EIC Polarimetry Efforts Meeting
June 26, 2025
https://indico.bnl.gov/event/28626/

HJET at RHIC

(what should be kept in mind when HJET is adapting to the EIC)

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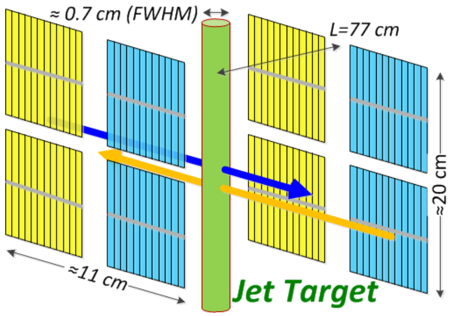
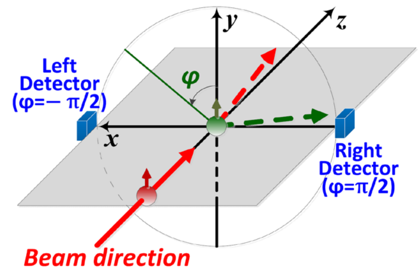
Beam polarization measurements at HJET





For vertically polarized $p^{\uparrow}p^{\uparrow}$ scattering at HJET:

$$\sin\varphi = \pm 1$$

$$A_N^j = A_N^b \approx 0.04$$

$$\frac{d^2\sigma}{dt d\varphi} = \frac{1}{2\pi}\frac{d\sigma}{dt} \times \left[1 + \left(A_N^j P_j + A_N^b P_b\right)\sin\varphi + \left(A_{NN}\sin^2\varphi + A_{SS}\cos^2\varphi\right)P_j P_b\right]$$

$$\boldsymbol{a = A_N P}$$

$$a = \frac{N_R^+ - N_L^+}{N_R^+ + N_L^+}$$

$$a = \frac{N_R^+ - N_R^-}{N_R^+ + N_R^-}$$

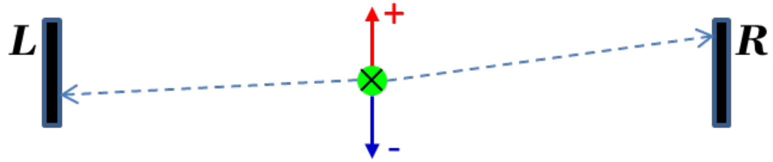
$$\Rightarrow$$

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

For concurrent measurement of the beam and jet asymmetries, the beam polarization $\boldsymbol{P_{\text{beam}}}$ can be related to the well known $\boldsymbol{P_{\text{jet}} \approx 0.96 \pm 0.001}$

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

Determination of Spin Correlated asymmetry



N_{LR}^{+-} is number of detected events depending on detector side and spin direction. a, ϵ, and λ are spin, acceptance and intensity asymmetries, respectively.

$$\begin{cases} N_R^+ = N_0(1+a)(1+\epsilon)(1+\lambda) \\ N_R^- = N_0(1-a)(1+\epsilon)(1-\lambda) \\ N_L^+ = N_0(1-a)(1-\epsilon)(1+\lambda) \\ N_L^- = N_0(1+a)(1-\epsilon)(1-\lambda) \end{cases} \Rightarrow$$

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

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

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

The "*square root formula*" gives exact and, thus, systematic error free solution if asymmetries a, ϵ, λ are uncorrelated.

Corrections to the "square root formula"

Sources of the first order corrections:

- Absolute values of polarizations for spin up and down are not the same $|P^+| \neq |P^-|$.
- Analyzing power is not the same for left and right detectors $A_N^{(R)} \neq A_N^{(L)}$.
- Acceptance ω in left and/or right detectors is spin dependent $\omega^+ \neq \omega^-$.

Systematic errors in asymmetry measurements:

$$\delta a^{\mathrm{syst}} = P\frac{\delta A_N^{(R)} + \delta A_N^{(L)}}{2} + \frac{\delta\omega_R - \delta\omega_L}{2}$$

$$\delta\lambda^{\mathrm{syst}} = P\frac{\delta A_N^{(R)} - \delta A_N^{(L)}}{2} + \frac{\delta\omega_R + \delta\omega_L}{2}$$

$$\delta\epsilon^{\mathrm{syst}} = \delta P A_N$$

$$P = \frac{|P^+|+|P^-|}{2}, \qquad \delta P = \frac{|P^+|-|P^-|}{|P^+|+|P^-|}$$

$$\delta\omega = \frac{|\omega^+|-|\omega^-|}{|\omega^+|+|\omega^-|}$$

$$\delta A_N = \frac{b}{1+b}\left(A_N^{\mathrm{bgr}} - A_N\right) - \frac{dA_N(T_R)}{dT_R}\,\delta T_R$$

b is the background fraction in the data and $T_R = -t/2m_p$ is the recoil proton energy

- Since the measured beam polarization P_{beam} and the intensity asymmetries λ_{beam} and λ_{jet} must not depend the recoil proton energy T_R, the measured functions $P_{\mathrm{beam}}(T_R)$, $\lambda_{\mathrm{beam}}(T_R)$, and $\lambda_{\mathrm{jet}}(T_R)$ can be used for a routine control over systematic errors.
- The measured spin asymmetry is insensitive to values of δP_{jet} and δP_{beam}. The effect is "absorbed" in the systematic error to the acceptance asymmetry.

Acceptance dependence on spin

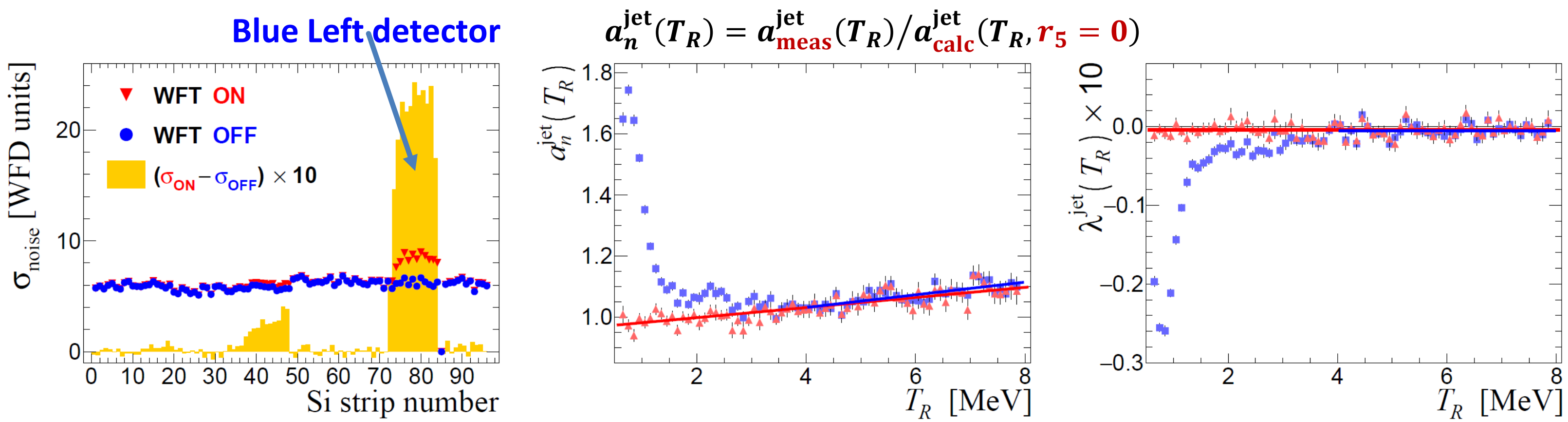


Figure 31: Left: Effective electronic noise for the jet spin up and down in Run 15. The difference scaled by factor 10 is shown by the histogram. For the measured jet spin (center) and intensity (right) asymmetries, ■ points are for the all *blue* Si detectors and ▲ are for the analysis with no strips 72–83 data used.

- In Run 15, RF field generated noise in one blue detector, which effectively altered the detector acceptance.
- Large systematic errors in measurement of jet spin and intensity asymmetries are strongly correlated.

$$\delta a^{syst} = -\delta\omega_L/2$$
$$\delta\lambda^{syst} = \delta\omega_L/2$$

The up/down average Jet Polarization

- **Depending on the RF transitions used:**

$$-P_- = \frac{n_1+n_2\cos 2\theta - 2n_1\epsilon_{1\to3}}{n_1+n_2} \approx 96\%$$

$$P_+ = \frac{n_1+n_2\cos 2\theta - 2n_2\cos 2\theta\,\epsilon_{2\to4}}{n_1+n_2} \approx 96\%$$

$$-P_0 = \frac{n_1-n_2\cos 2\theta - 2n_1\epsilon_{1\to3} + 2n_2\cos 2\theta\,\epsilon_{2\to4}}{n_1+n_2} \approx 4\%$$

$$\cos 2\theta = \frac{B_{hold}}{\sqrt{B_{hold}^2+B_c^2}} = 0.921$$

$$n_2/n_1 = 1.00239$$

The BRP counts:

$$m_- = n_1\epsilon_{1\to3} + n_2$$
$$m_+ = n_1 + n_2\epsilon_{2\to4}$$
$$m_0 = n_1\epsilon_{1\to3} + n_2\epsilon_{2\to4}$$

- **The up/down average polarization, needed for calibration of the beam polarization:**

$$P_{\text{jet}} = \frac{|P_+|+|P_-|}{2} = 1 - \frac{n_2}{n_1+n_2}\times\left[1-\cos 2\theta + \epsilon_{1\to3} + \epsilon_{2\to4}\cos 2\theta\right]$$

$$= \frac{1+\cos 2\theta}{2} - \frac{m_0}{m_+ + m_-} + \mathcal{O}(0.01\%)$$

$$|P_+ + P_-| \approx 0.2\%$$

96.1%
(defined by the holding field magnet)

$\sim 0.3\%$
(measured by the Breit-Rabi polarimeter)

Analyzing power in Left/Right detectors

Analyzing power as a function of the momentum transfer squared t (or equivalently as a function recoil proton energy $T_R = -t/2m_p$ may be different for left and right detectors,

$$A_N^{(L)}(T_R) \neq A_N^{(R)}(T_R),$$

e.g., due to inaccurate energy calibration of the detectors.

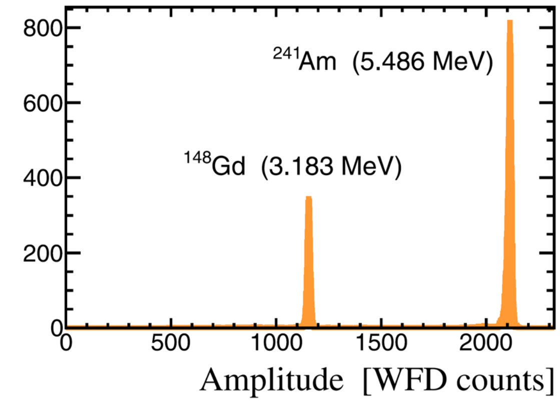
$$\delta a^{\text{syst}}(T_R) = P\,\frac{\delta A_N^{(R)}(T_R) + \delta A_N^{(L)}(T_R)}{2}$$

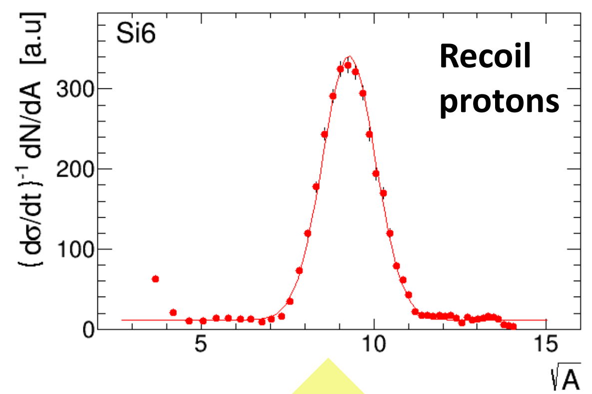
$$\delta \lambda^{\text{syst}}(T_R) = P\,\frac{\delta A_N^{(R)}(T_R) - \delta A_N^{(L)}(T_R)}{2}$$

- In some cases, the effect can be identified by studying dependence of measured $\lambda(T_R)$ on the recoil proton energy (but not always)
- Nevertheless, **if no background**, since the same events are used to calculated jet and beam asymmetries, the measurement average ratio $a_{\text{beam}}/a_{\text{jet}}$ is insensitive to possible values of $\delta A_N^{(R)}(T_R)$ and $\delta A_N^{(L)}(T_R)$

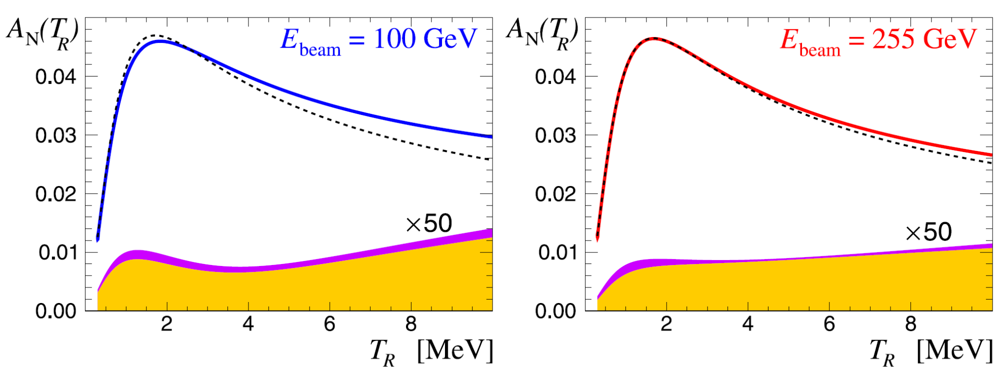
Can unpolarized jet be considered for EIC?

- If no background and no acceptance dependence on spin, the beam polarization can be precisely determined with no knowledge of the analyzing power.
- Alternatively, if $A_N(T_R)$ is known, the polarization can be found with accuracy better than 1% because
  - T_R is well calibrated due to α- calibration
  - Elastic events can be well isolated $\frac{z_R - z_{\rm jet}}{L} = \sqrt{\frac{T_R}{2m_p}\frac{E_{\rm beam}+m_p}{E_{\rm beam}-m_p}}$
  - The background can be accurately subtracted. In particular, "molecular hydrogen" background is inessential (*not a background at all*) in this case.
- $A_N(T_R)$ was precisely measured at HJET for 100 and 250 GeV proton beams allowing beam polarization measurements in the beam energy range 100 – 255 GeV



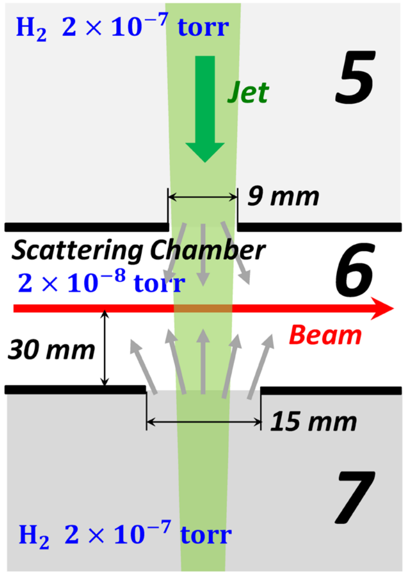


The elastic distribution shape is defined by the jet profile and, thus, should be the same for all Si strips.

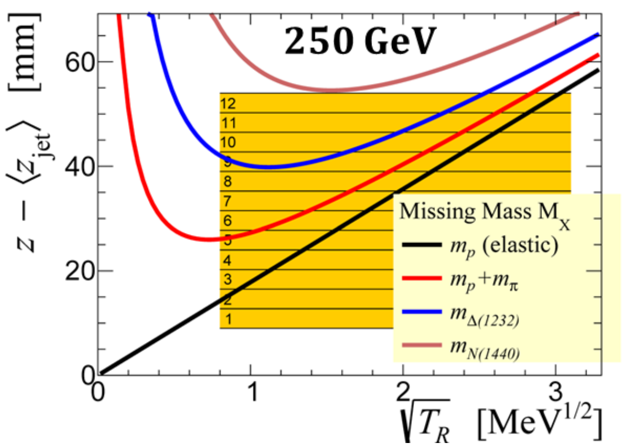


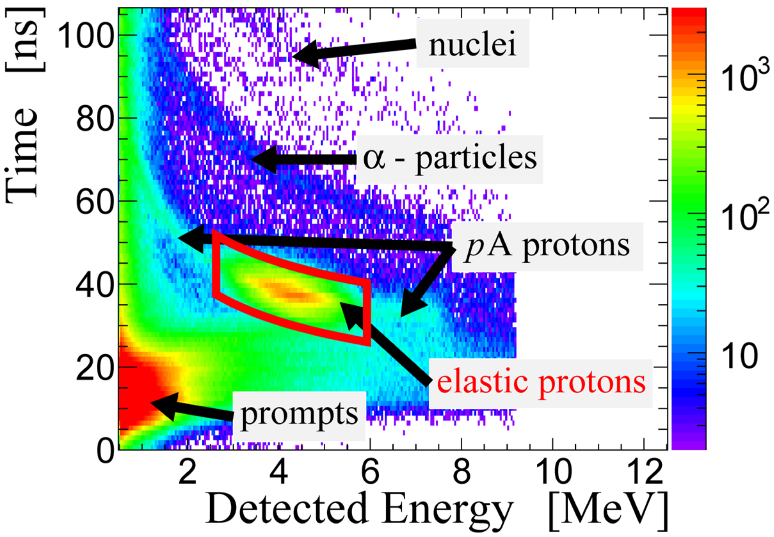
Background sources in HJET measurements at RHIC

- Molecular hydrogen in the Jet
- Molecular hydrogen in the beam gas
- pA scattering
- Inelastic $pp \to pX$ scattering

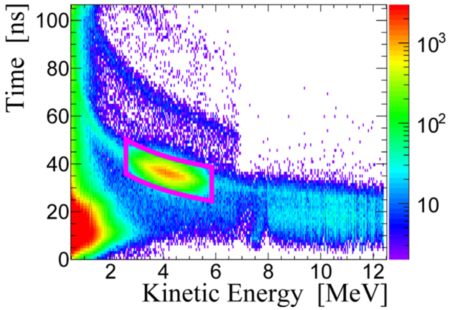


Molecular Hydrogen is any protons in the beam path "unseen" by the Breit-Rabi polarimeter: p, H, H_2, H_2O. It effectively dilutes the jet polarization.





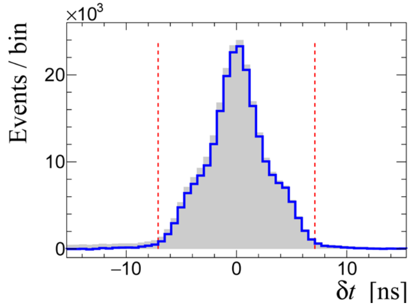
Event Selection Cuts



$$0.6 < T_R < 10.6\ \mathrm{MeV}$$

$$\frac{z_{\mathrm{strip}} - z_{\mathrm{jet}}}{L} = \sqrt{\frac{T_{\mathrm{strip}}}{2m_p} \frac{E_b + m_p}{E_b - m_p + T_{\mathrm{strip}}}}$$

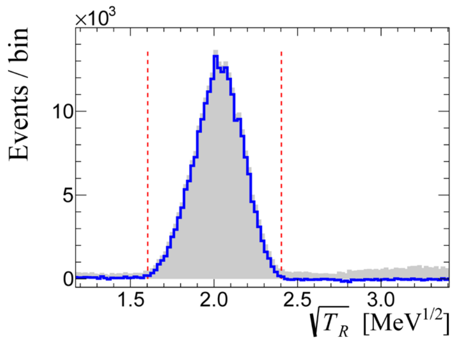
The recoil proton energy range used in data analysis is constrained by the detector geometry and background rate.



$$\delta t = t - t_p(T_R)$$

$$t_p(A) = t_0 + \sqrt{\frac{m_p}{2T_R(A)}}\frac{L}{c}$$

The recoil mass test
δt distribution is defined by bunch longitudinal distribution



$$\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{\mathrm{strip}}}$$

The missing mass test
$\delta\sqrt{T_R}$ distribution is defined by the jet distribution along the beam

- **To isolate elastic events, only δt and $\delta\sqrt{T_R}$ were used (and energy T_R range cut).**
- **The cuts are the same for all Si strips.**

Missing Mass in $p_{\mathrm{beam}} + p_{\mathrm{target}} \rightarrow p_X + p_{\mathrm{recoil}}$ *scattering*

$$M_X^2 = m_p^2 - 2(E_b + m_p)T_R + 2\sqrt{E_b^2 - m_p^2}\sqrt{(2m_p + T_R)T_R}\,\sin\theta_R$$

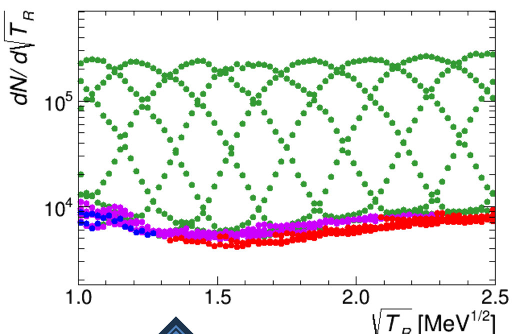
For elastic *pp* scattering: $M_X = m_p \quad \Longrightarrow \quad \tan\theta_R = \dfrac{z_R - z_{\mathrm{jet}}}{L} = \sqrt{\dfrac{T_R}{2m_p}\dfrac{E_b + m_p}{E_b - m_p + T_R}} \approx \sqrt{\dfrac{T_R}{2m_p}}$

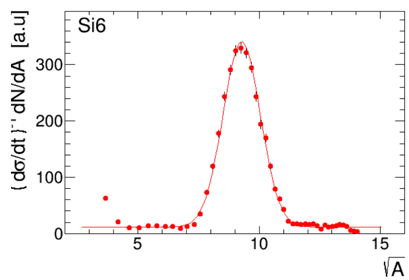
Denoting,
the missing mass cut criteria
may be replaced by

$$\frac{z_{\mathrm{strip}} - z_{\mathrm{jet}}}{L} = \sqrt{\frac{T_{\mathrm{strip}}}{2m_p}\frac{E_b + m_p}{E_b - m_p + T_{\mathrm{strip}}}}$$

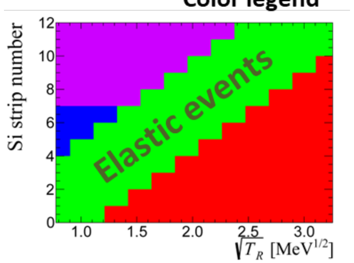
$$\boldsymbol{\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{\mathrm{strip}}} \approx 0}$$

Variations of $\delta\sqrt{T}$ are defined by thickness of jet and width of Si strip
$\sigma_z^2 = \sigma_{\mathrm{jet}}^2 + \Delta^2/12 = 2.7^2 + 3.7^2/12 = (2.9\ \mathrm{mm})^2$
It is independent on recoil proton energy.





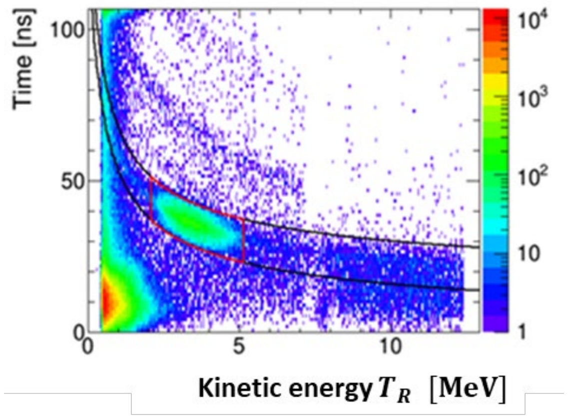
Color legend



Missing mass cut is actually the sameas the $\sqrt{T}$ cut, but is the beam energy and the strip location dependent and, consequently, less convenient.

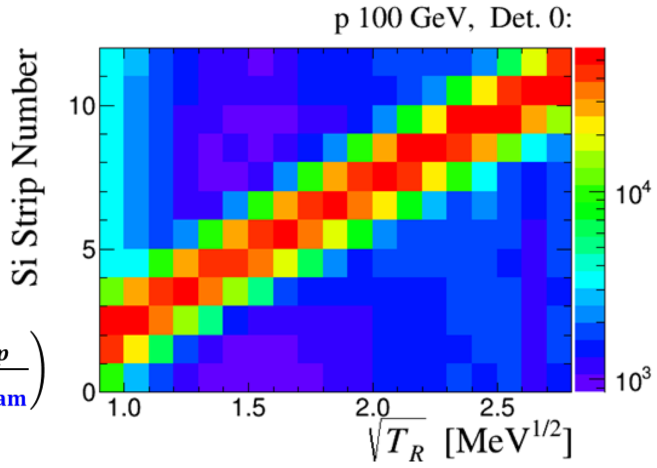
$$\delta M_X^2 = M_X^2 - m_p^2 \approx -2(E_b + m_p)\sqrt{T_{\mathrm{strip}}}\ \delta\sqrt{T_R}$$

The beam gas hydrogen and pA backgrounds



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

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



- For fixed T_R, the background rate is **<u>approximately</u>** the same in all strips of the Si detector.
  - *Beam gas hydrogen:* flat density distribution over z_{jet}
  - pA *scattering:* no dedicated direction for the detected nuclear breakup proton.
- Therefore, background events can be straightforwardly subtracted (separately for each combination of the beam and jet spins) from the elastic data.
- However, the subtraction can be affected by
  - Inelastic $pp \to pX$ events
  - Tracking of the recoil protons in the Holding Field magnet.

Background in the 2009 Phys. Rev. D publication

Main sources of the background:

- $p + A \to p^* + (X + p)$
- Beam gas protons (aka "molecular hydrogen")

For fixed T_R, background rate is almost the same in all Si strips of the detector, which allows simple subtraction of the background.

However, some corrections due to recoil proton tracking in the holding magnet is needed. Such corrections require knowledge of the "molecular hydrogen rate"

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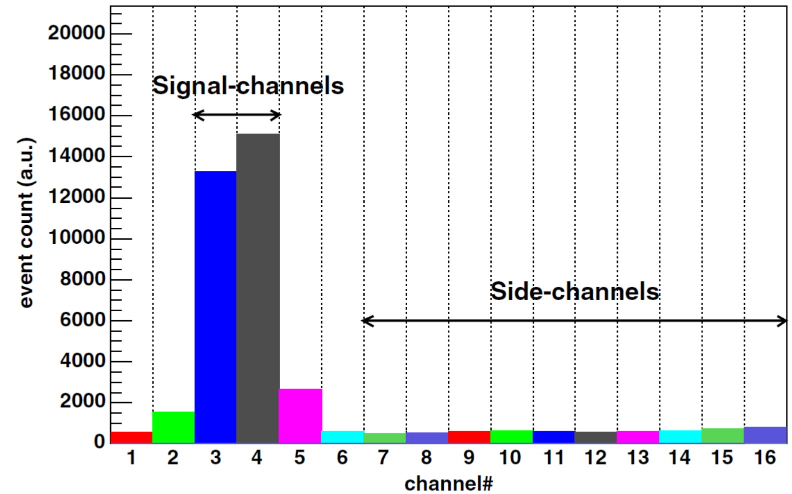


FIG. 9 (color online). Event distribution for the $1.4 < T_R < 1.8$ MeV interval as a function of channel number from the $\sqrt{s} = 13.7$ GeV data sample for one detector (Si #1). A detector covers recoil angles of $10 < \theta_R < 98$ mrad. For each T_R bin pp elastic events were selected in strips centered around the expected θ_R angle.

Beam gas and pA background subtraction

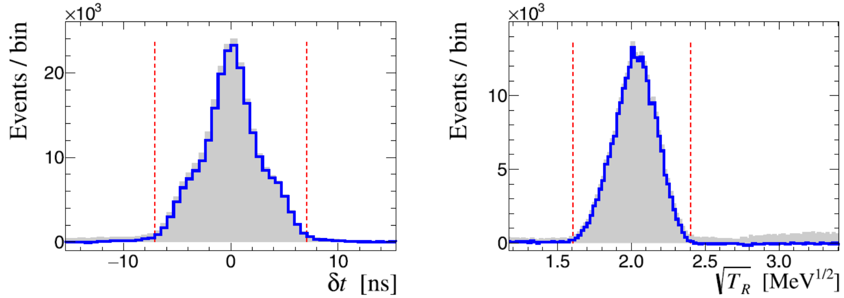


Fig. 17. Elastic *pp* events isolation. Event selection cuts are shown by the dashed red lines. The $\delta\sqrt{T}$ cut is applied for events in the δt histogram, and the δt cut is applied in the T_R histogram. Filled histograms show the distributions before the background subtraction.

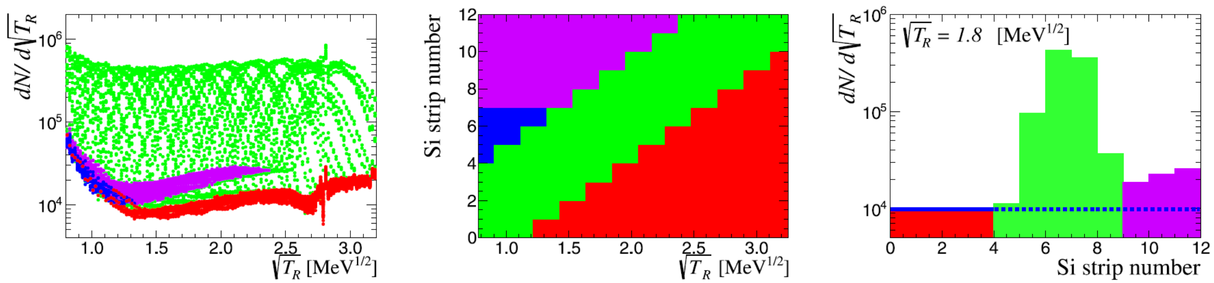


Fig. 18. The superposition of $dN/s\sqrt{T_R}$ distributions for all Si strips (left). The markers colors depending on the strip location in a detector and recoil proton energy are explained in center histogram. Green color is used for elastic events, red and blue for backgrounds, and violet specifies the area contaminated by the inelastic events. An example of background subtraction for fixed, $T_R = 3.6$ MeV recoil proton energy is shown in the right histogram. The background determined in the red (and/or blue, depending on T_R) area is extrapolated to the signal (green) area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

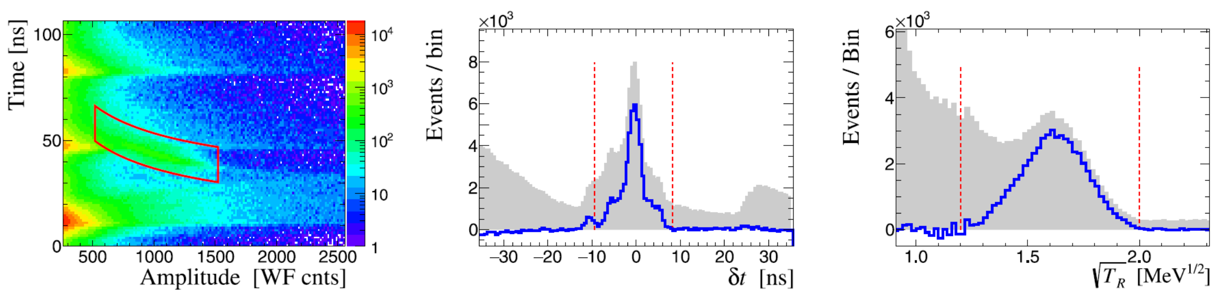
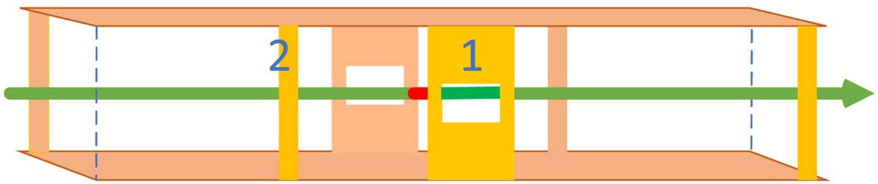


Fig. 19. An example of the background subtraction in case of very high background rate. Gray filled and blue solid line histograms show event distributions respectively before and after background subtraction. Dashed red lines indicate event selection cuts used. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Separation of the beam gas hydrogen and pA backgrounds



$$\frac{z_{\text{strip}} - z_{\text{jet}}}{L} = \sqrt{\frac{T_{\text{strip}}}{2m_p}\,\frac{E_b + m_p}{E_b - m_p + T_{\text{strip}}}}$$

- Recoil proton shadowing by the RF shield enables isolation and normalization of the beam-gas background.
- A proper design of the RF shield baffles could further enhance background subtraction capabilities at the EIC.

Recoil proton shadowing by Baffle 2 observed in the single-beam measurement with the magnetic field turned off.

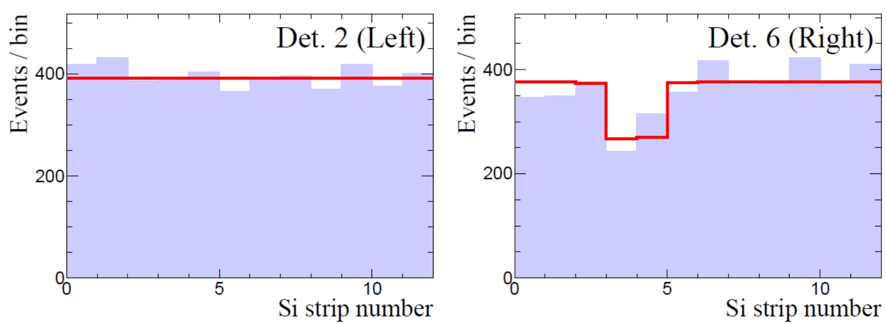
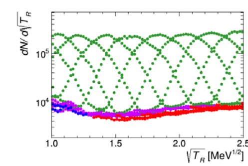
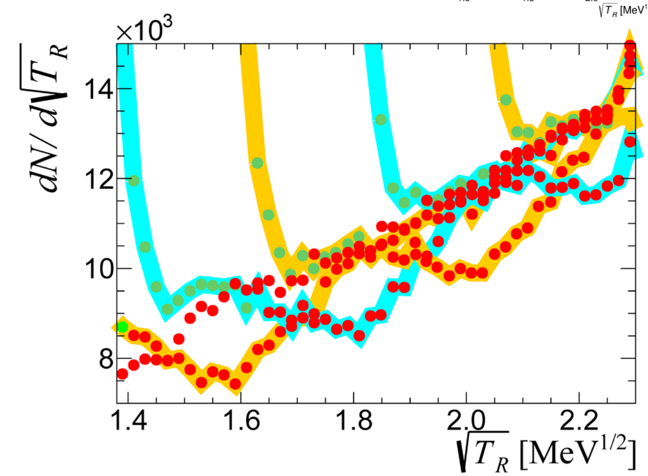


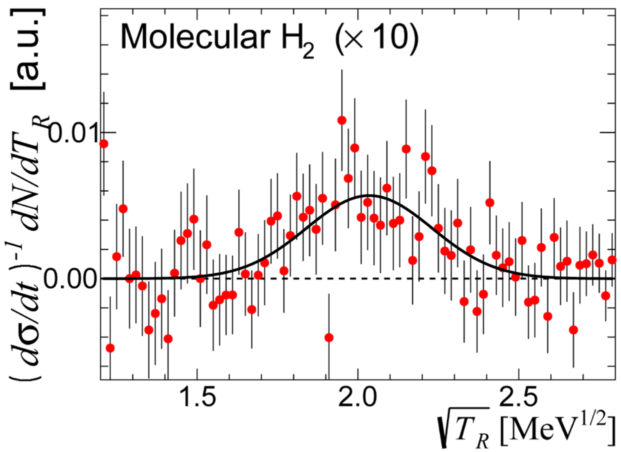
Figure 8: Experimental evaluation of the background rates [12]. The measurements have been done with a single (*blue*) 3.85 GeV/nucleon gold beam. The holding field magnet was switched off. The recoil protons $\left(1.3 < \sqrt{T_R} < 1.4\ \text{MeV}^{1/2}\right)$ were detected in the *backward* detectors. The effect of the recoil proton shadowing (by wall 2) is clearly seen in the right side detector. There was no shadowing in the left side detector.

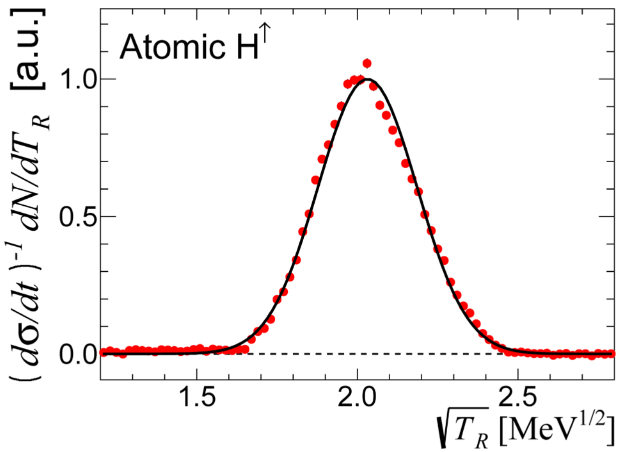
Regular data analysis: the dips in the $dN/d\sqrt{T_R}$ distributions are attributed to the presence of Baffle 1.





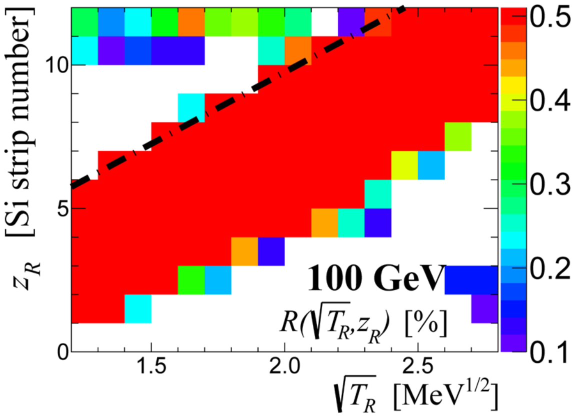
Molecular hydrogen fraction in the Jet

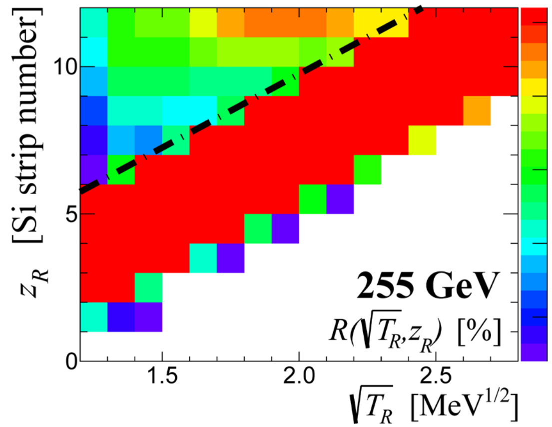


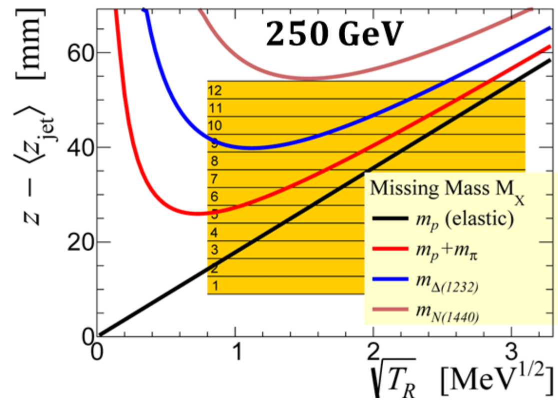


- To evaluate the hydrogen molecule fraction, two runs were conducted with the dissociator turned ON (producing atomic H) and OFF (molecular H_2).
- A flat background—primarily from beam-gas and pA interactions—was subtracted.
- Relative normalization of the measured distributions was based on the run durations and beam intensities as recorded by the Wall Current Monitor (WCM).
- Assuming that the molecular H_2 content in the jet is suppressed by a factor of 10 (as suggested by Anatoli) when the dissociator is ON, the residual H_2 fraction in the polarized jet was estimated to be approximately **0.05%.**

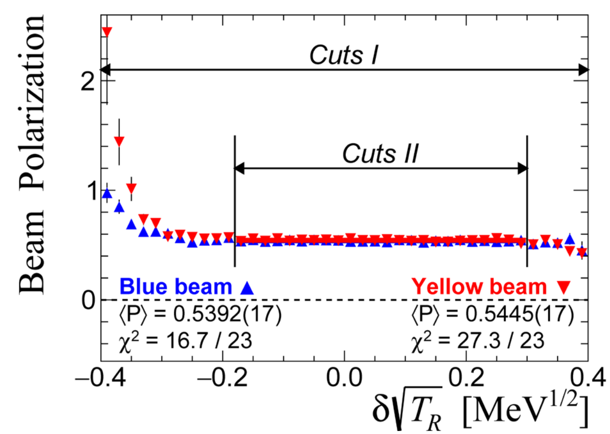
Inelastic $pp \to pX$ scattering







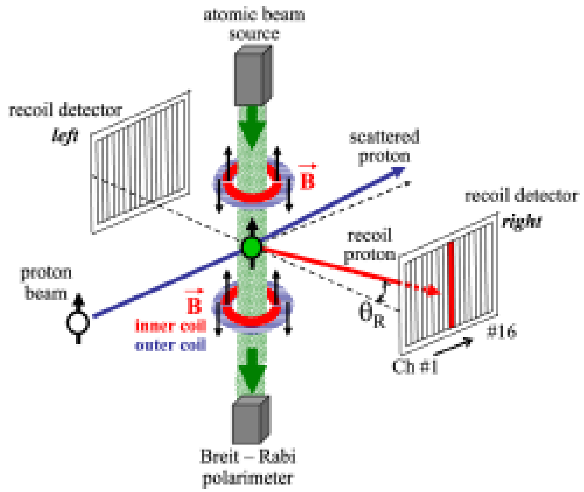
- For a 250 GeV beam, the inelastic fraction in the HJET data is non-negligible.
- However, these inelastic events can be efficiently excluded from the elastic sample using appropriate selection cuts.
- Importantly, for $T_R < 2$ MeV, background subtraction becomes unreliable at 250 GeV, limiting the usable recoil energy range.
- Although only one hadronic beam will be present at EIC, it may still be beneficial to retain the backward detectors (used for the opposite beam at RHIC), as they can significantly improve the accuracy of background subtraction.

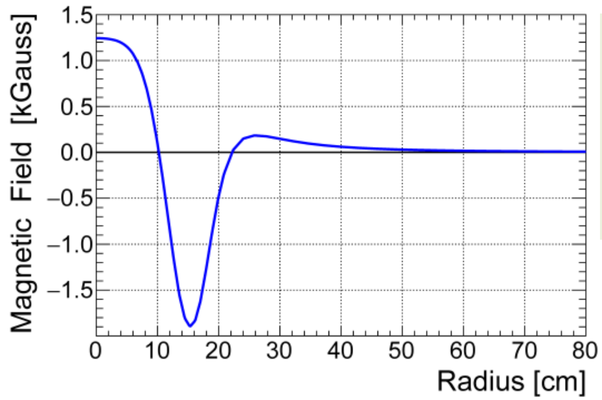


Role of the Target Gas Analyser (TGA)

- The TAG system may play a critical role in evaluating the molecular hydrogen fraction in the polarized atomic hydrogen jet.
- However, background sources in HJET are not limited to—and may not even be dominated by—molecular hydrogen in the jet or beam gas.
- Therefore, from the EIC perspective, it is essential to retain and further develop the RHIC HJET methods for monitoring and normalizing background processes.

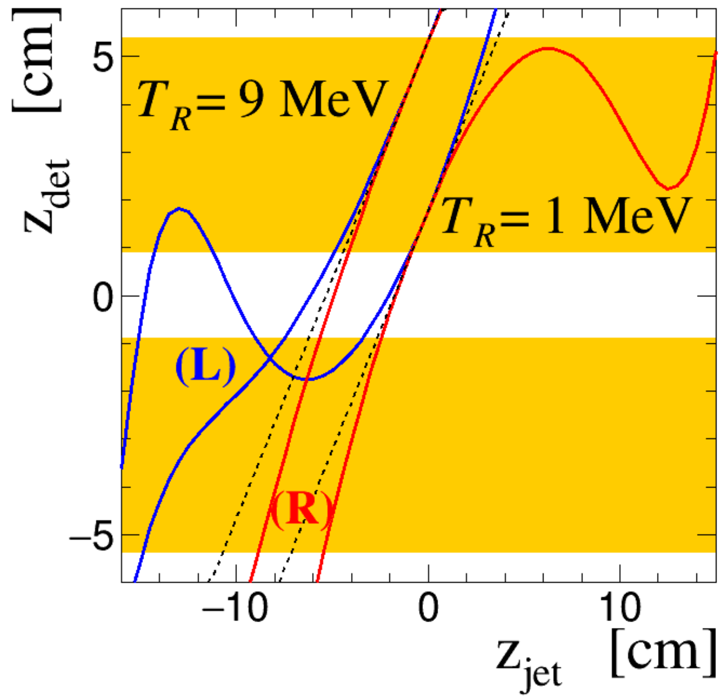
Recoil proton tracking in the magnetic field





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

$$\frac{z_R - z_j}{L} = \sqrt{\frac{T_R}{2m_p}\frac{E+m_p}{E-m_p}} \pm \frac{\beta}{L\sqrt{2m_pT_R}}$$



- 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 $T_R < 2$ MeV, the corresponding systematic error in value of the polarization may be $1 \div 3\%$.
- In the data analysis, the residual background was simulated.

Some effect of the magnetic field tracking

b/b_{MH} is fraction of the background retained after the subtraction.

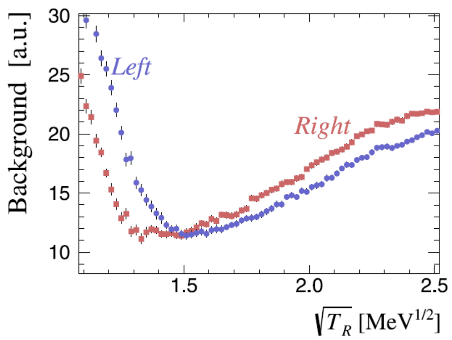


Fig. 26. Comparison of the background $dN/d\sqrt{T_R}$ rate in left and right side detectors.

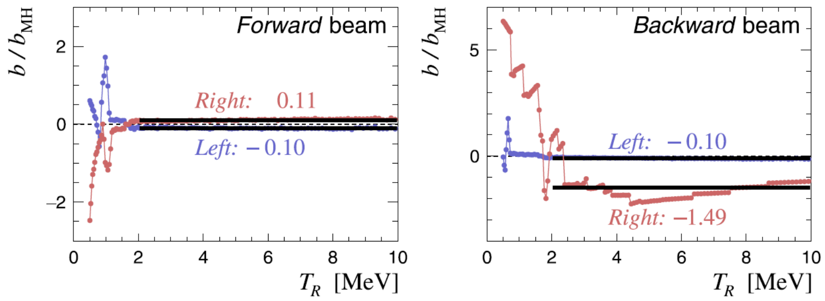


Fig. 27. Simulation of the residual H_2 backgrounds for *forward* and *backward* beams. Backgrounds in left and right (relative to the *forward* beam) detectors are shown separately. The average values are given for the $2 < T_R < 10$ MeV energy range.

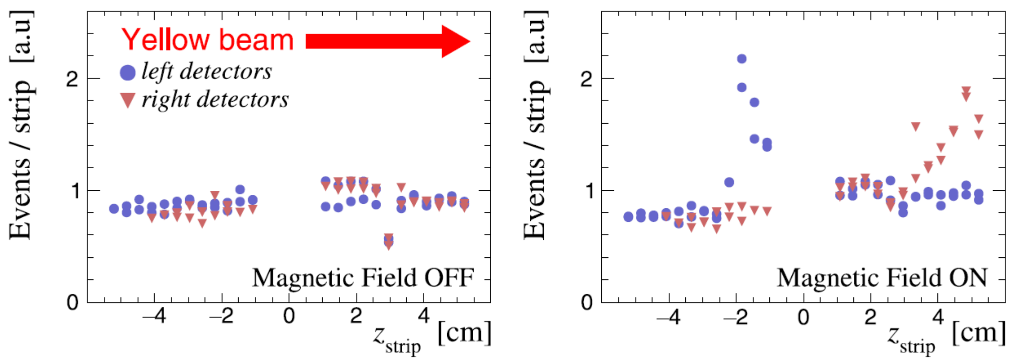


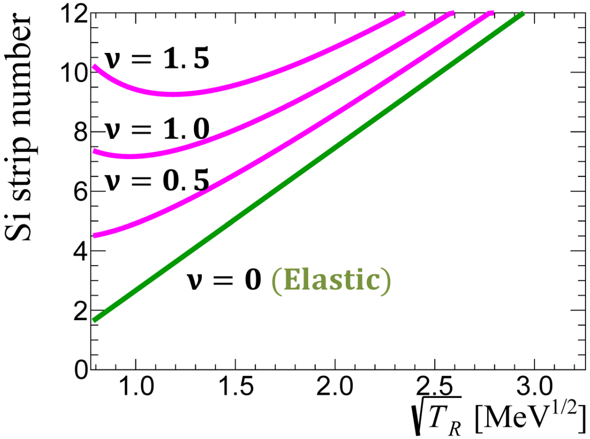
Fig. 39. Recoil proton z-coordinate distribution for $T_R = 1.0 \pm 0.1$ MeV with the holding field magnet On and Off. The measurements were done with *yellow* Gold beam and H_2 injected to Chamber 7.

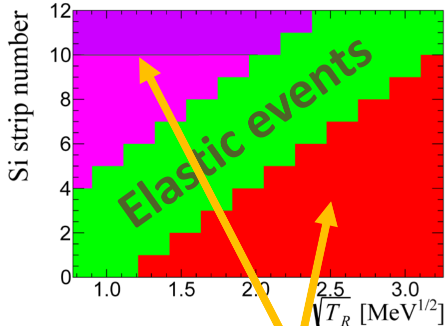
Inelastic scattering

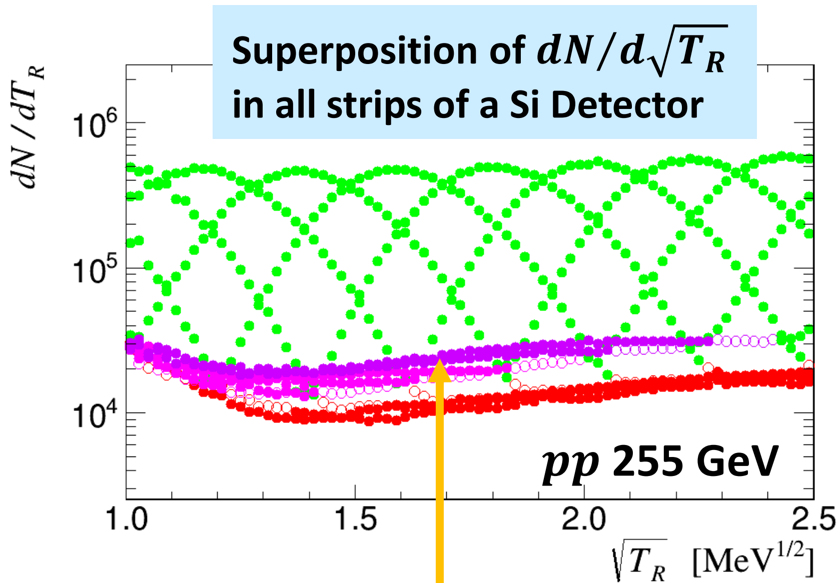
At the HJET, the elastic and inelastic events can be separated by comparing recoil proton energy and angle (discriminated by the Si strip location):

$$\tan\theta_R = \frac{z_{str} - z_{jet}}{L} = \sqrt{\frac{T_R}{2m_p}} \times \left(1 + \frac{m_p \Delta}{T_R E_{\text{beam}}}\right), \qquad \Delta = M_X - m_p, \qquad \nu = \frac{\Delta\ [\text{MeV}]}{E_{\text{beam}}\ [\text{GeV}]}$$

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







- The inelastic background populates the violet/magenta area and, thus, can be estimated by comparison with background in red area.
- For the 255 GeV pp scattering, the π-production events $p + p \to (X' + \pi) + p$ ($\Delta > m_\pi = 135\ MeV,\ \ \nu > 0.5$) are well seen at about $\sim 5\%$ relative to elastic rate.