CNFS Workshop on
Beam Polarization and Polarimetry at EIC
June 26 – July 1, 2020 (online)
https://indico.bnl.gov/event/7583/

On feasibility of absolute ^{3}He *beam polarization measurements at EIC using the HJET*

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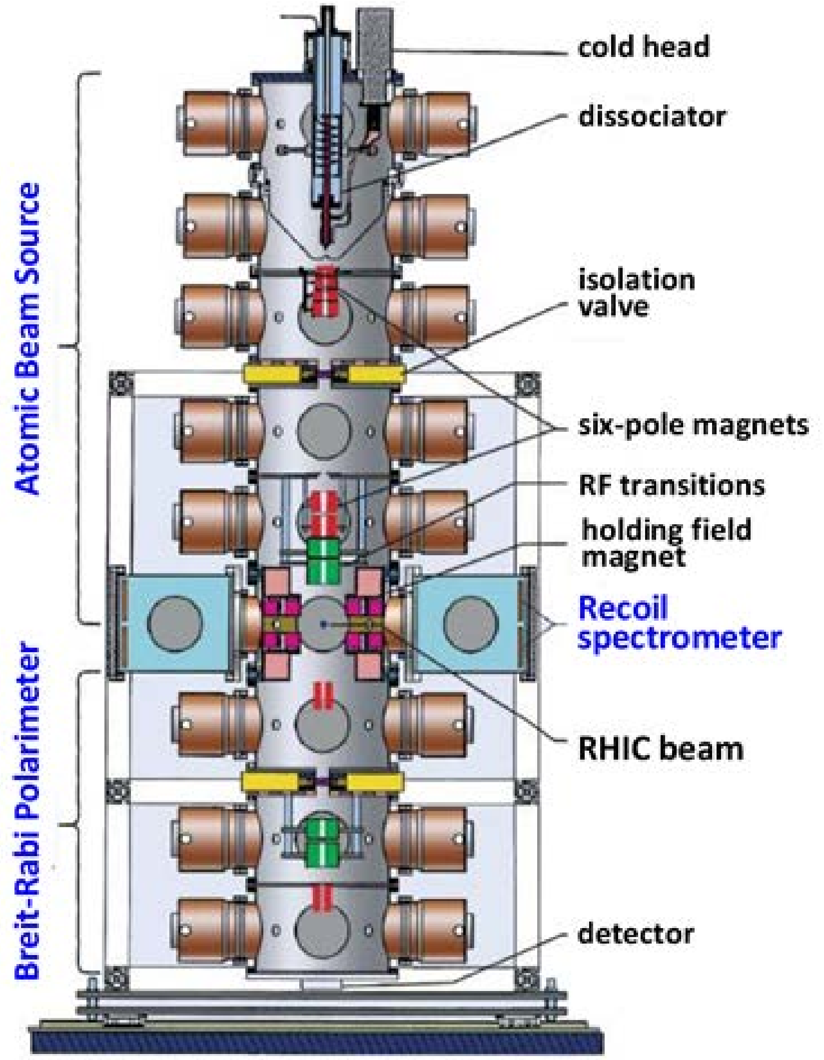
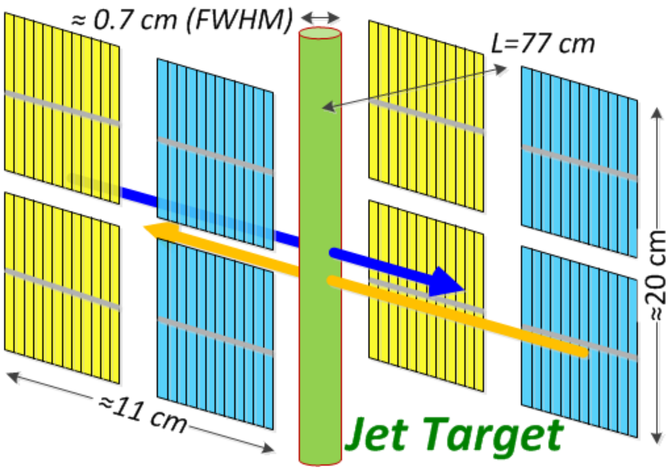
The Polarized Atomic Hydrogen Gas Jet Target (HJET)

- The HJET is in operation since 2004.
- The atomic hydrogen polarization in the Jet is 95.7%
- Jet intensity 12.6×10^{16} atoms/sec
- Jet density 1.2×10^{12} atoms/cm^2
- Jet profile $\sigma = 2.6$ mm
- The Jet polarization is flipped every 5 min.



- **The target with no walls and/or windows**
  - ✓ Continuous beam polarization measu-rement with no disturbing the RHIC experiments.
  - ✓ The recoil protons can be precisely measured in the energy range of 0.6 – 10 MeV (the CNI analyzing power maximum)
- **The beam polarization can be related to the atomic Hydrogen polarization which is precisely determined, $\sim 96 \pm 0.1\%$ by a Breit-Rabi polarimeter**

The recoil spectrometer



The recoil proton kinematics:

$$\tan\theta_R = \frac{z_{\text{det}} - z_{\text{jet}}}{L} = \frac{\kappa\sqrt{T_R}}{L} \qquad \kappa \approx 18\,\frac{\text{mm}}{\text{MeV}^{1/2}}$$

The energy range, $0.5 < T_R < 10\ \text{MeV}$, is defined by the detector geometry.

The analyzing power (B.Z. Kopeliovich and L.I. Lapidus, 1974):

$$A_N(t) \approx \sqrt{\frac{2T_R}{m_p}} \times \frac{\mu_p - 1}{T_c/T_R + T_R/T_c} \qquad T_c \approx 1.0\ \text{MeV} \qquad t = -2m_pT_R$$

The measured single spin asymmetries:

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

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

$\langle A_{\text{N}} \rangle \sim 0.037$

The rate and acceptance systematic errors are strongly suppressed

Proton Runs 15 (100 GeV) & 17 (255 GeV)

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

Proton Beam Polarization:

$$P_{\text{beam}} = \frac{a_{\text{beam}}}{a_{\text{jet}}} P_{\text{jet}} \qquad P_{\text{jet}} = 0.957$$

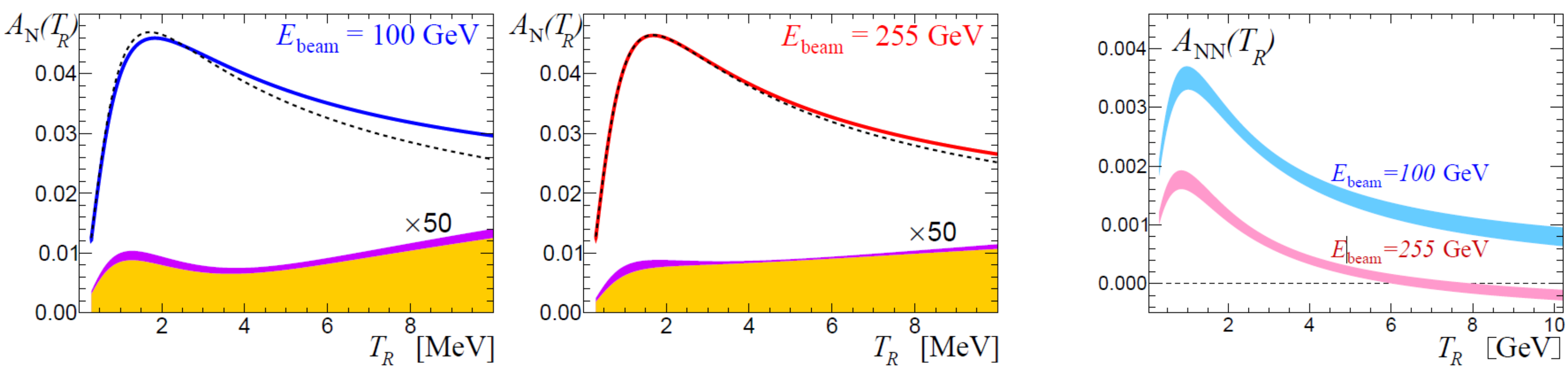
Typically, for 8 hour store (Run 17, 255 GeV):

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

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

Elastic *pp* analyzing powers:

Single Spin **Double Spin**



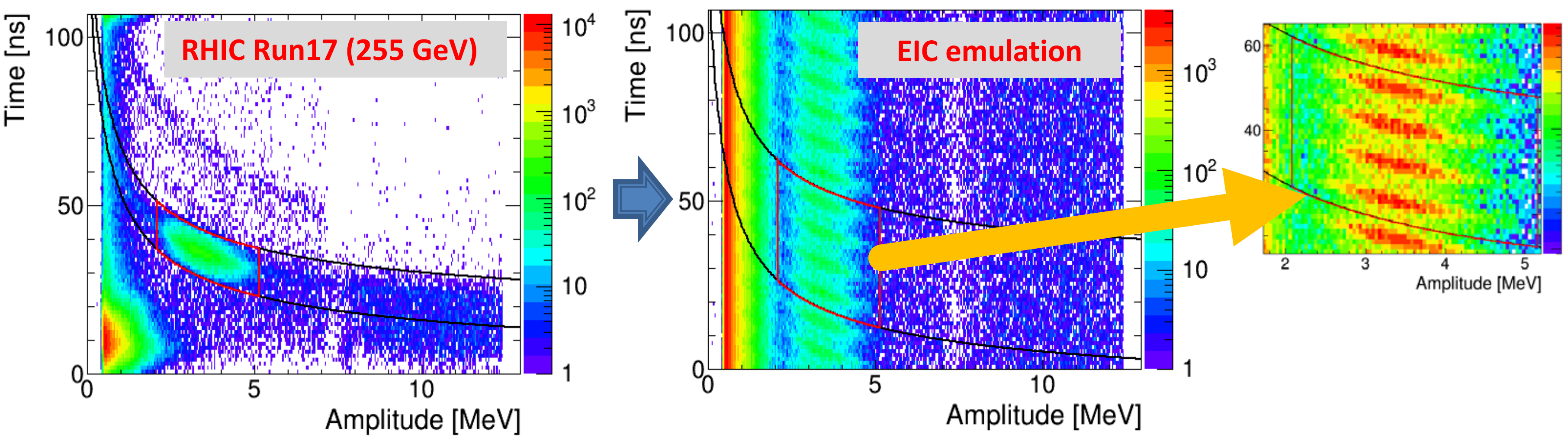
- **The displayed analyzing powers are model independent**
- **The analyzing powers can be extrapolated to other beam energies**

Emulation of the HJET performance at EIC using RHIC 255 GeV data

To emulate HJET performance at EIC (eRHIC), we used the Run17 data and for every event the measured time was shifted with $\tau/12 = 8.9$ ns step (τ =107 ns is bunch spacing at RHIC):

$\boldsymbol{t \Longrightarrow t' = t + k\tau/12}$ [k is randomly chosen from $k \in (= -1.5, -0.5, 0.5, 1.5\ )$]

$\boldsymbol{t' \Longrightarrow t' - 2\tau/3\ ,\ t',\ t' - 2\tau/3}$ [triplicate number of events]



For the HJET rates, the event pileup can be neglected. Therefore, the emulation must well reproduce the measurements at EIC including **all backgrounds**.

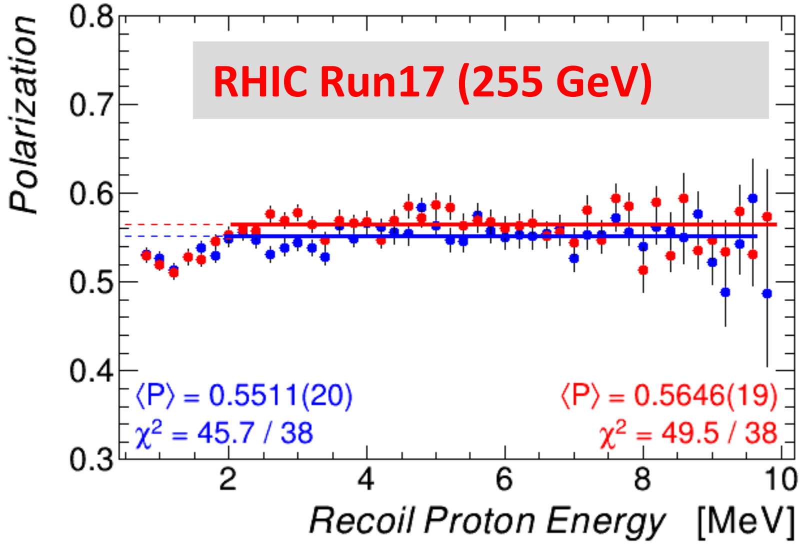
The emulation gives worse condition of the measurements than it is expected at EIC:

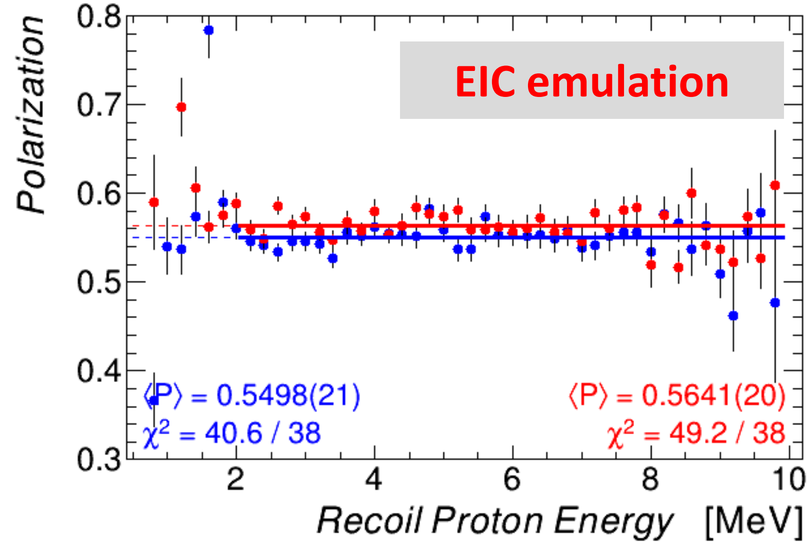
- The background rate will be factor 2 lower (only one proton beam)
- The bunch spacing will be larger, 10.1 ns vs 8.9 ns
- The bunch length will be much shorter.

Beam Polarization measurements. EIC vs RHIC.

The emulated EIC data was processed using regular RHIC HJET software.

(Since actually the same **elastic** data is used in both plots, the statistical errors are strongly correlated)





- For recoil proton energy above **2 MeV**, the EIC and RHIC results are well consistent.
- The EIC polarization is systematically shifted by only $|\Delta P/P| \lesssim 0.3\%$.
- An estimate of the systematic uncertainties in the absolute polarization measurements at EIC is $\delta P_{syst}/P \lesssim 0.6\%$.

We are optimistic about possibility to use RHIC HJET at EIC.

Nonetheless, some improvements might be critically important:

- **Double layer detectors**
- **No magnetic field (unpolarized HJET?)**
- **Optimization of the bias voltage in Si detectors**
- **Lower noise electronics**

High Density Unpolarized Hydrogen Gas Jet

- **The accuracy achieved at HJET in determining $A_N(t)$ allows one to use a higher density unpolarized hydrogen jet target in a high precision absolute polarimeter, e.g., at EIC.**
- Considering the unpolarized H-jet thickness of a $10^{14}\ \mathrm{H_2/cm^2}$ (with the jet profile similar to the HJET one), the higher EIC beam intensity and a possibility to increase the recoil proton detectors solid angle, one can expect 1000 times higher elastic pp event rate compared to that in the RHIC HJET measurements.
- ⇒ $\sigma_P^{stat} \sim 1\%$ per **3 min** exposure.
- Such a polarimeter can provide measurements of the polarization decay and the beam spin tilt.
- The main sources of the systematic errors (at HJET) can be eliminated in unpolarized jet.
- ⇒ $\sigma_P^{syst}/P < 0.4\%_{\mathbf{HJET}} \oplus 0.5\%_{\mathbf{AN}} \oplus 0.3\%_{\mathbf{bunch\ spacing}} \approx 0.7\%$

However, for a realistic design of the high density jet must consider the following effects:

- The beam destroying by the dense target.
- Background generating for EIC experiments
- The DAQ upgrade (for much higher data rate) and possible increase of the systematic errors.
- Optimization of the jet density / jet profile.
- …

Polarized $^3\mathrm{He}\,(h^{\uparrow})$ *Elastic Scattering off Proton Target*

For the CNI scattering, the amplitude is described by 2 helicity terms:

None-flip: $\boldsymbol{\phi_+(s,t) = \frac{\langle ++|\mathcal{M}|++\rangle + \langle +-|\mathcal{M}|+-\rangle}{2}}$

Spin-flip: $\boldsymbol{\phi_5(s,t) = \langle ++|\mathcal{M}|+-\rangle}$

$$\boldsymbol{\phi = \phi^{\mathrm{h}} e^{-i\delta_C} e^{Bt/2} + \phi^{\mathrm{em}} e^{B_e t/2}}$$

Using normalization on $\mathrm{Im}\,\phi_+(s,0) = s\sigma_{\mathrm{tot}}(s)/8\pi$, the amplitudes can be presented as:

$$\varphi_+^{\mathrm{h}} = \rho + i \qquad \varphi_+^{\mathrm{em}} = -\frac{t_c}{t} \qquad t_c = -8\pi\alpha Z_h/\sigma_{\mathrm{tot}}^{hp}$$

$$\varphi_5^{\mathrm{h}} = \frac{\sqrt{-t}}{m_p} \times r_5, \quad r_5 = R_5 + iI_5 \qquad \varphi_5^{\mathrm{em}} = -\frac{t_c}{t}\frac{\sqrt{-t}}{m_p} \times \kappa_h', \qquad \kappa_h' = \frac{\mu_h}{Z_h} - \frac{m_p}{m_h} - \frac{m_p}{E_{\mathrm{beam}}}$$

$$\frac{\mathrm{GeV}}{\mathrm{nucleon}}$$

Analyzing power: $\boldsymbol{A_N^{hp}(t) \approx \frac{\sqrt{-t}}{m_p} \times \frac{\kappa_h' - 2I_5^{hp} - 2R_5^{hp}\, t/t_c}{t_c/t - 2(\rho + \delta_C) + t/t_c}}$

To provide 1% or better systematic error in the $^3\mathrm{He}$ **beam polarization measurement, the theoretical accuracy of the analyzing power should be:** $\boldsymbol{\frac{\langle|\delta A_N|\rangle}{\langle A_N\rangle} < 0.8\%}$

$h^{\uparrow}p$ scattering in the unpolarized hydrogen jet

For elastic scattering at HJET, in terms of the recoil proton energy $T = -t/2m_p$,

$$A_N^{hp}(T) = \sqrt{\frac{2T}{m_p}} \times \frac{\kappa'_h - 2I_5^{hp} - 2R_5^{hp}\, T/T_c}{T_c/T - 2\tilde{\rho} + T/T_c}$$

$0.7(?) < T < 10\ \mathrm{MeV}, \quad T_c \approx 0.7\ \mathrm{MeV}, \quad \tilde{\rho} = \rho^{hp} + \delta_C^{hp}, \quad \kappa'_h \approx -1.41\ (100\ \mathrm{GeV})$

The beam polarization can be measured as a function of the recoil proton energy T

$$P_{\mathrm{meas}}(T) = P_{\mathrm{beam}} \times (1 + a + b\ T/T_c)$$

where a and b are systematic corrections due to uncertainties in the analyzing power. Since b can be determined from the measurements, only a contributes to the systematic error in the beam polarization value.

$$\sigma_P^{A_N}/P = \delta a = \frac{2\delta I_5^{hp}}{\kappa'_h} \oplus \delta\tilde{\rho} \oplus \frac{\delta^{\mathrm{cal}} T/T}{2}$$

Systematic error in the energy calibration

What do we know from elastic $p^{\uparrow}p^{\uparrow}$ study at HJET

Hadronic spin-flip amplitudes: $\delta I_5^{pp} \sim 0.4\%$

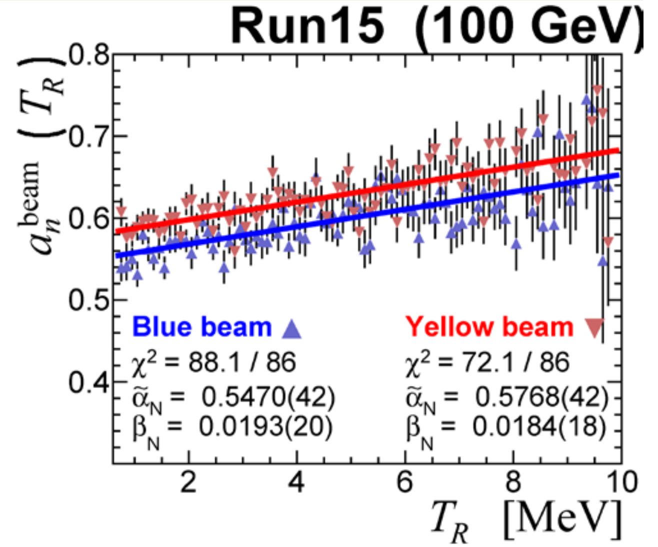
100 GeV: $I_5 = -0.53 \pm 0.29 \pm 0.47\ \%$

$R_5 = -1.64 \pm 0.08 \pm 0.15\ \%$

255 GeV: $I_5 = +1.94 \pm 0.25 \pm 0.25\ \%$

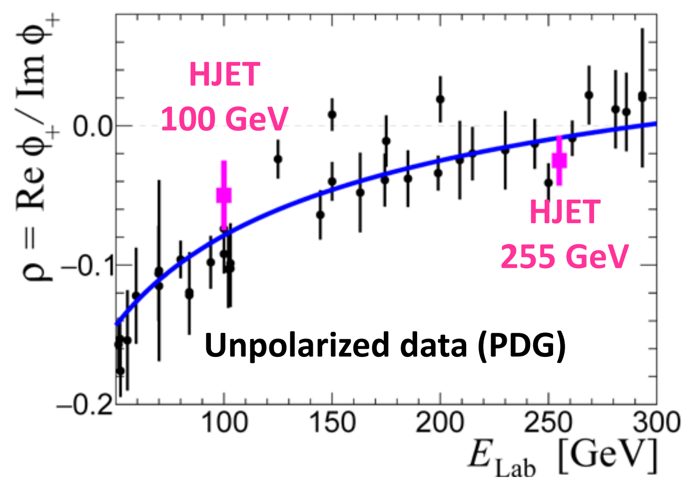
$R_5 = -0.79 \pm 0.05 \pm 0.08\ \%$

$$a_n^{\text{beam}} = a_N^{\text{beam}} / A_N(r_5 = 0) \approx P_{\text{beam}} \times \left(1 + 2I_5/\kappa_p' + 2R_5/\kappa_p'\ T_R/T_c\right) = \tilde{\alpha}_N \times (1 + \beta_N T_R/T_c)$$



Systematic error in energy calibration: $\delta^{\text{cal}}T/T < 1\%$

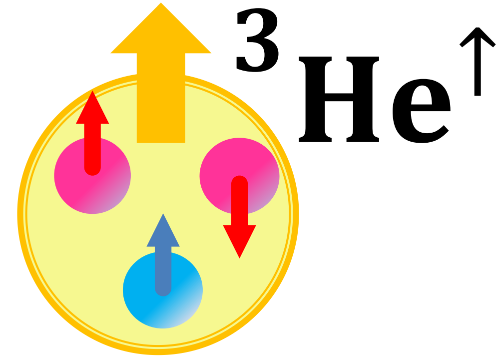
For elastic *pp* scattering the value of $\tilde{\rho}$ is well known from the global fit of the unpolarized pp data.



In the fit with ρ being a free parameter, it was evaluated with accuracy $\delta\tilde{\rho} \sim 2\%$. At minimum 20-fold increase in statistics is need to achieve required (statistical) accuracy in this method.

Potentially, the value of $\tilde{\rho}$ can be determined with very low statistical error from the measured event rates. However, this method <u>was not studied</u> at HJET.

How theory can help?



For ^{3}He, the dominant (~90%) component of the ground-state nuclear wave function is the fully space-symmetric S state.

Assuming:

- **The ^{3}He is in pure S state:** *the two protons are coupled to spin singlet (Pauli principle) and all the spin is carried by neutron*
- **The $p\ ^3$He scattering is given by pure isoscalar $(I=0)$ exchange:**

$$\sigma_{\text{tot}}^{pn}=\sigma_{\text{tot}}^{pp},\quad \rho^{pn}=\rho^{pp},\quad r_5^{p^\uparrow n}=r_5^{n^\uparrow p}=r_5^{p^\uparrow p}$$

$$\boldsymbol{\rho^{hp}=\rho^{pp},\quad r_5^{p^\uparrow h}=r_5^{p^\uparrow p},\quad r_5^{h^\uparrow p}=r_5^{p^\uparrow p}/3}$$

$$\boldsymbol{\delta I_5^{hp}\approx\delta I_5^{pp}/3\sim 0.15\%}$$ **(negligible)**

"This is almost certainly true at RHIC but corrections can be made when using the approach at lower energy",
N.H. Buttimore, E. Leader, and T.L. Trueman, Phys. Rev. D **64**, 094021 (2001)

The correction to $r_5^{h^\uparrow p}$ due to non-pure S state can be evaluated by comparing ^{3}He and neutron magnetic moment effects $\frac{(\mu_h-\mu_n)/Z_h}{\mu_n/Z_h-m_p/m_h}\approx\mathbf{0.08}$ which **may be neglected**.

The **unpolarized hydrogen gas jet** can be used to measure the ^{3}He beam polarization at EIC with 1% accuracy **IF**

- The value of $\tilde{\rho}=\rho^{hp}+\delta_C^{hp}$ can be determined, experimentally or theoretically, with accuracy better than $\boldsymbol{\delta\tilde{\rho}<0.005}$.
- It will be proved that inelastic (the ^{3}He break-up) scattering component is controllable.

$h^{\uparrow}p/p^{\uparrow}h$ asymmetry ratio in the polarized hydrogen jet

The uncertainty $\delta^{\text{cal}}T/T$ and $\delta\tilde{\rho}$ can be eliminated if the beam ^{3}He and the jet proton spin asymmetries are concurrently measured:

$$P(T) = P_{\text{jet}}\,\frac{a_N^{\text{beam}}}{a_N^{\text{jet}}} \times \frac{\kappa'_p - 2I_5 - 2R_5\,T/T_c}{\kappa'_h - \frac{2}{3}I_5 - \frac{2}{3}R_5\,T/T_c} = P_{\text{beam}} \times (1 + a + b\,T/T_c)$$

Here, $r_5 \equiv r_5^{pp}$ and $\kappa'_p = \mu_p - 1 - m_p^2/m_h E_{\text{beam}} \approx +1.79$ $(100\ \text{GeV})$

$$\sigma_P^{A_N}/P = \delta a = \left(2/3\kappa'_h - 2/\kappa'_p\right) \times \delta I_5^{pp} \sim 0.6\%$$

The **polarized hydrogen gas jet** can measure the ^{3}He beam polarization at EIC with 1% accuracy

- ✓ For every beam energy, the elastic pp hadronic amplitude should be precisely determined.
- ✓ An effect of inelastic (the ^{3}He break-up) scattering is expected to be negligible

An example of the correction to analyzing power

More accurate expression for the dominant contribution to the analyzing power is

$$\varphi_5^{em}\ \mathrm{Im}\,\varphi_+^{\mathrm{h}} \ \propto\ \kappa \times (1-\rho\delta_C)$$

where, for the hp scattering, $\rho\delta_C \sim 0.004$.

For the unpolarized jet, the correction changes the measured polarization

$$\delta P/P \approx \rho\delta_C \approx 0.4\%$$

should be considered.

For $h^{\uparrow}p/p^{\uparrow}h$ asymmetry ratio, the correction is canceled in κ_h/κ_p

$$P_{\mathrm{beam}}^{(\mathrm{meas})} \ \propto\ \frac{\kappa_p' \times (1-\rho\delta_C) - 2I_5^{pp} - 2R_5^{pp}\,T/T_c}{\kappa_h' \times (1-\rho\delta_C) - \frac{2}{3}I_5^{pp} - \frac{2}{3}R_5^{pp}\,T/T_c}$$

$$\delta P/P = \left(2/3\kappa_h' - 2/\kappa_p'\right) I_5^{pp} \times \rho\delta_C \ \sim\ 0.006\%$$

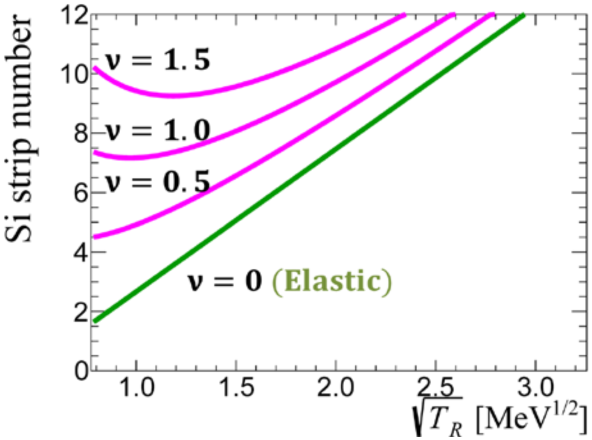
and can be neglected.

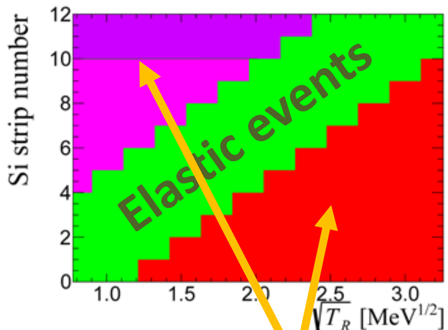
Inelastic scattering

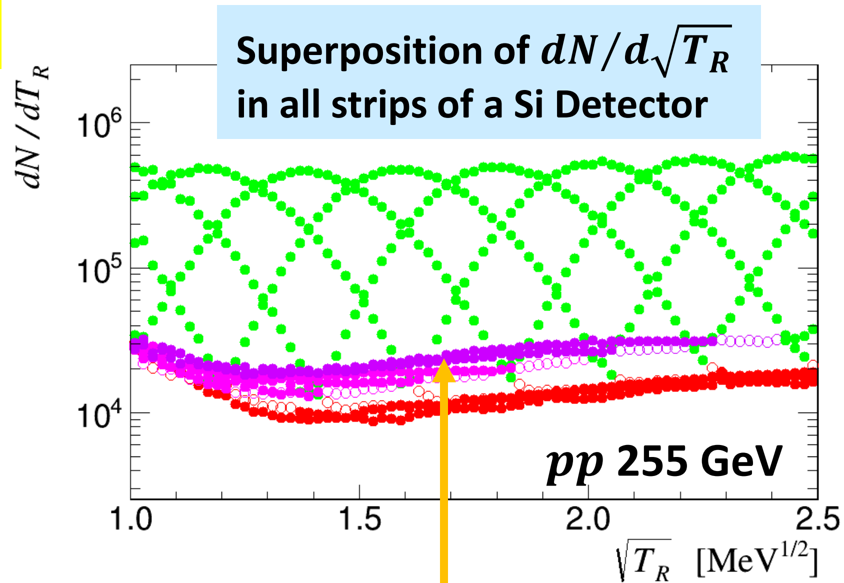
At the HJET, the elastic and inelastic events can be separated by comparing recoil proton energy and angle (discriminated by the Si strip location):

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

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



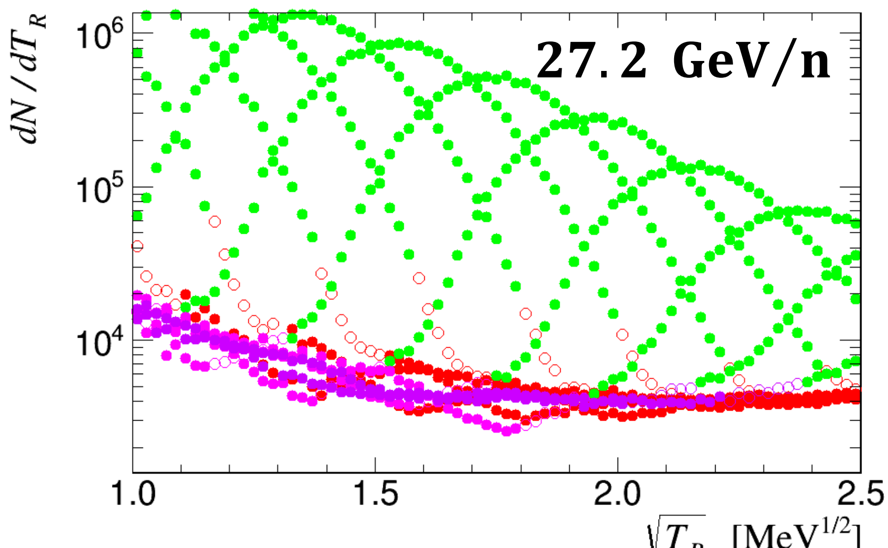


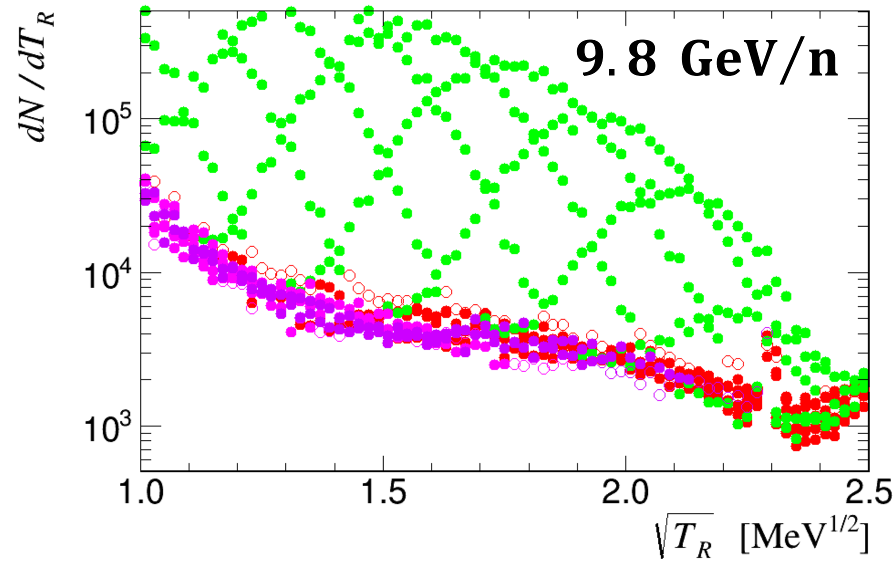


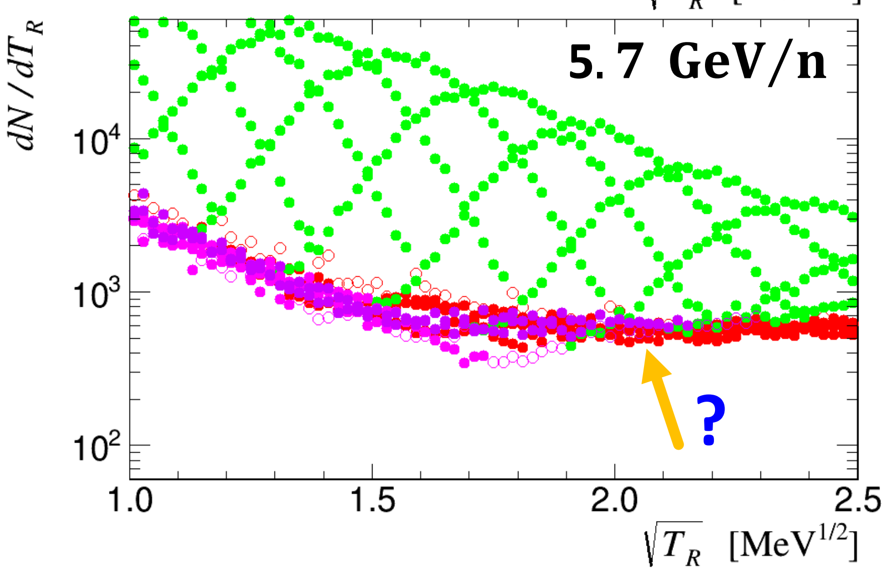
- The inelastic background populates the violet/magenta area and, thus, can be estimated by comparison with background in red area.
- For the 255 GeV pp scattering, the π-production events $p + p \to (X' + \pi) + p$ $(\Delta > m_\pi = 135\ MeV,\ \ \nu > 0.5)$ are well seen at about $\sim 5\%$ relative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

Au *beam scattering in HJET*

Separation energies: $S(p) = \mathbf{5.8\ MeV},\ S(n) = \mathbf{8.1\ MeV}$







No evidence of inelastic events at **27.2** and **9.8 GeV**, but a possible indication (<1%) at **5.7 GeV**

A possible interpretation (not proved!):

$\mathrm{Au} + p \rightarrow (\mathrm{A}_1 + \mathrm{A}_2) + p \quad (\Delta > 8\ \mathrm{MeV})$

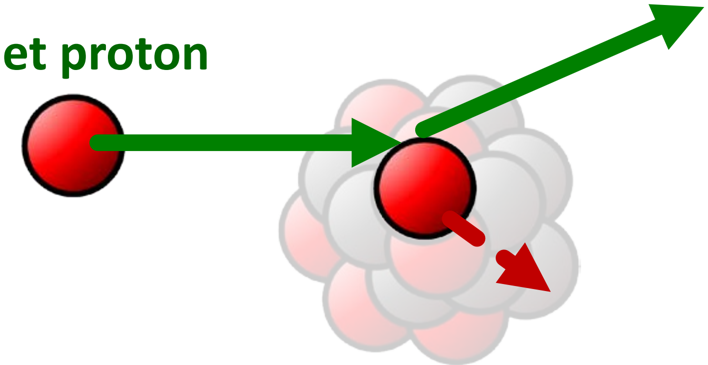
no visible breakup events.

$\mathrm{Au} + p \rightarrow \mathrm{Au}^* + p \quad (\Delta < 8\ \mathrm{MeV})$,

gold excitation, is seen at relative rate of $\sim 1\%$.

Why Au *breakup is not observed at HJET ?*

For incoherent proton-nucleus scattering:



Simple kinematical consideration gives:

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

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

For the He3 scattering off the jet proton:

$$\phi^{\mathrm{h}}(t) = \phi^{\mathrm{h}}(0) F_H(t); \qquad F_H(t) = \exp\left(\frac{B}{2} + \frac{57\ \mathrm{GeV}^{-2}}{4}\right) t; \qquad dF_H/dt = \frac{1}{6}\langle r^2 \rangle = \frac{1}{2}\langle r_x^2 \rangle$$

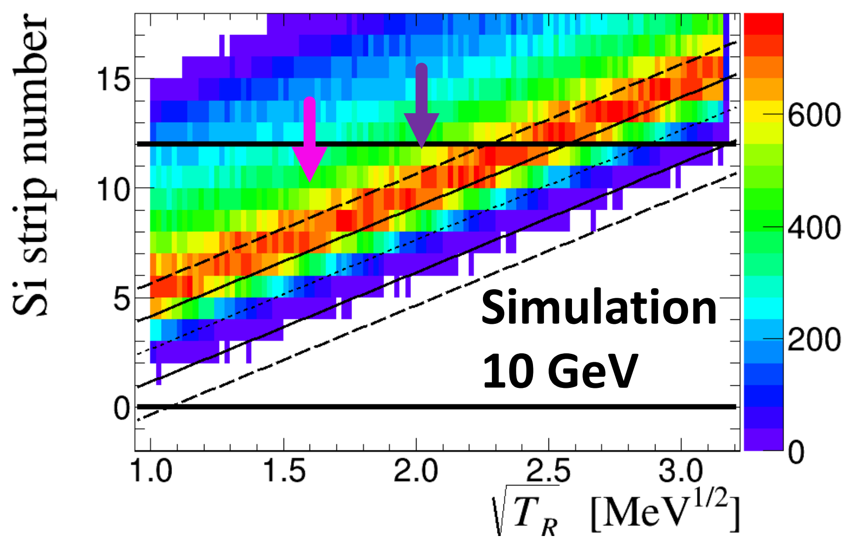
$$\Rightarrow \quad \langle p_x^2 \rangle^{1/2} = \langle r_x^2 \rangle^{-1/2} \approx 190\ \mathrm{MeV}/c$$

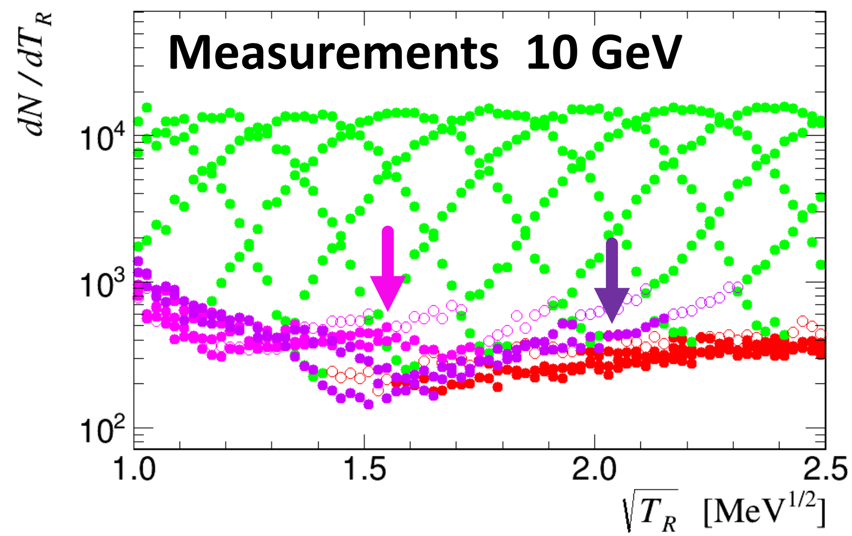
$$dN/d\Delta \propto \exp\frac{-(\Delta - \Delta_0)^2}{2\Gamma^2} \times C(T_R, \Delta)$$

$$\Delta_0 = \frac{2}{3} T_R, \quad \Gamma = 8.6\sqrt{T_R} \quad [\mathrm{MeV}]$$

$C(T_R, \Delta)$ is a correction factor due to the breakup amplitude and the phase space effects.

Breakup fraction for deuteron beam (10, 20, and 30 GeV)





- The experimental distributions are affected by the recoil proton tracking in magnetic field and the shadowing effect.
- The experimental results **qualitatively** agree with the simulation model:
  - For $\sqrt{T_R} \sim 2.0$ MeV$^{1/2}$, the isolated (*above dashed line*) breakup events can be seen strips **11-12**.
  - For $\sqrt{T_R} \sim 1.5 - 1.6$ MeV$^{1/2}$, these events are dominated in strips **9-10**.
- The model based breakup rate estimates are consistent for 10, 20, and 30 GeV:

$$\tilde{f}_d(T_R \sim 4\ \text{MeV}) = \frac{(d\sigma/dt)_{\text{breakup}}}{(d\sigma/dt)_{\text{elastic}}} = \mathbf{1.2 \pm 0.4\%}$$

- An extrapolation to ^{3}He beam (phase space only) gives: $\tilde{f}_h(T_R \sim 4\ \text{MeV}) = \mathbf{0.8 \pm 0.3\%}$

Analyzing power dependence on the beam ^{3}He *breakup*

Since the breakup events fraction is small at HJET, we can consider only the dominant term in the analyzing power:

$$A_N \propto \frac{\phi^{em}_{spin-flip}\,\mathrm{Im}\,\phi^{had}_{non-flip}}{\left|\phi^{em+had}_{non-flip}\right|^2}$$

$$\phi^{em}_{spin-flip} \propto \kappa = \mu/Z - m_p/m \;\Longrightarrow\; \kappa \times (1 + f_\kappa)$$

$$f_\kappa^p = 0, \qquad f_\kappa^h \sim \Delta/6\kappa m_h \approx 0$$

Electromagnetic form factors are not considered here.

$$\mathrm{Im}\,\phi^{had}_{non-flip} \le \left|\phi^{had}_{non-flip}\right| \;\Longrightarrow\; \left|\phi^{had}_{non-flip}\right| \times (1 + f)$$

$$f^p = f^h \;\sim\; 0.3\%$$

$$\left|\phi^{em+had}_{non-flip}\right|^2 \propto d\sigma/dt \Longrightarrow d\sigma/dt \times (1 + \tilde{f})$$

$$\tilde{f}^p = \tilde{f}^h \sim \; 0.8\%$$

Estimates made in the model dependent analysis of the deuteron scattering in HJET

The model independent upper limits:

$f \lesssim 3\%, \qquad \tilde{f} \lesssim 5\%$

Interpretation of the corrections used:

$$A_N(t) \Longrightarrow A_N(t) \times \frac{1 + \int d\Delta[1 + f'_\kappa(t,\Delta)]f'(t,\Delta)}{1 + \int d\Delta\, \tilde{f}'(t,\Delta)}$$

$$f(t) = \int f'(t,\Delta)d\Delta$$

Measured P_{beam} *dependence on the beam* $^3\mathrm{He}$ *breakup*

The unpolarized HJET:

$$\delta^{\mathrm{br}}P/P \approx -\tilde{f} \sim -\mathcal{O}(2\text{-}3\%)$$

For a precision determination of the $^3\mathrm{He}$ beam polarization an accurate (<0.5%) study of the $d\sigma/dt$ is needed including the evaluation of the breakup component for the HJET geometry. Low energy, 5-20 GeV $^3\mathrm{He}$ beams can (should) be used to study the breakup effects.

The polarized HJET:

Possible $^3\mathrm{He}$ breakup can be neglected in determination of the $^3\mathrm{He}$ beam polarization from the measured $h^{\uparrow}p/p^{\uparrow}h$ asymmetry ratio:

$$\left|\delta^{\mathrm{br}}P/P\right| \approx \left|\left(2/3\kappa_h' - 2/\kappa_p'\right) I_5^{pp} \times f\right| < 0.05\%$$

(even if the model independent upper limit of $f < 3\%$ is used)

Polarized ^{3}He *Jet*

- The ^{3}He beam polarization can be directly related to the ^{3}He jet polarization

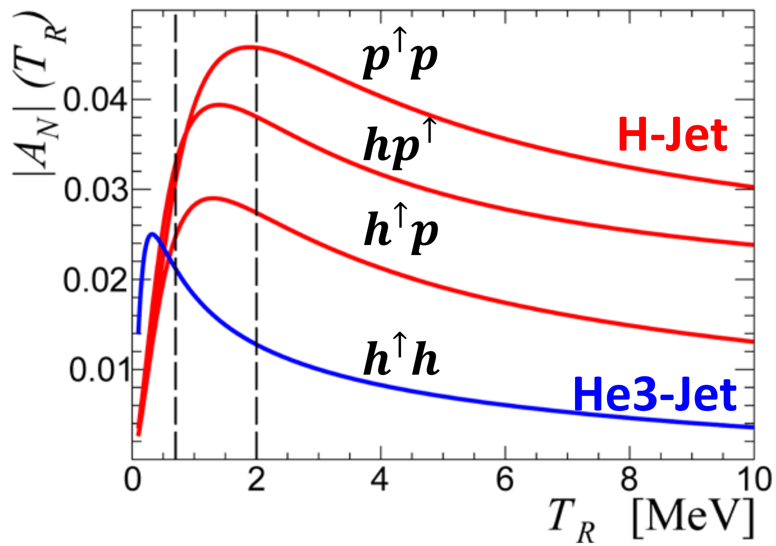
$$P_{\rm beam} = P_{\rm jet} \times a_{\rm N}^{\rm beam} / a_{\rm N}^{\rm jet}$$

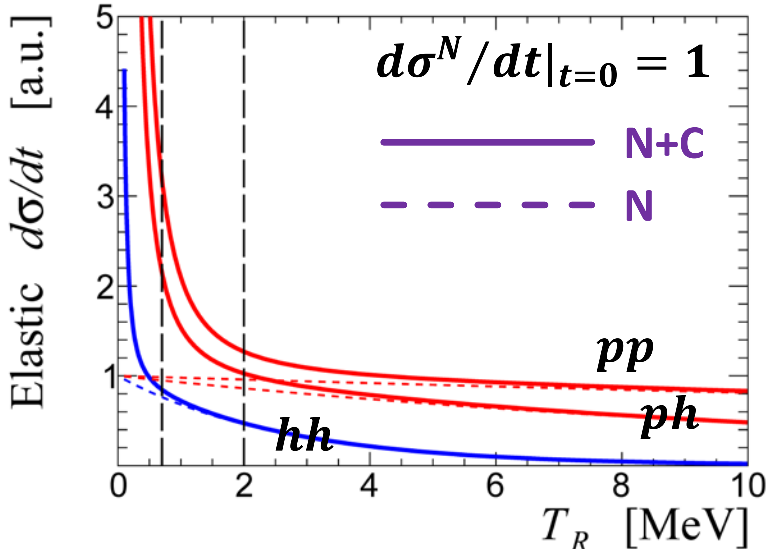
- The beam ^{3}He breakup must not alter the measured ratio $a_{\rm N}^{\rm beam} / a_{\rm N}^{\rm jet}$ and, subsequently, the measured beam polarization.

However, experimental uncertainties for such a polarimeter are not necessary the same as for the HJET, due to

- the Jet ^{3}He breakup background (p and d) in the Si detectors
- the recoil ^{3}He kinematics is "less friendly" for data analysis than that of protons in HJET.

For the given momentum transfer t: $T_R \propto m_R^{-1}$, $\mathrm{ToF} \propto m_R$, $z_{\rm str} - z_{\rm jet} \propto m_R^{-1}$



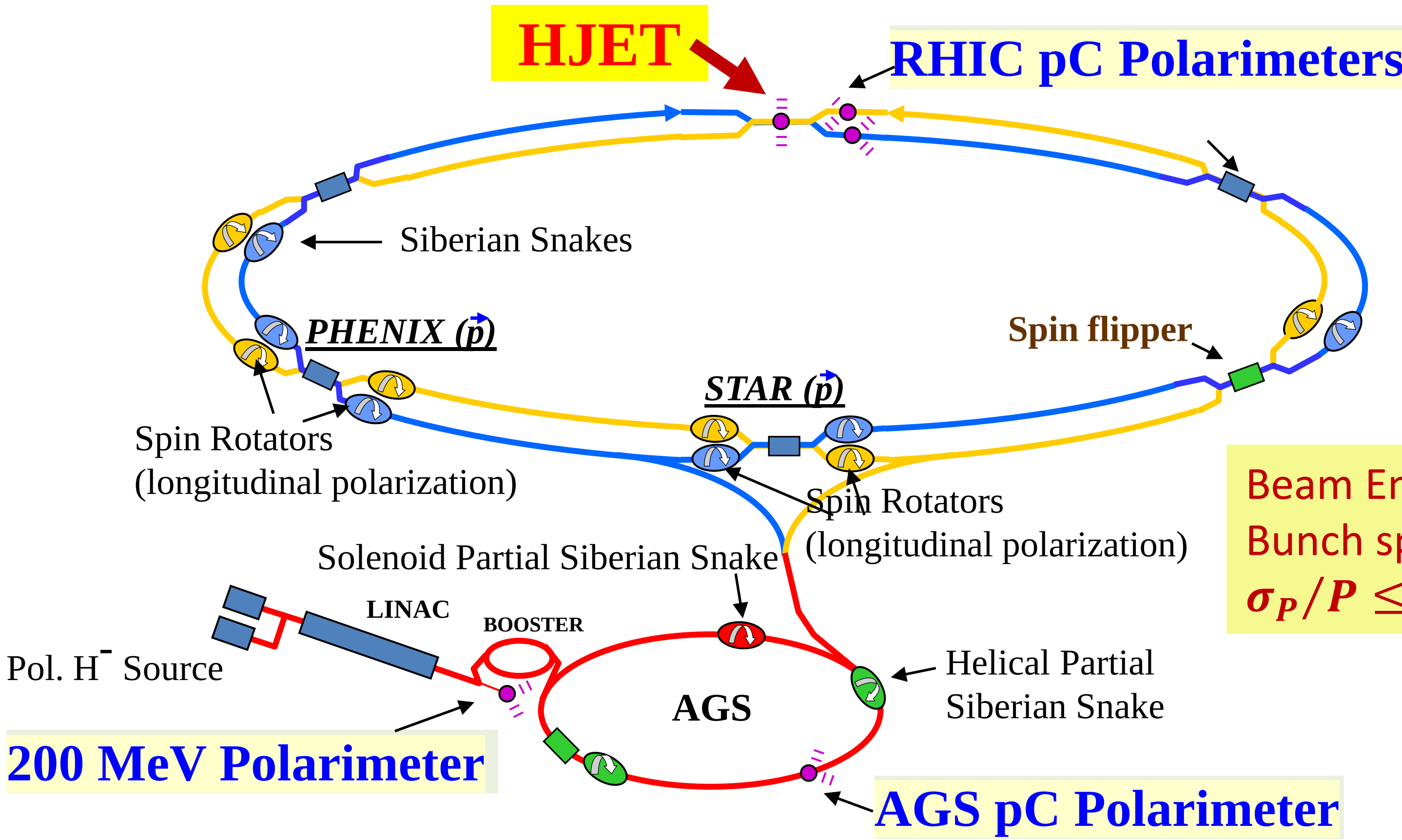


Summary

- Since 2004, the HJET shows excellent performance at RHIC
- The HJET can provide proton beam polarization measurements at EIC with required accuracy $\boldsymbol{\sigma_P^{syst}/P \lesssim 1\%}$, however further improvements are very important.
- High density unpolarized hydrogen jet might strongly enhance the hadronic (not only proton) polarimetry at EIC:
- For the $^3\mathrm{He}$ and $^2\mathrm{H}$ beams, the HJET elastic data contamination by inelastic (breakup) events is about **1%**.
- The elastic $^3\overrightarrow{\mathrm{He}}\,p$ hadronic spin flip amplitude can be related to the proton-proton one which may be measured by HJET in polarized proton Run.
- Feasibility of the absolute $^3\mathrm{He}$ beam polarization measurements were considered for
  - ✓ **Unpolarized H-Jet**: the beam polarization monitoring with $\boldsymbol{\sigma_P^{syst}/P = \mathcal{O}(2\text{-}3\%)}$.
  - ✓ **Polarized $\overrightarrow{\mathbf{H}}$-Jet**: the beam polarization measurements with $\boldsymbol{\sigma_P^{syst}/P \lesssim 1\%}$, but for every beam energy, the elastic pp analyzing power should be pre-determined.
  - ✓ **Polarized $^3\overrightarrow{\mathbf{He}}$ -Jet**: the measurement is free from the theoretical uncertainties, but systematic accuracy achieved at H-Jet cannot be directly projected to $^3\mathrm{He}$-Jet.

Backup

Polarized Proton Beams at RHIC

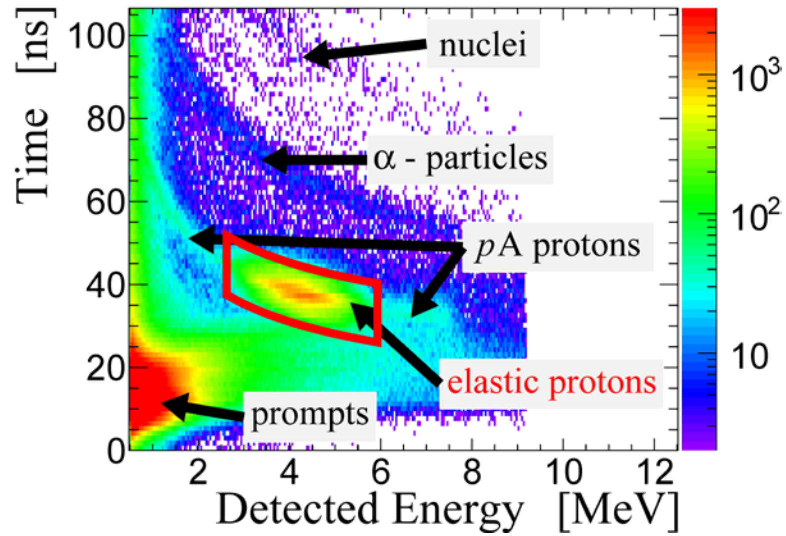


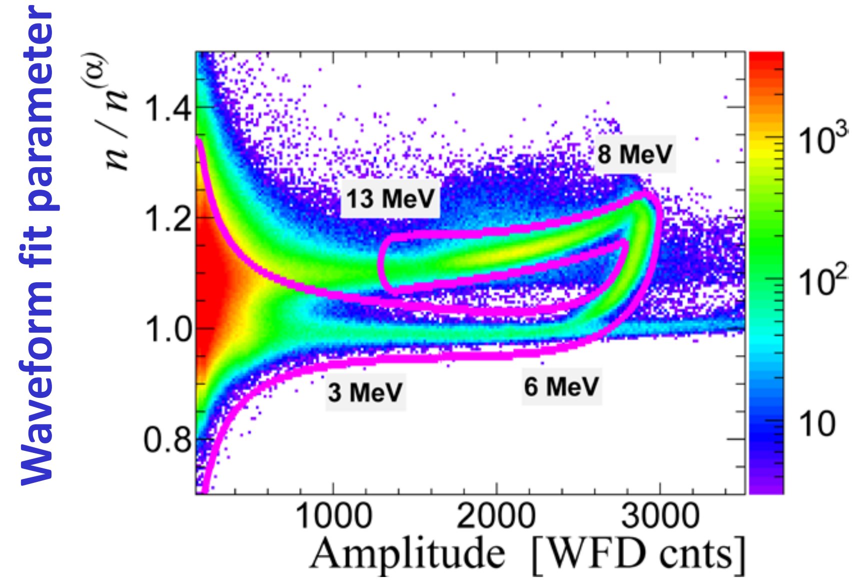
Beam Energy: **100 – 255 GeV**
Bunch spacing: **107 ns**
$\sigma_P/P \leq 5\%$ (*required*)

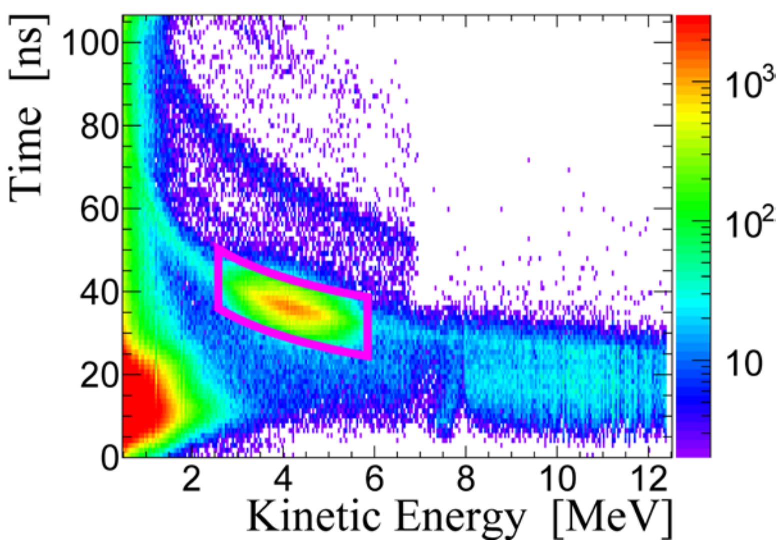
EIC ➡

$p^\uparrow, d^\uparrow, h^\uparrow$ (^{3}He) in yellow ring
Beam Energy: **41 – 275 GeV**
Bunch spacing: **10 ns**
$\sigma_P/P \leq 1\%$ (*required*)

Punch-through proton reconstruction







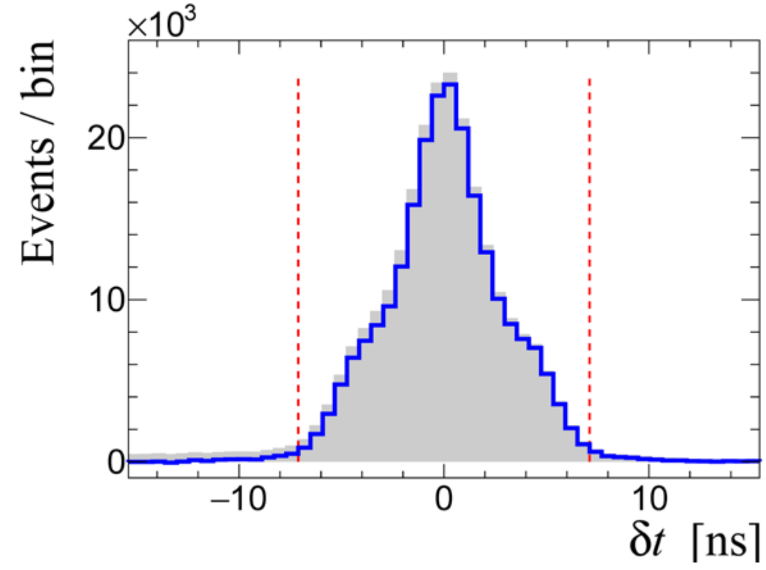
- **The recoil protons with energy above 7.8 MeV punch through the Si strip and, thus, only part of the kinetic energy is deposited.**
- **To reconstruct kinetic energy in such events, we employed the signal waveform dependence on the recoil proton energy.**
- **Such reconstruction will be critically important for EIC bunch spacing of 10 ns since punch-through signal from one bunch can be mixed with stopped proton event from other bunch.**

Elastic $pp \to pp$ events isolation

Recoil mass (T_R vs **ToF**):

$$\delta t = t - t_0 - \frac{L}{c}\sqrt{\frac{m_p}{2T_R}} \approx 0$$

δt variations are dominated by the bunch length and, thus, are the same for **all Si strips.**



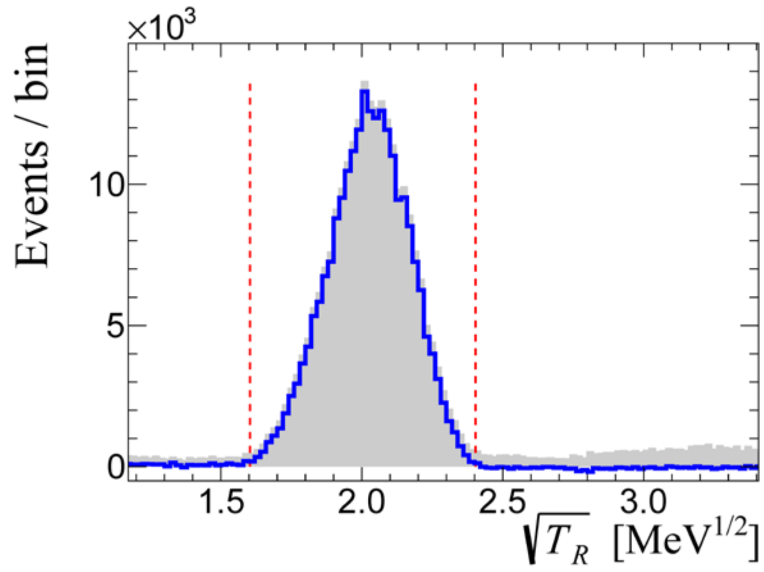
Missing mass (T_R vs z_{strip}):

$$M_X^2 = m_p^2 - 2(E_{\text{beam}} + m_p)\sqrt{T_R} \times \left(\sqrt{T_R} - \sqrt{T_{\text{str}}}\right)$$

$$\sqrt{T_{\text{str}}} = \frac{\langle z_{\text{str}} - z_{\text{jet}} \rangle}{18\ \text{mm MeV}^{-1/2}}$$

$$\delta\sqrt{T_R} = \sqrt{T_R} - \sqrt{T_{\text{str}}} \approx 0$$

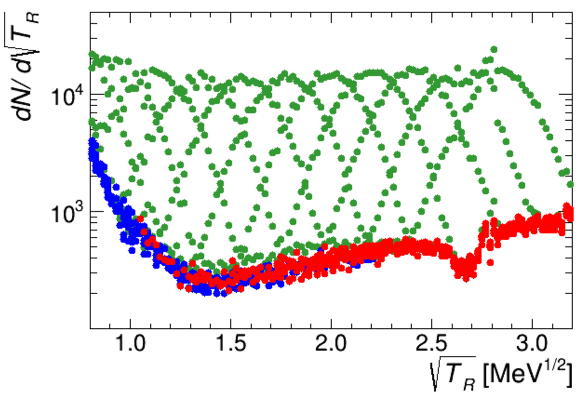
$\delta\sqrt{T_R}$ variations are dominated by the jet profile and, thus, are the same for **all Si strips.**



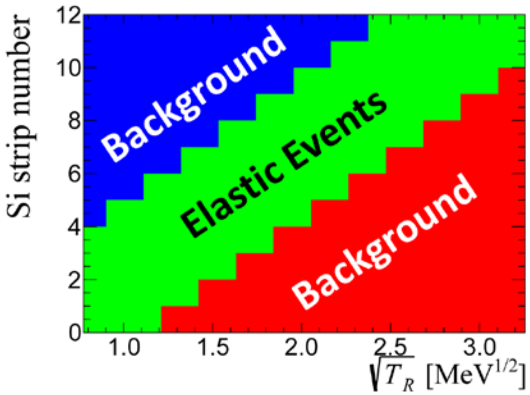
Background subtraction

The background subtraction is based on a (confirmed) assumption that dN^{bgr}/dT_R background rate is the same in all strips of a Si detector.
An example is given for 100 GeV beam.

dN/dT_R superposition for one Si detector



Color Legend



Since the background is routinely evaluated separately for

- **every Si detector (12 strips),**
- **every signal time bin**
- **every $\sqrt{T_R}$ bin,**
- **every combination of the jet and beam spins,**

the background energy dependence and spin asymmetries, if any, are properly accounted in the subtraction.

The background subtraction corrections were applied to properly account for effects of

- **the inelastic $p + p \to X + p$ scattering**
- **the recoil proton tracking in the holding field magnet**

$\Rightarrow$ $\sigma_P^{syst}/P \lesssim 0.5\%$

Inclusive $^3\mathrm{He}\,p$ scattering at HJET

$$\left(\frac{dN}{dT}\right)_{incl} = \left(\frac{dN}{dT}\right)_{el} \times \left[1 + \int_{\Delta_{pd}}^{\Delta_0+2.5\Gamma} |r(T,\Delta)|^2 \Phi_2(\Delta)\, dF_{\mathrm{BW}}(T)\right]$$

$\Delta_{pd} = 5.5\ \mathrm{MeV}$ is the $h^* \to pd$ threshold

$\Phi_2(\Delta) = \frac{\sqrt{2m_p m_d}}{4\pi m_h}\sqrt{\frac{\Delta-\Delta_{pd}}{m_h}}$ is phase space

$r(T,\Delta)$ is the effective breakup amplitude (relative to the elastic one)

$$r(T=0,\Delta) = 0$$
$$r(T, \Delta < \Delta_{pd}) = 0$$

$$dF_{\mathrm{BW}}(T) = \frac{\pi^{-1}\,\Gamma/2\, d\Delta}{(\Delta-\Delta_0)^2 + (\Gamma/2)^2}$$

$\Delta_0 = \Delta_0(T), \qquad \Gamma = \Gamma(T)$

$$\int dF_{\mathrm{BW}} = 1$$

$$dF_{\mathrm{BW}} \xrightarrow{\Gamma\to 0} \delta(\Delta-\Delta_0)\, d\Delta$$

The model based assumptions:

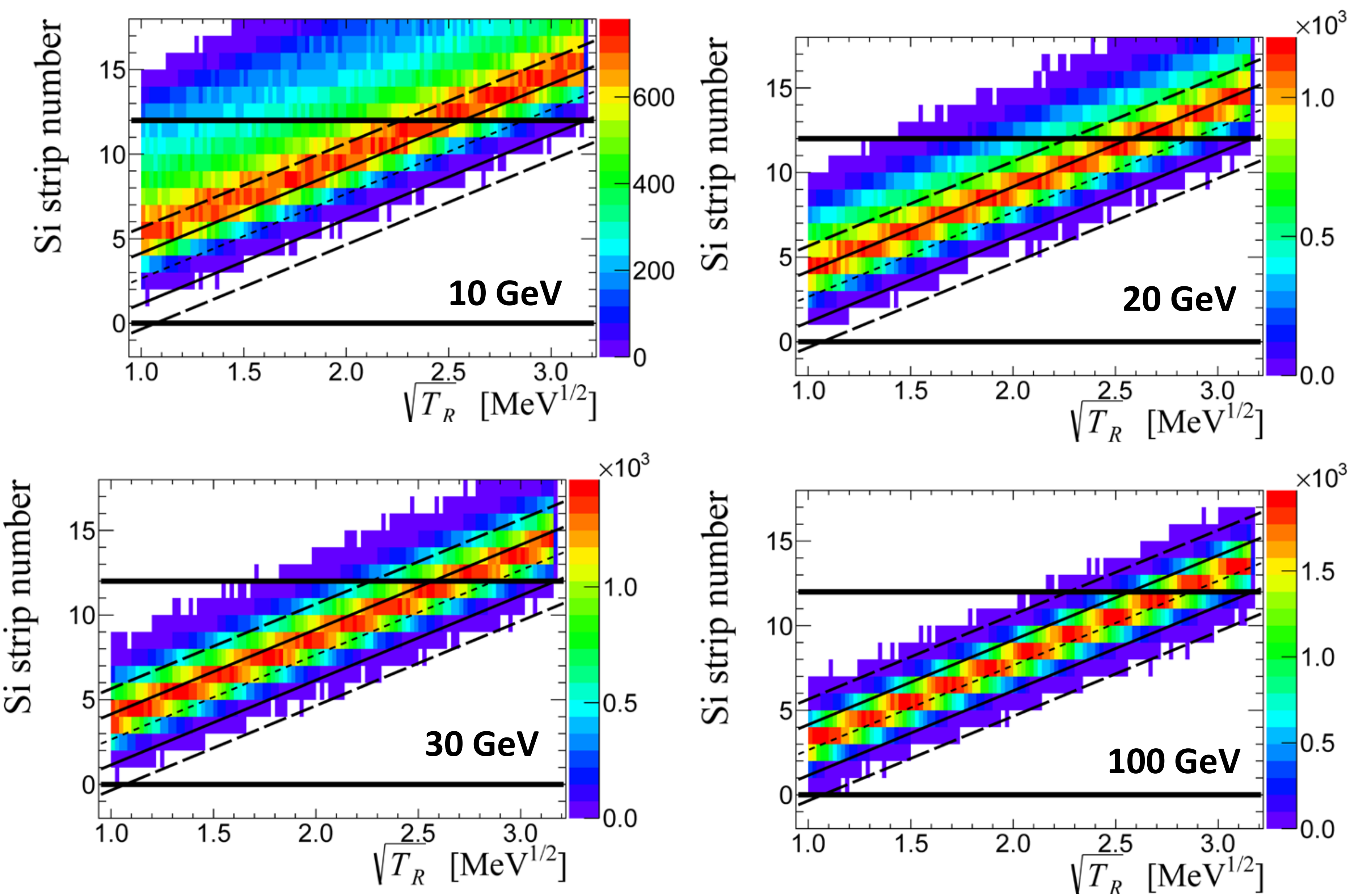
$\Delta_0 = 2T/3,$

$\Gamma = 8.6\sqrt{T_R}\ \ [\mathrm{MeV}]$

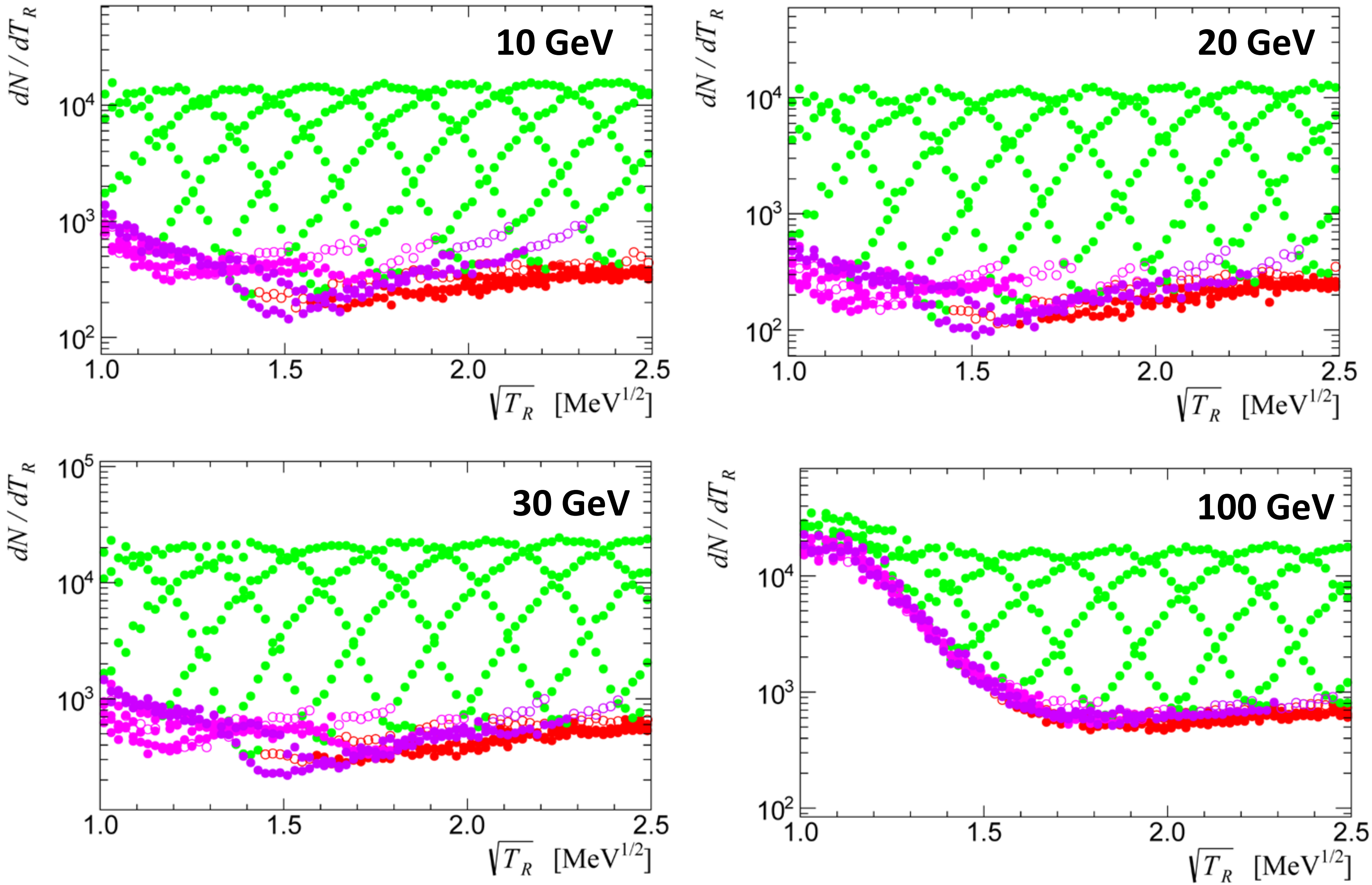
$r(T, \Delta > \Delta_0 + 2.5\Gamma) = 0$

$r(T,\Delta) \approx \mathrm{const}$ where non-zero

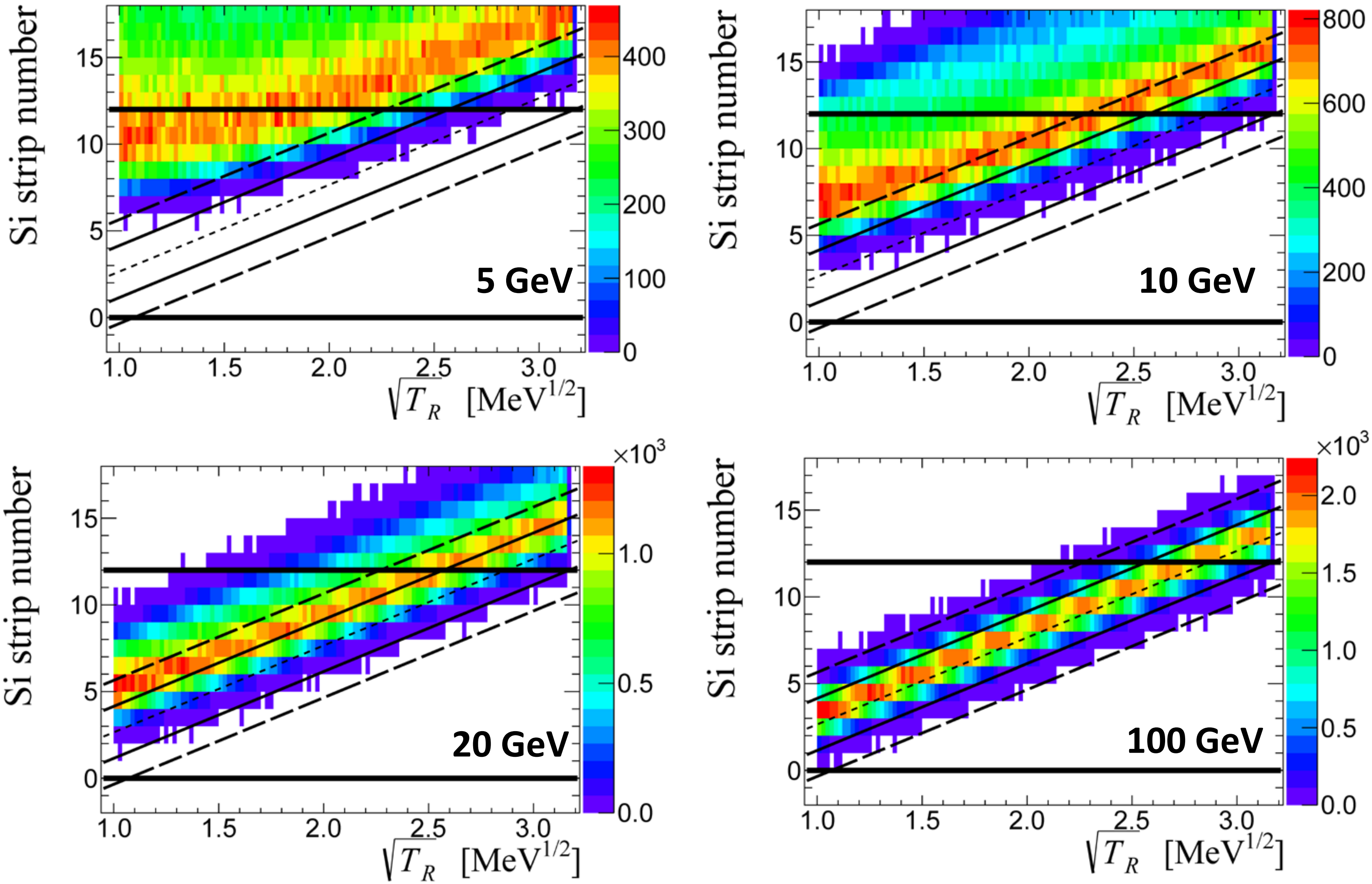
Breakup rates for the deuteron beam



$dN/d\sqrt{T_R}$ distributions for the deuteron beam



Breakup rates for the He3 beam

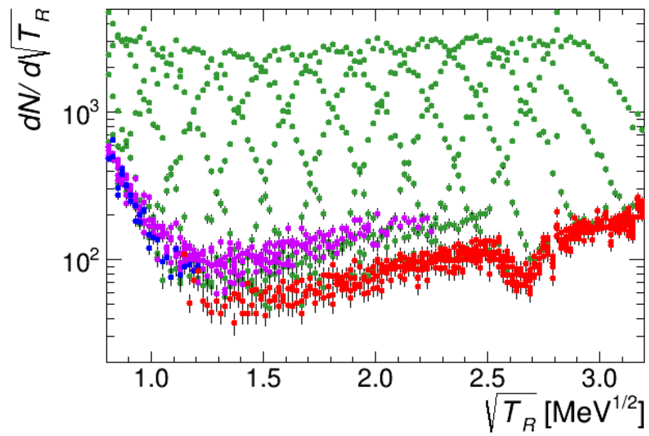


How well the inelastic

$$h + p \to (d + p) + p$$

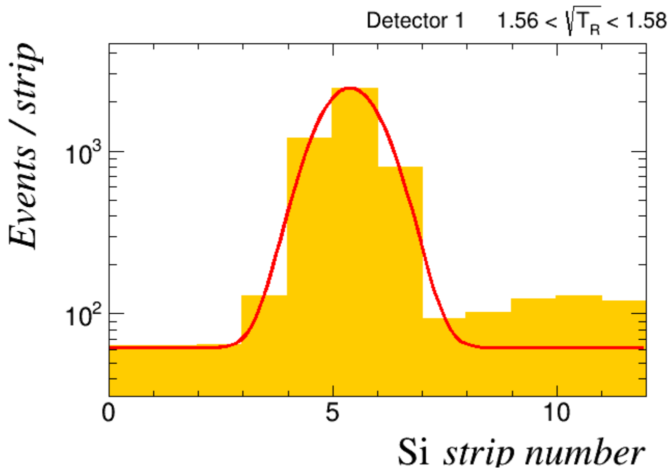
background rate can be evaluated ?

$p + p \to (p + \pi + \ \ldots) + p$
background in one detector for the 255 GeV 8-hour store 20571 (WCM=19)



For an 8-hour single He3 10.4 GeV beam store, one can expect the following sensitivity (1-sigma) to the inelastic background:

$$\frac{\text{background}}{\text{elastic peak}} \sim 3 \times 10^{-4} \sqrt{\frac{(d\sigma/dt)^{(\text{el.})}_{pp}}{(d\sigma/dt)^{(\text{el.})}_{hp}} \times \frac{19}{\text{WCM}}}$$

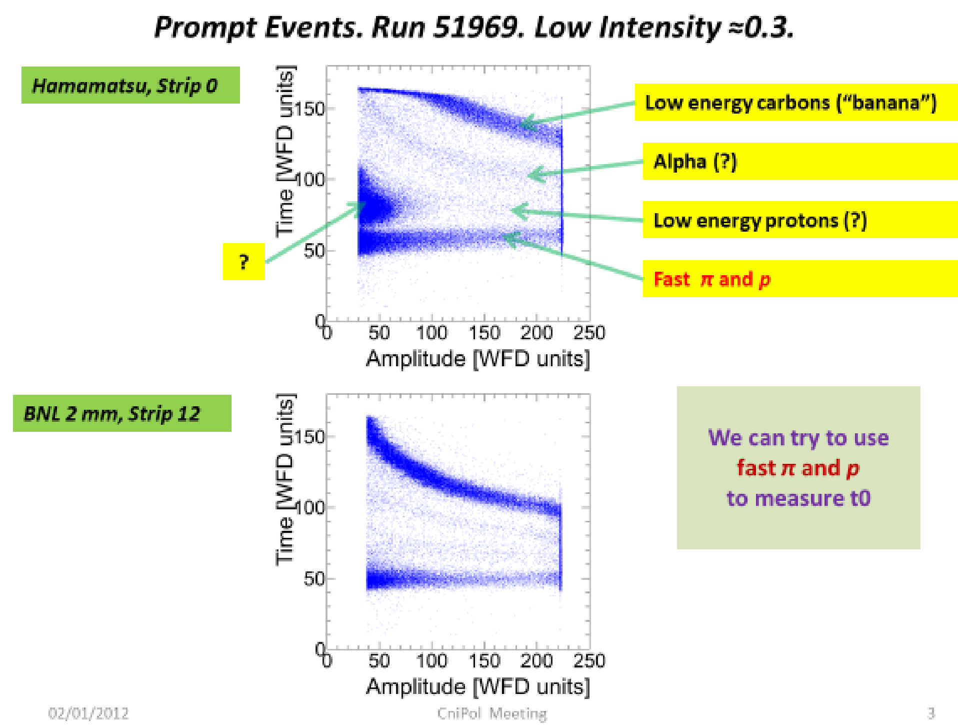


- The He3 injection energy is 10.4 GeV. Thus, only a few hour setup is expected.
- The measurements with lower beam energy (5-7 GeV) may also be extremely helpful

Background caused by the target He3 breakup

- **This background may give a lot of protons and deuterons in the detectors**
- **For eRHIC bunch spacing, the proton, deuteron, and helion bananas from different bunches will cross each other creating a mess.**

Example from the AGS pCarbon (2012)



Could we do a short test measurement injecting (unpolarized) He3 to HJET
- **through ABS**
- **to chamber 7?**

!

Kinematics dependence on the Beam + Target

$p + p$: $$z_R - z_{\text{jet}} \approx L\sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p}{E_p} + \frac{m_p\Delta^*}{E_pT_R}\right]$$

$A + p$: $$z_R - z_{\text{jet}} \approx L\sqrt{\frac{T_R}{2m_p}} \times \left[1 + \frac{m_p^2/M_A}{E_p} + \frac{m_p\Delta^*}{E_pT_R}\right]$$

$p + A$: $$z_R - z_{\text{jet}} \approx L\sqrt{\frac{T_R}{2M_A}} \times \left[1 + \frac{M_A}{E_p} + \frac{m_p\Delta^*}{E_pT_R}\right]$$

$A + A$: $$z_R - z_{\text{jet}} \approx L\sqrt{\frac{T_R}{2M_A}} \times \left[1 + \frac{m_p}{E_p} + \frac{m_p\Delta^*}{E_pT_R}\right]$$

$$E_p = E_{\text{beam}} \times \frac{Am_p}{M_A} \approx E_{\text{beam}}$$
$$\Delta^* = \Delta \times (1 + \Delta/2m_{\text{beam}})$$

E_{beam} is given in GeV/nucleon units
E_p is the jet proton energy in the beam frame

Summary

- Since 2004, the HJET shows excellent performance at RHIC
  - ✓ Very low systematic uncertainties: $\sigma_P^{syst}/P \lesssim 0.5\%$
  - ✓ Analyzing power was precisely determined for 100 and 255 GeV beam
- The HJET can provide proton beam polarization measurements at EIC with required accuracy $\sigma_P^{syst}/P \lesssim 1\%$ for the part of the recoil proton energy range.
  - ✓ Extension to the full range is very important and requires an improvement of the polarimeter.
- High density unpolarized hydrogen jet might be extremely helpful tool for the hadronic (not only proton) polarimetry at EIC:
  - ✓ $\sigma_P^{stat} \sim 2\%/\text{min}$ $\sigma_P^{syst}/P < 0.7\%$
  - ✓ However no detail study of the polarimeter design was not done yet which can change the above estimates.
- The ^{3}He beam polarization measurements at EIC was preliminary evaluated:
  - ✓ The elastic data contamination by the beam ^{3}He breakup events is $\mathcal{O}(1\%)$
  - ✓ Unpolarized hydrogen jet: $\sigma_P^{syst}/P = \mathcal{O}(1\%)$.
  - ✓ Polarized HJET: $\sigma_P^{syst}/P \lesssim 0.8\%$
  - ✓ He3-Jet: σ_P^{syst}/P is defined by the systematic uncertainties of the measurement, which are expected to be larger than those at the HJET.
- **Using HJET, the ^{3}He beam polarization at EIC can be measured with required accuracy of $\sigma_P^{syst}/P \lesssim 1\%$**