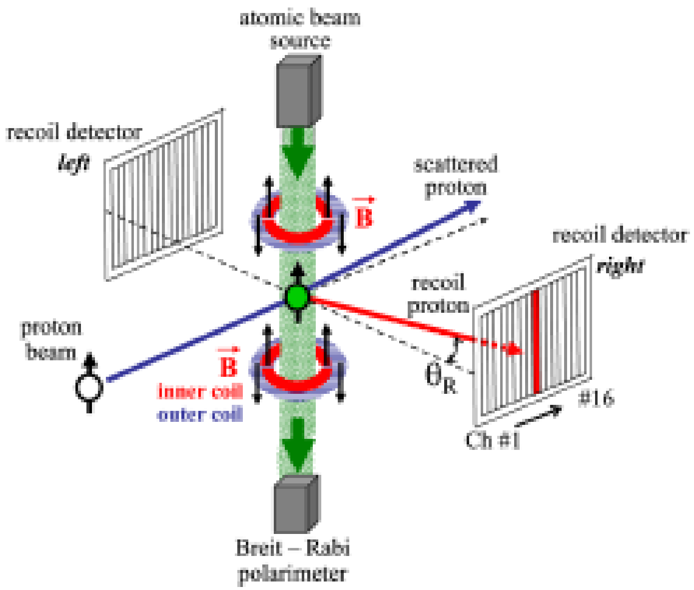
proton beam 100 GeV

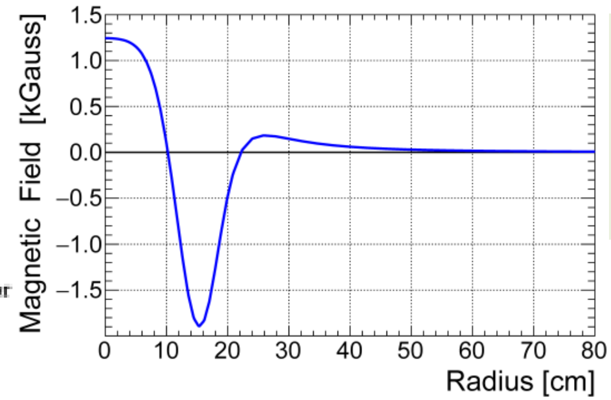


255 GeV

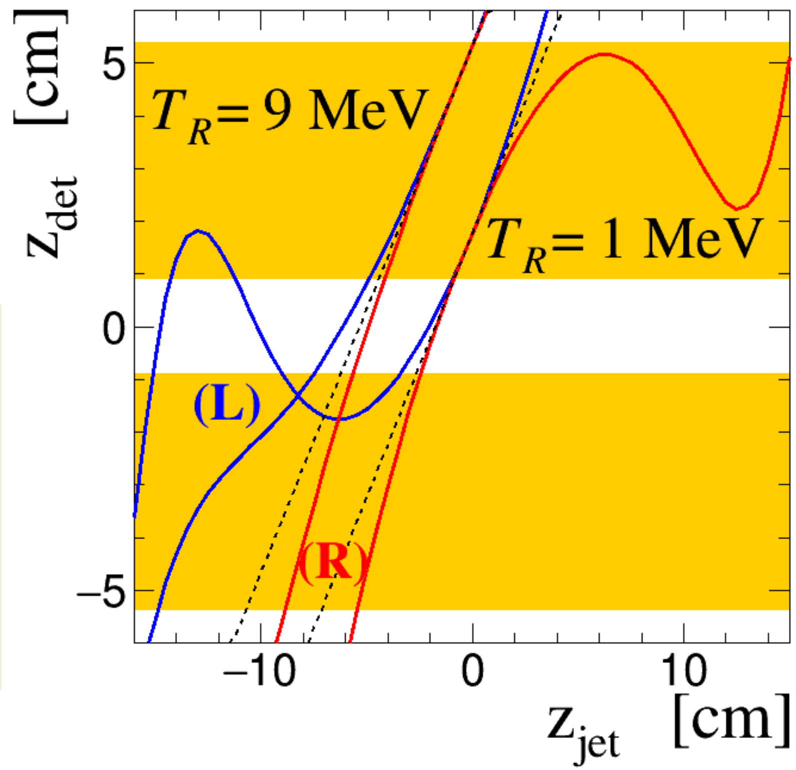


Recoil proton tracking in the magnetic field





Currents in the Helmholtz coils are adjusted to minimize alteration of the recoil proton z-coordinate in the Si detector

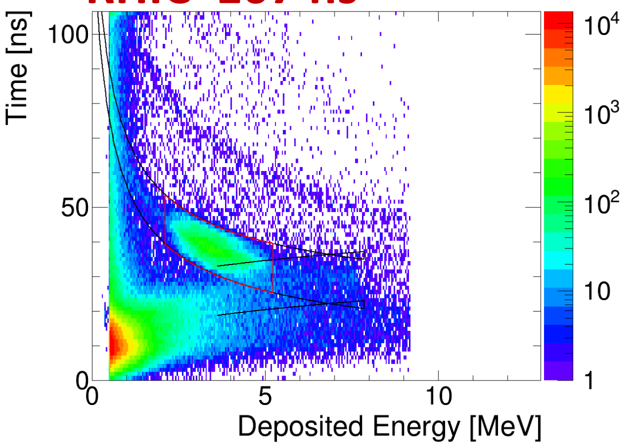


- Depending on the z_{jet} coordinate of the scattering point, the recoil proton track bending in the magnetic field may result in incorrect background subtraction.
- For $T_R < 2\ \mathrm{MeV}$, the corresponding systematic error i value of the polarization may be $1 \div 3\%$.
- In the data analysis, the residual background was simulated.

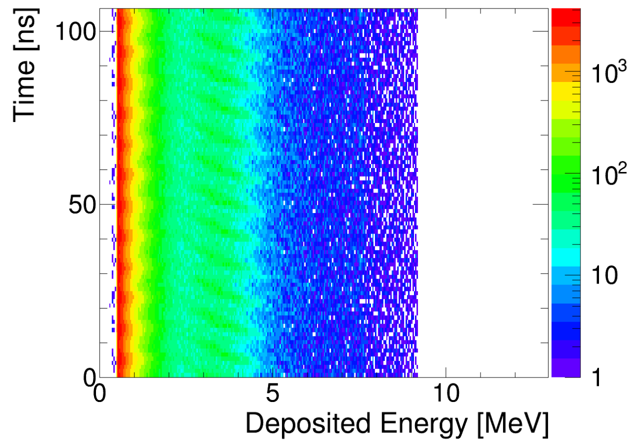
The anticipated “bunch spacing” problem at EIC.

Significant decreasing of the bunch spacing, **107 ns → 10 ns**, at EIC may be an issue due to mixing prompts and elastic pp signals from different bunches.

RHIC 107 ns

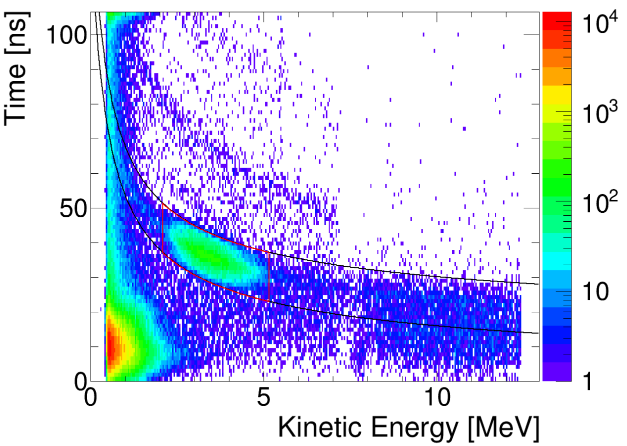


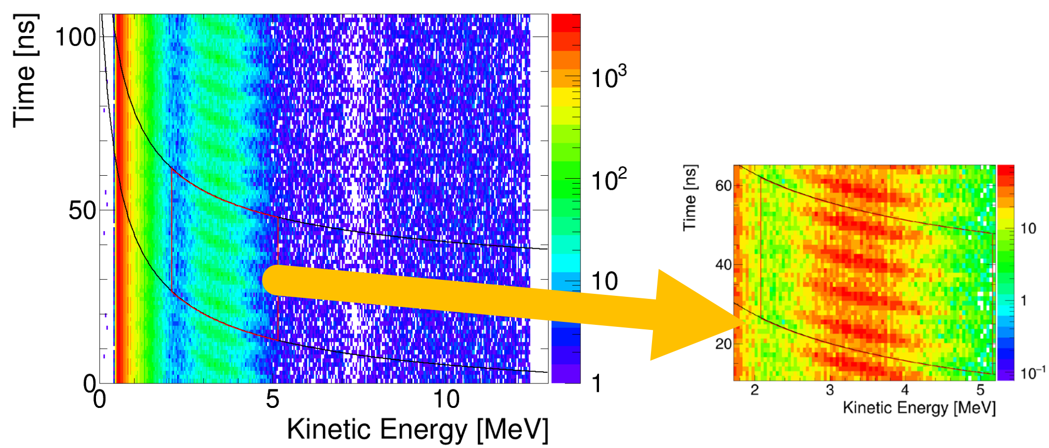
EIC 8.9 ns



HJET performance at EIC can be easily emulated by using RHIC experimental data and shifting the measured time with 8.9 ns (107/12) step.

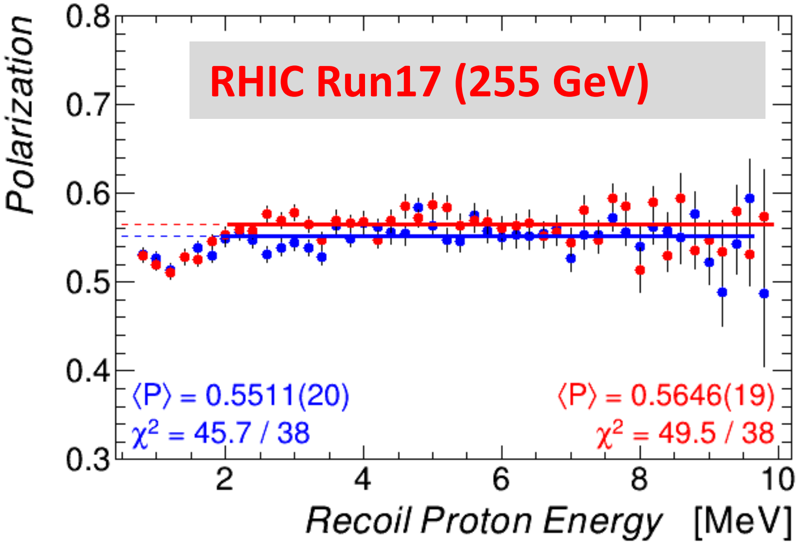
Usage of the reconstructed kinetic energy results in a significant improvement.

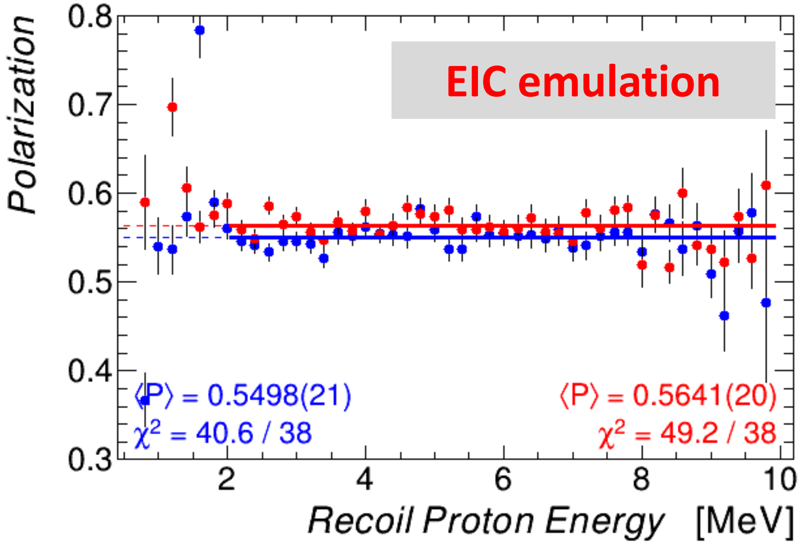




Proton Beam Polarization measurements. EIC vs RHIC.

The emulated (8.9 ns bunch spacing) data was processed using regular HJET software.



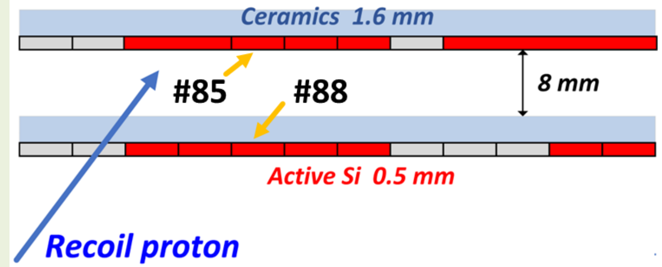


- Since the same events are used in two (107 and 8.9 ns bunch spacing) determination of the beam polarization, only bunch spacing related systematic errors can contribute to the discrepancy in the two distributions.
- For $T_R > 2\ \mathrm{MeV}$, the corresponding errors are small, $|\delta P/P \lesssim 0.2\%|$.
- In the RHIC measurements, the following kinetic energy cuts were used,

  $T_R > 0.7\ \mathrm{MeV}\ (100\ \mathrm{GeV})$ and $T_R > 2.0\ \mathrm{MeV}\ (255\ \mathrm{GeV})$

Prototype of a double-layer detector for HJET

- The prompts **are usually considered** as fast charged particles, which penetrate the Si detectors.
- To veto prompts, a prototype of a double layer detector was assembled and tested
- Although the prototype design was not optimized, a reliable vetoing of the prompts was foreseen.



The prototype did not work as expected.

For the non-vetoed events (about 30-40% of all prompts):

- Time of flight is consistent with speed of light.
- The wave form shape is like that of stopped particles in the Si strip.

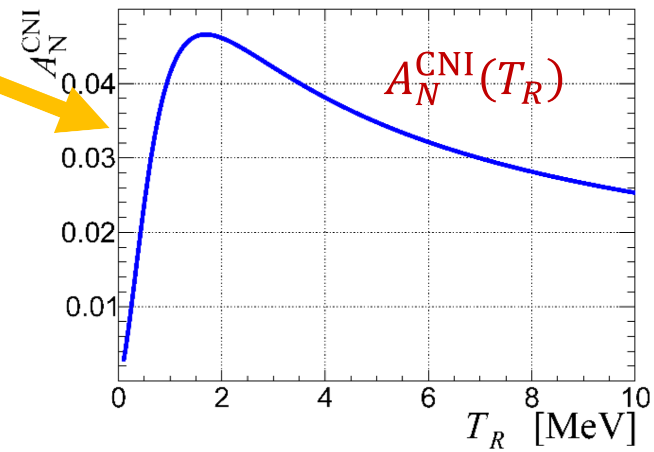
My best **guess** is that non-vetoed prompt events are due to the Si nuclear breakup by a γ (from a π^0 decay) or ultra-fast minimum ionizing charged particles (which are not detected in the Si strip due to low dE/dx). In this case there may be no correlation between signals in two detector layers. However, I have no realistic model for such a process and, consequently, **have no proves that the guess is correct.**

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

$\kappa_p = \mu_p - 1 = 1.793$
$T_c = 4\pi\alpha/m_p\sigma_{tot} \approx 1\ \text{MeV}$
$\rho = -0.079 \quad (E_{beam} = 100\ \text{GeV})$
$\delta_C = 0.024 + \alpha \ln T_c/T_R$

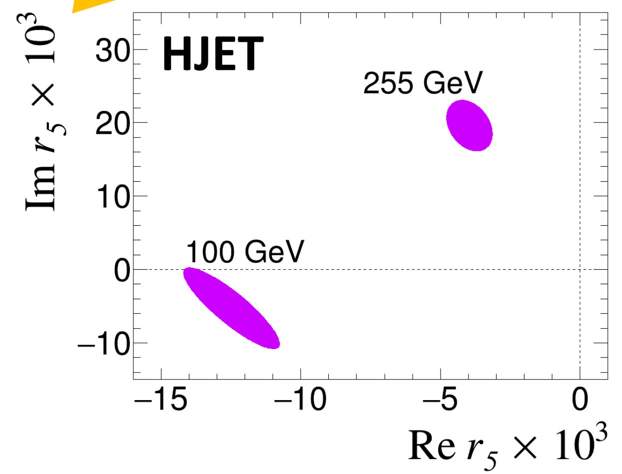
$$A_N(T_R = -t/2m_p) = a_{jet}(T_R)/P_{jet}$$

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



$$\mathbf{A_N(T_R)/A_N^{CNI}(T_R) = 1 - \frac{2I_5}{\kappa_p} - \frac{2R_5}{\kappa_p}\frac{T_R}{T_c}}$$

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



- $A_N^{CNI}(T_R)$ is known with high precision, $\delta A_N^{CNI}/A_N^{CNI} = \mathcal{O}(0.1\%)$
- Linear dependence of A_N/A_N^{CNI} on T_R was verified in the HJET measurements. **The linearity test is essential to identify possible systematic errors.**
- The hadronic spin-flip parameter is small, $|r_5| \sim 2\%$ (measured at HJET)

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

$\kappa_p/\kappa_h = -1.283$

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)],

$$r_5^{ph} \approx r_5^{pp}$$
$$r_5^{hp} \approx r_5^{pp}\langle P_N\rangle \approx r_5^{pp}/3$$

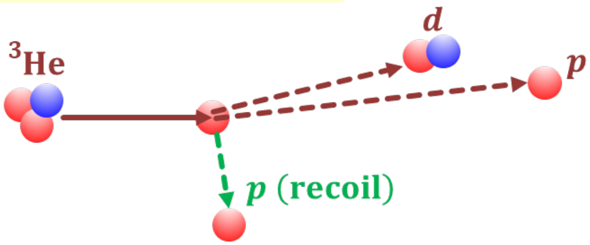
Systematic error in the ^{3}He beam polarization measurement:

$$\sigma_P^{\text{syst}}/P = 0.5\%_{r_5^{pp}} \oplus 0.2\%_{\text{theor}}$$

^{3}He breakup

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

A counter-intuitive observation in the HJET measurements with 3.8-100 GeV/n Au beams:
no evidence (<0.5% of elastic rate)of Au breakup were found in the data analysis



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 $\Delta = M_X - M_A$ is missing mass excess, $m^* = m_p$ and p_x is the target nucleon transverse momentum.

Since T_R and, consequently, Δ are small at HJET, the breakup is strongly suppressed by the phase space factor.

Assuming the following p_x distribution,

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

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

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

If the elastic and breakup events cannot be separated in the data:

$$d\sigma_{el}(T_R) \to d\sigma_{el}(T_R) + \int d\Delta \frac{d\sigma_{\rm brk}(T_R,\Delta)}{d\Delta}\varepsilon_{\rm acc.}(T_R,\Delta) = d\sigma_{el}(T_R) \times [1 + \omega(T_R)]$$

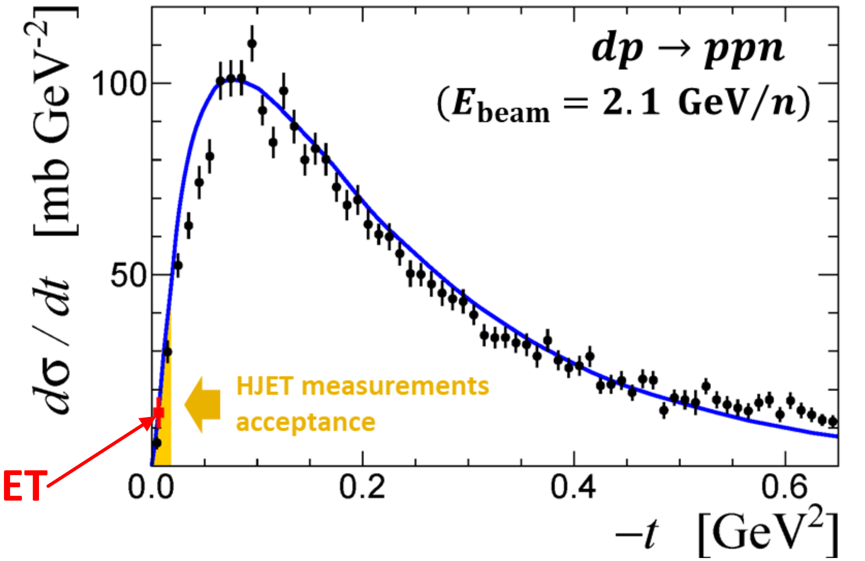
$\omega(T_R) \to 0$ if $T_R \to 0$

Experimental evaluation of $\omega(T_R)$

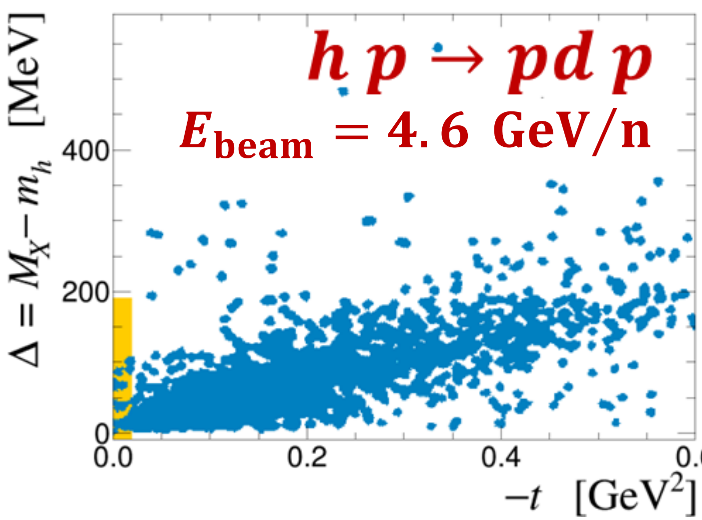
AP, Phys. Rev. C **108**, 025202 (2023)

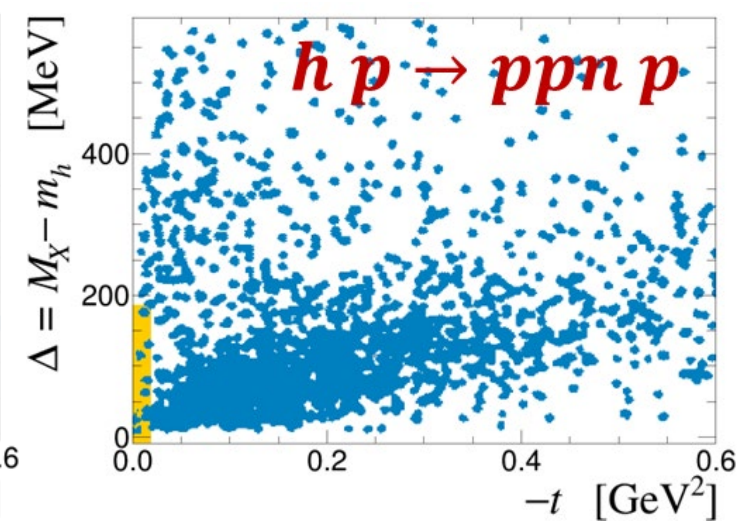
- In the deuteron measurements at HJET, it was found $\omega_d(T_R = 3.5\ \mathrm{MeV}) = 5.0 \pm 1.4\%$, and an extrapolation to the $^3\mathrm{He}$ breakup, $\langle\omega_h\rangle_{1-10\ \mathrm{MeV}} = 2.4 \pm 0.4\%$, had been done.
- The estimates were found to be in reasonable agreement with the hydrogen bubble chamber measurements in Dubna.

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



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





Breakup corrections to the ^{3}He beam polarization

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

The breakup corrections,

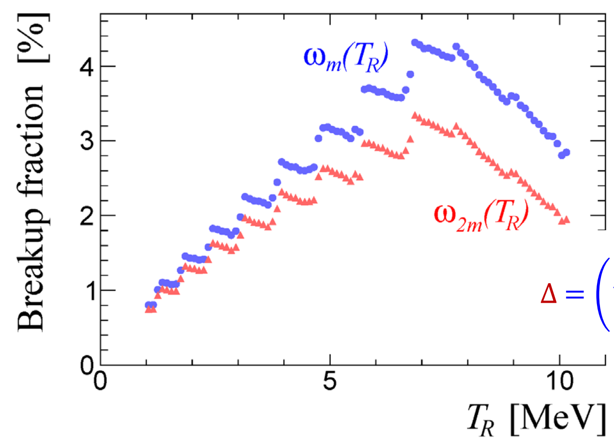
$$1 + \omega_{\text{int}}(T_R), \qquad \omega_{\text{int}} \in \{\omega_\kappa^p, \omega_I^p, \omega_R^p, \omega_\kappa^h, \omega_I^h, \omega_R^h\}$$

can also modify the interference terms in the analyzing power ratio

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

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:

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



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

Assuming **linear fit** of the measured polarization $P^h_{\text{meas}}(T_R)$, $T_R > 2$ MeV, the following estimate can be done :

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

In a more accurate fit, the breakup correction can be reduced to a negligible level

Summary

- Systematic uncertainties σ_P^{syst}/P in the absolute calibration of the proton and ^{3}He beam polarization at EIC were estimated (predicted) as

  $\boldsymbol{p}$: $0.6\%_{\text{meas}}$

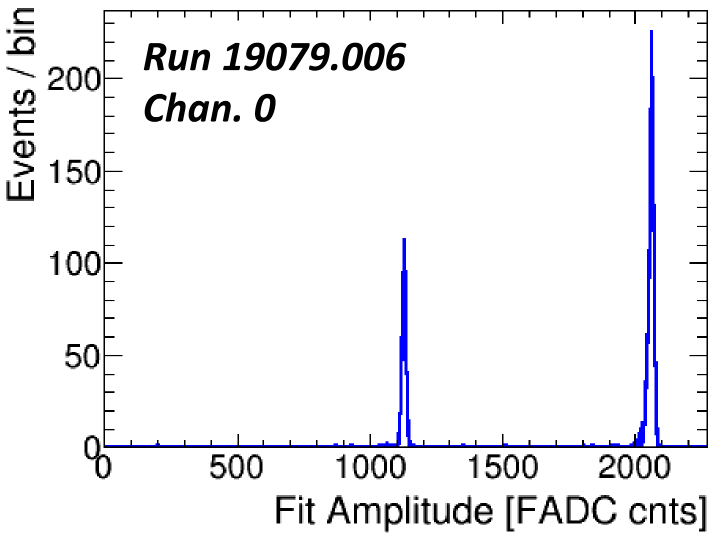
  $^{\mathbf{3}}\mathbf{He}$: $0.6\%_{\text{meas}} \oplus 0.5\%_{r_5^{pp}}$
- For the helion beams with energy <100 GeV/n , proton-proton r_5^{pp} may be needed to be pre-determined before the ^{3}He beam polarization measurement
- To improve the data analysis (*including the development of the calibration methods*), the following can (should) be considered:
  - Optimization of the reconstruction of the punch-through recoil proton kinetic energy
  - More accurate analysis of the recoil proton tracking in the magnetic field.
  - Optimization of the detector geometry for better evaluation of the background.
  - Understanding of the prompts.
  - More accurate theoretical analysis of the breakup corrections to the ^{3}He beam polarization measurements

From the analysis done, it follows that

HJET, *as it was designed for RHIC Spin Program*, has a capability to precisely, $\sigma_P^{\text{syst}}/P \lesssim 1\%$, measure absolute polarization of the proton and helion beams at EIC.

Backup

Calibration Using Alpha-sources



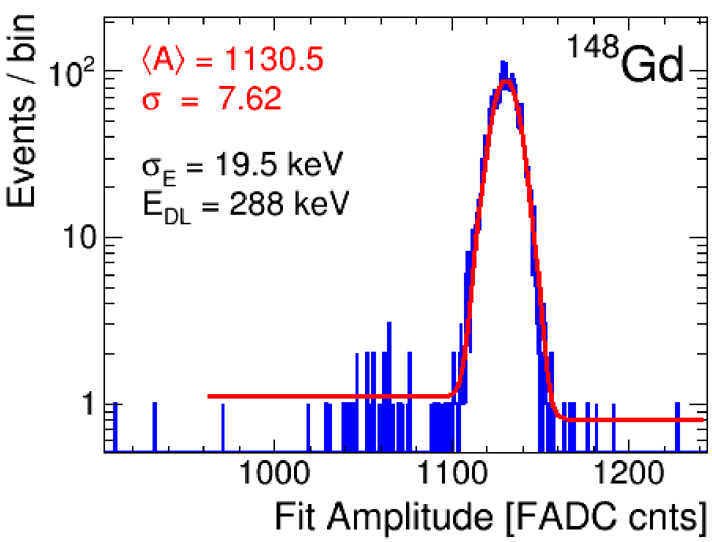
All Si detectors are exposed by 2 α-sources:

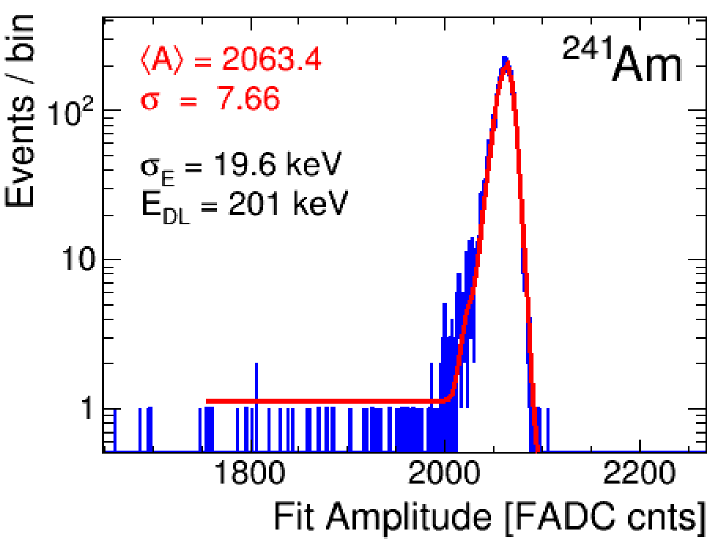
$^{148}Gd\ \ (3.183\ MeV)$

$^{241}Am\ \ (5.486\ MeV)$

Gain ($\alpha{\sim}2.5\ \ keV/cnt$) and dead-layer thickness ($x_{DL}{\sim}0.37\ mg/cm^2$) were measured for every Si strip.

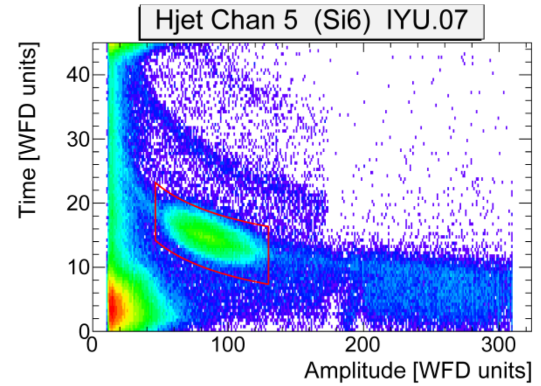
Energy resolution $\sigma_E\ \approx\ 20\ keV$ is dominated by electronic noise.
(For CAMAC DAQ $\sigma_E{\sim}30\ keV$)

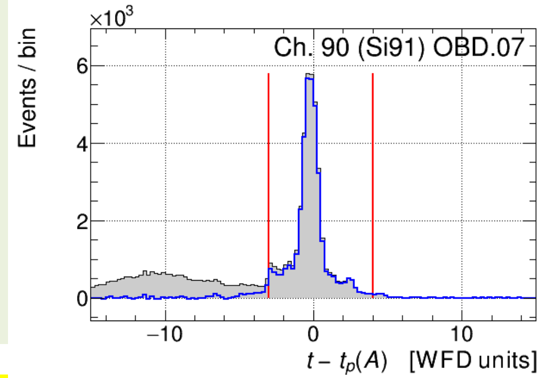


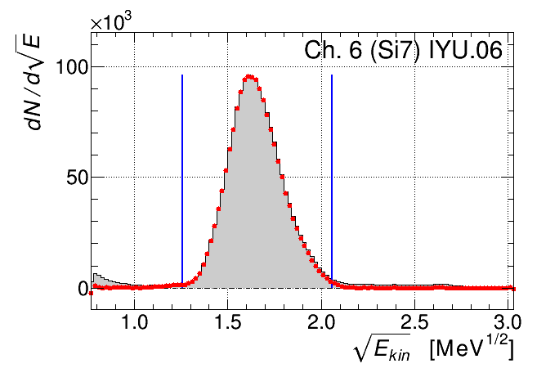


Event Selection Cuts.

1. **Recoil proton kinetic energy** $\boldsymbol{T_R}$.
   The measured kinetic energy range $(0.5 \div 11 \text{ MeV})$ is limited by the detector geometry and the trigger threshold)
2. **"Recoil mass cut":** $\boldsymbol{\delta t = t_m - t_p(A)}$
   $t_p(A)$ is the expected proton signal time for the measured amplitude A. It depends on gain, dead-layer and time offset which are found in calibrations.
   The δt distribution is defined by the beam bunch longitudinal profile.
3. **"Missing mass cut":** $\boldsymbol{\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{strip}}}$
   T_{strip} is the energy corresponding to the strip center. It is determined in the geometry alignment. The $\delta\sqrt{T_R}$ distribution is defined by the jet density profile.







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

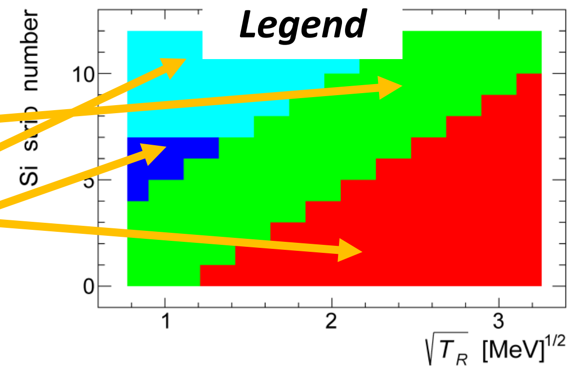
Two sets of cuts used in Run 2017 analysis

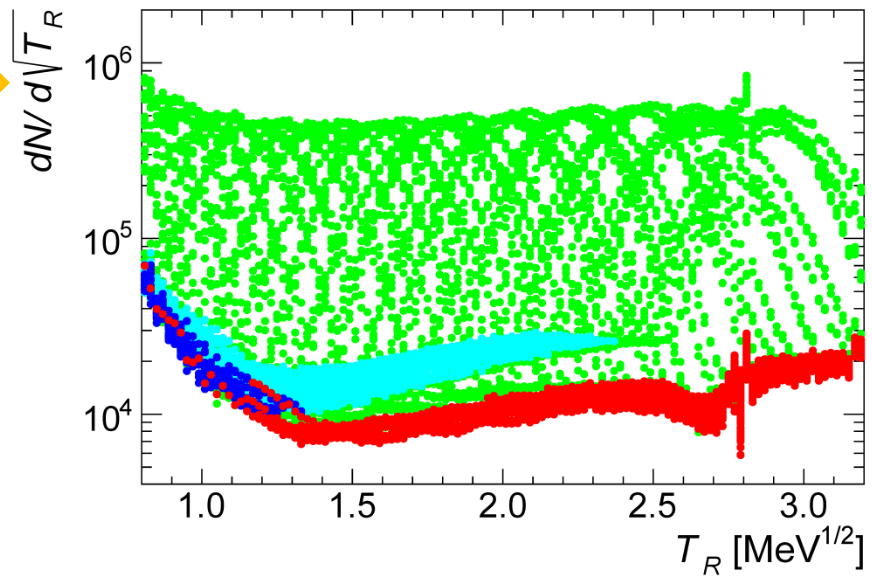
Minimum statistical error cuts	**Minimum systematic error cuts**
$0.6 < T_R < 10$ MeV	$3.2 < T_R < 7.6$ MeV
$-7 < \delta t < 7$ ns	$-7 < \delta t < 7$ ns
$-0.4 < \delta\sqrt{T_R} < 0.4$ MeV$^{1/2}$	$-0.18 < \delta\sqrt{T_R} < 0.3$ MeV$^{1/2}$

Background subtraction

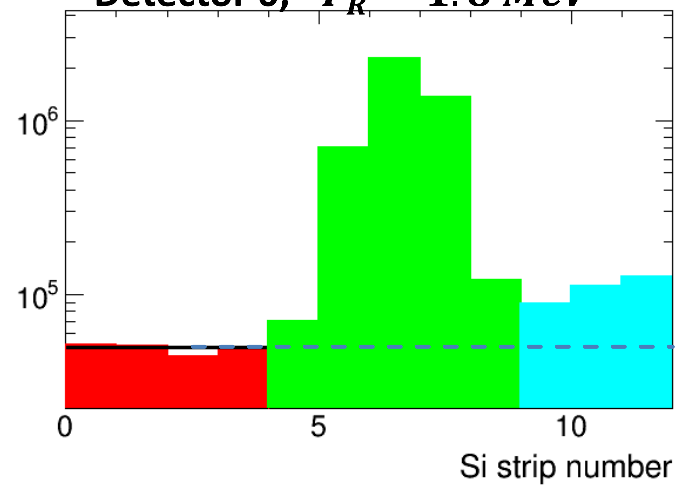
Superposition of the $dN/d\sqrt{T_R}$ for all Si strips.

- **Elastic *pp***
- **Inelastic pp**
- **Background**



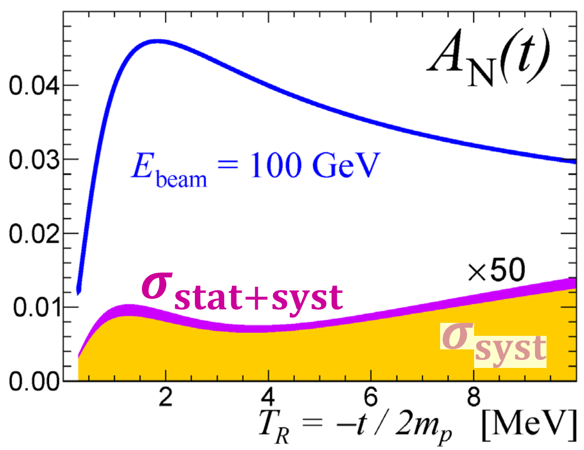


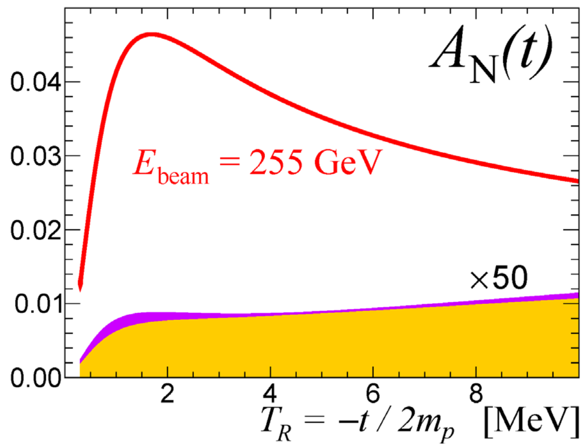
- **The background subtraction is based on the assumption that background $dN/d\sqrt{T_R}$ distribution is the same for all Si strips.**
- **In the data analysis, the background is determined/subtracted independently for**
  - **every detector**
  - **every $\sqrt{T_R}$ bin**
  - **every combination of beam/jet spins (to properly account background analyzing power if any)**



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

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

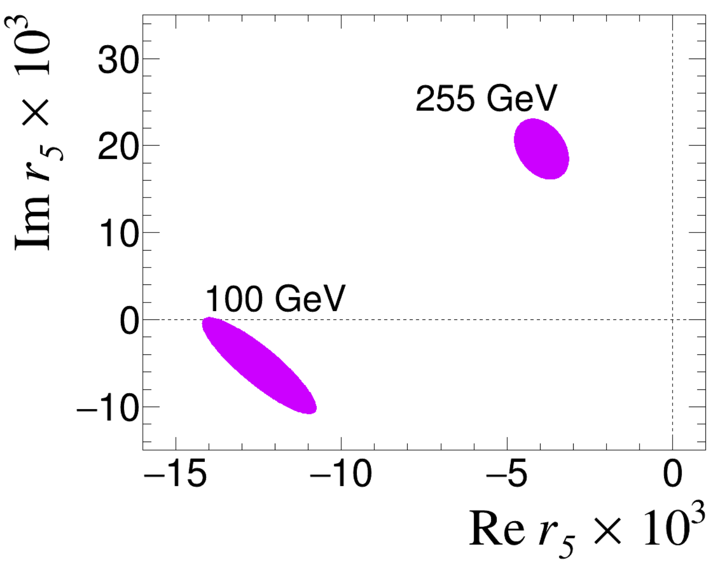
The measured hadronic spin flip amplitudes:

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

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

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

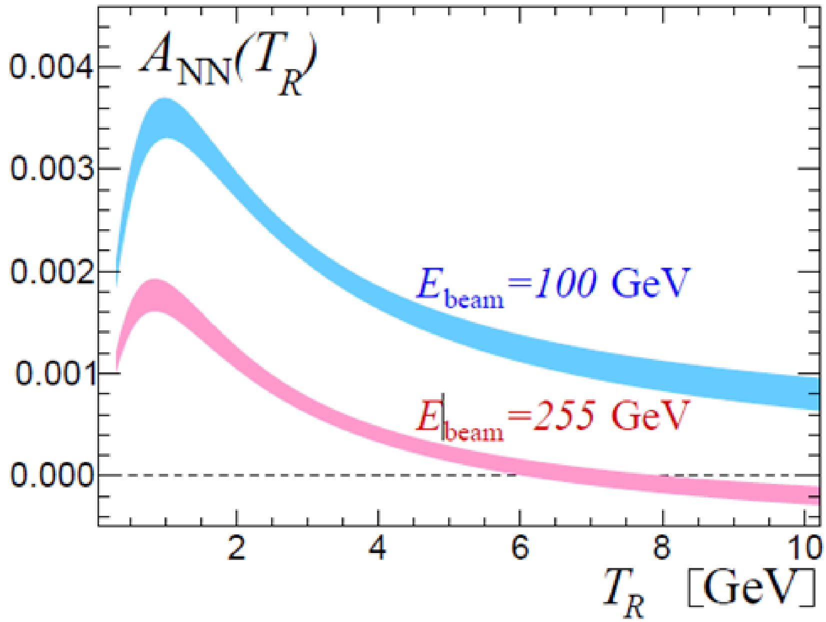
$$R_5 = R_5^{\rm PRL} + (3.1_{\rm abs.} + 0.8_{r_p}) \times 10^{-3}$$



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

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

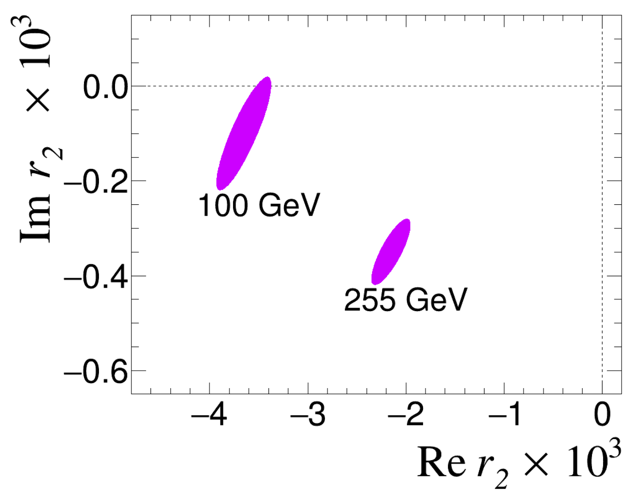
$$\frac{d^2\sigma}{dt\,d\varphi} \propto \left[1 + A_{\mathrm{N}}(t)\sin\varphi\,(P_b + P_j) + A_{\mathrm{NN}}(t)\sin^2\varphi\,P_b\,P_j\right]$$ (at HJET, $\sin\varphi = \pm 1$)



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

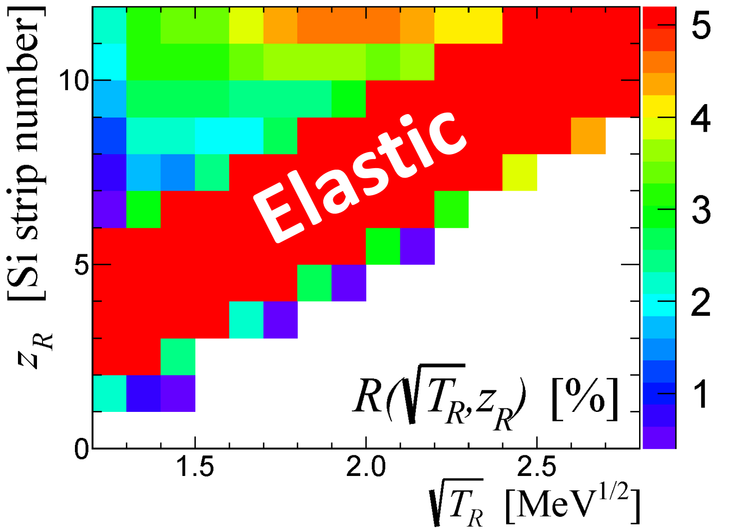
$\sqrt{s} = 13.76$ GeV $\quad R_2 = (-3.65 \pm 0.28_{\mathrm{stat}}) \times 10^{-3}$
$\quad I_2 = (-0.10 \pm 0.12_{\mathrm{stat}}) \times 10^{-3}$

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



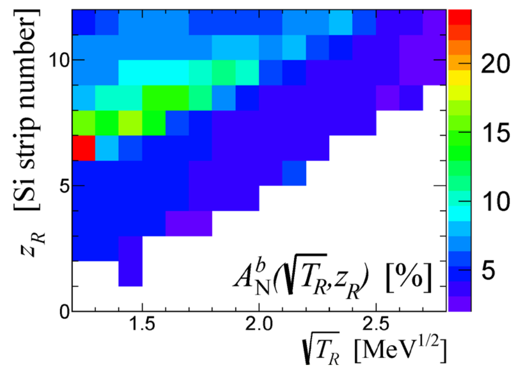
$$p^{\uparrow}_{\text{beam}} + p^{\uparrow}_{\text{jet}} \rightarrow X_{\text{beam}} + p_{\text{jet}}$$

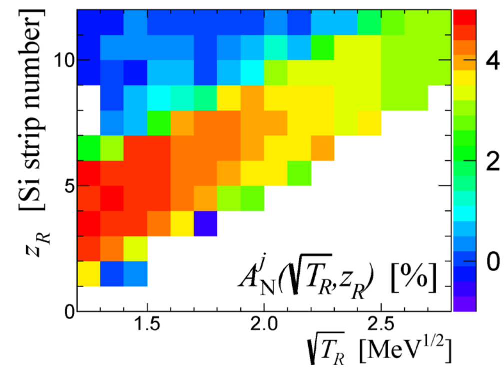
$R(T_R, z_R) = N_{\text{bin}}(T_R, z_R)/N^{el}_{\text{max}}$

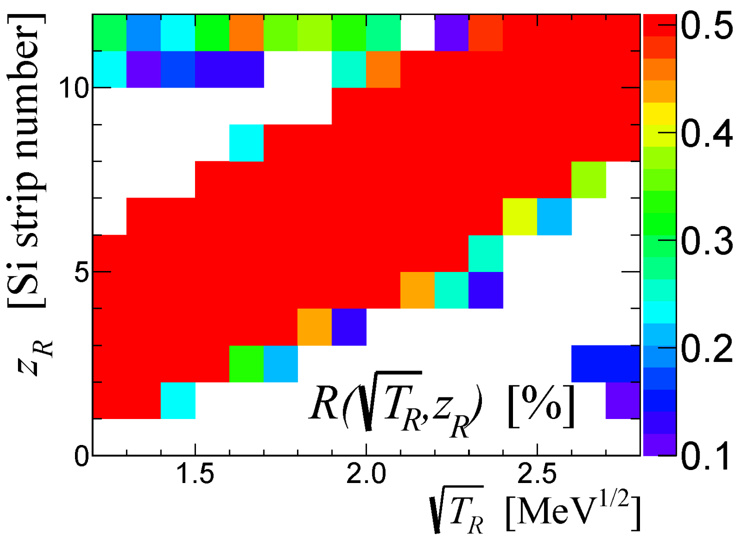


255 GeV

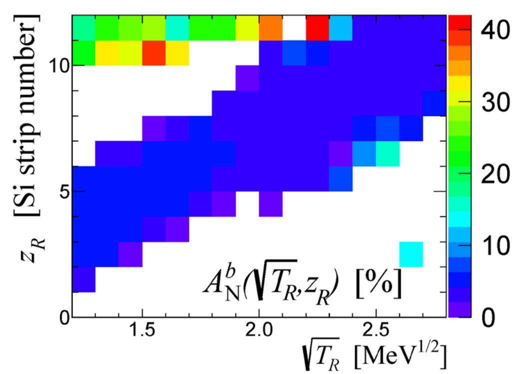
For the inelastic scattering
$\Delta > m_\pi$

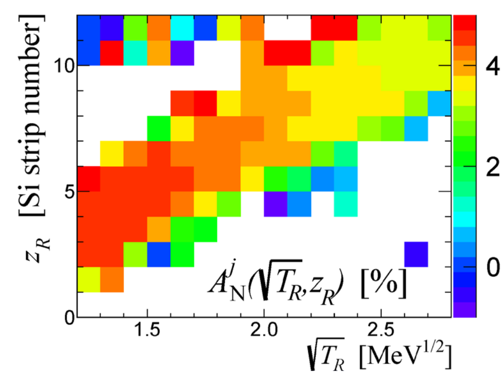




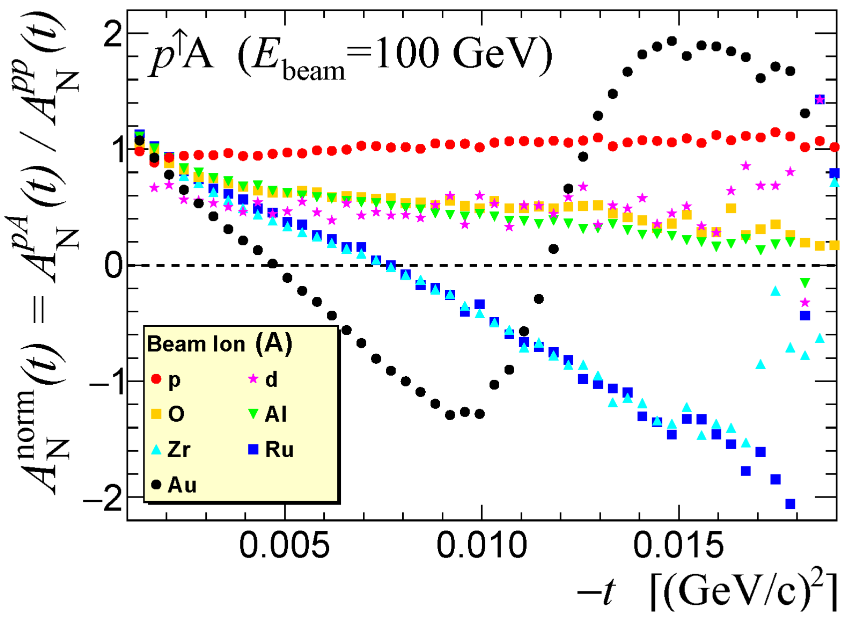


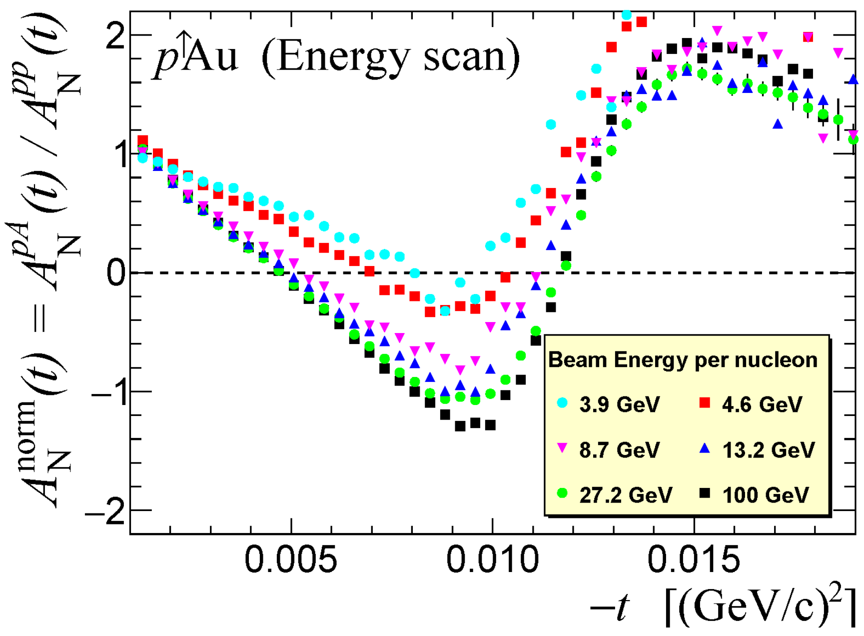
100 GeV





Proton-nucleus Scattering at HJET





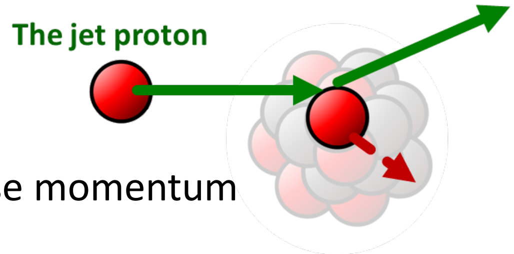
In the Au beam measurements at HJET ($\Delta \gtrsim 4$ MeV, $3.8 < E_{\text{beam}} < 100$ GeV/n), no evidence of the breakup fraction in the elastic data was found.

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

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

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

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

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

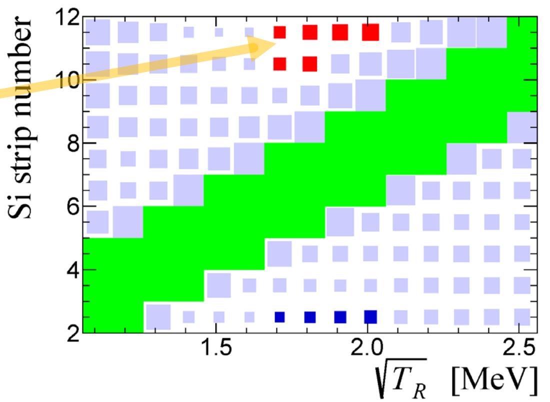
- The breakup fraction $\omega(T_R,\Delta)$ dependence is pre-defined by the nucleon momentum distribution in a nuclei.
- In the HJET measurements, $\Delta < 50\ \mathrm{MeV}$ is small.
- The breakup to elastic amplitude ratio, $\psi(T_R,\Delta)$, is about independent of the T_R and Δ.
- The $h \to pd$ breakup is strongly suppressed by the phase space factor $\omega(T_R,\Delta) \propto \sqrt{\Delta-\Delta_{\mathrm{thr}}^h}$.
- For the $h \to ppn$ breakup the suppression is much stronger $\omega(T_R,\Delta) \propto \left(\Delta-\Delta_{\mathrm{thr}}^h\right)^2$.
- 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 $d \to p + n$ $\left(\Delta^d_{\mathrm{thr}} = 2.2\ \mathrm{MeV}\right)$ were isolated for 10, 20, and 31 GeV data.



- The breakup was evaluated for $2.8 < T_R < 4.2\ \mathrm{MeV}$

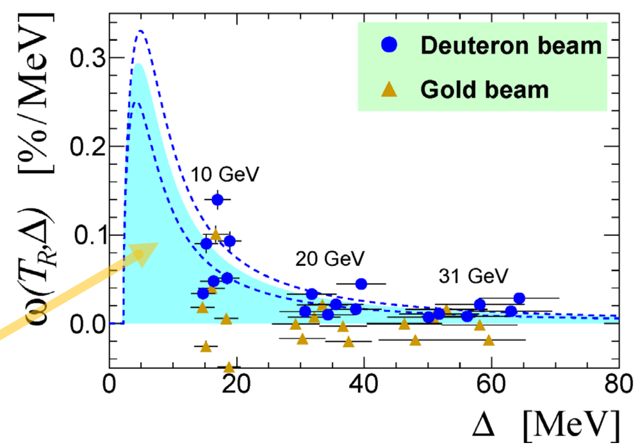
- In the data fit, the $d \to pd$ breakup fraction $\omega(T_R, \Delta)$ was parameterized,

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

- For $T_R \sim 3.5\ \mathrm{MeV}$, 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.