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The prospects on hadronic polarimetry at EIC

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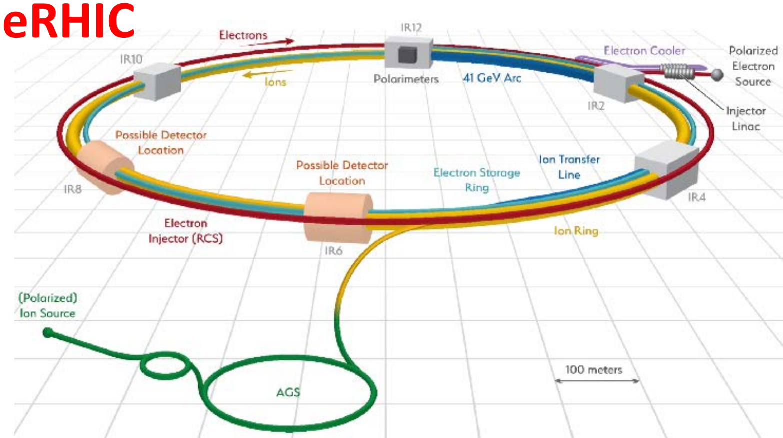
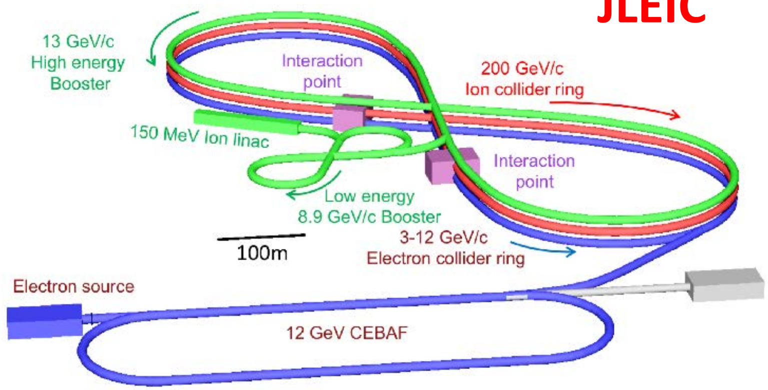
Hadronic Polarimetry at EIC

eRHIC



JLEIC



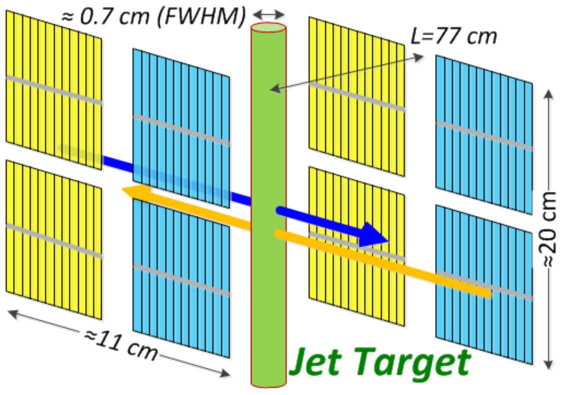
The EIC requirement for the proton beam polarization measurement is $\sigma_P/P \lesssim 1\%$

- **The EIC proposed bunch energies and intensities are similar to what are used at RHIC. This suggests to use a similar hadronic polarimetry at EIC.**
- **However, reducing bunch spacing from 107 ns (RHIC) to 10.1 ns (eRHIC) or 2 ns (JLEIC) might be an issue. A special study is needed.**

The goal of this report is to project our experience in absolute polarization measurements of proton beams at RHIC to EIC.

- **For estimates, the RHIC Run2017 255 GeV proton beams data was used.**
- **For projection to EIC, 8.9 ns bunch spacing, which is 1/12th of the RHIC one, was assumed**

The Polarized Atomic Hydrogen Gas Jet Target (HJET)



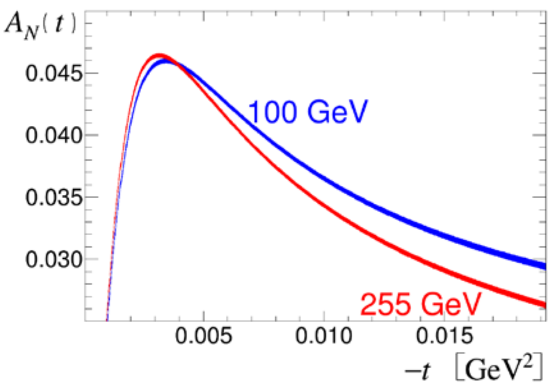
The absolute beam average polarization is determined by measuring jet and beam correlated asymmetries:

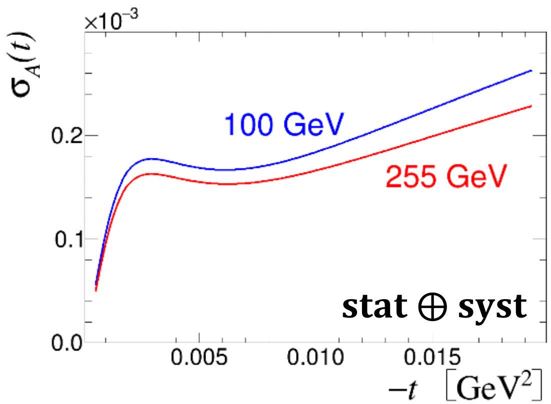
$$a_{jet} = \langle A_N \rangle P_{jet} \qquad a_{beam} = \langle A_N \rangle P_{beam}$$

$$P_{beam} = \frac{a_{beam}}{a_{jet}} P_{jet} \qquad P_{jet} = 0.96$$

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

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





In RHIC Runs 15 (100 GeV) and 17 (255 GeV), a precise measurement of the analyzing power $A_N(t)$ has been done. The result can be reliably extrapolated to the EIC beam energy range of 41-275 GeV

Employing of unpolarized Jet with a 10-fold density could strongly improve the statistical accuracy of the polarization measurements (at EIC):

$$\sigma_P^{stat} \lesssim 1\%/\text{ hour}, \qquad \sigma_P^{syst}/P \lesssim 1\%$$

Polarization decay time and spin tilt can also be precisely measured.

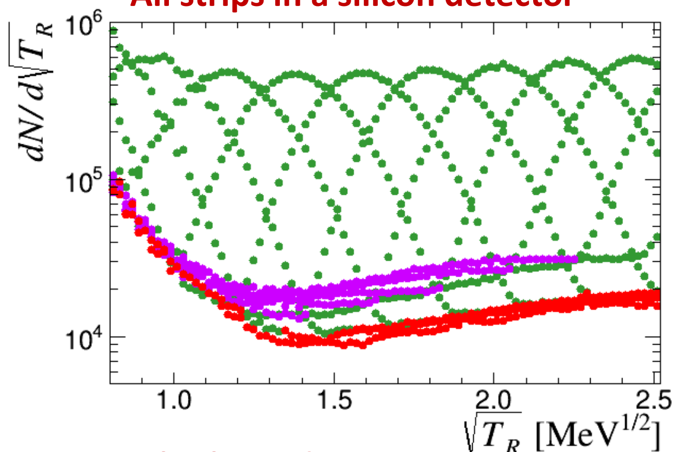
Systematic uncertainties in HJET measurements

The asymmetries are measured with low systematic uncertainties.
(↑↓ and ± are beam an jet spins, respectively)

$$a_N^{\mathrm{jet}} = \langle A_N \rangle P_{\mathrm{jet}} \frac{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} + \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} - \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} - \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} + \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} + \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} + \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}$$

$$a_N^{\mathrm{beam}} = \langle A_N \rangle P_{\mathrm{beam}} \frac{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} - \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} + \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} - \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}{\sqrt{N_R^{\uparrow+}N_L^{\downarrow-}} + \sqrt{N_R^{\downarrow+}N_L^{\uparrow-}} + \sqrt{N_R^{\uparrow-}N_L^{\downarrow+}} + \sqrt{N_R^{\downarrow-}N_L^{\uparrow+}}}$$

All strips in a silicon detector



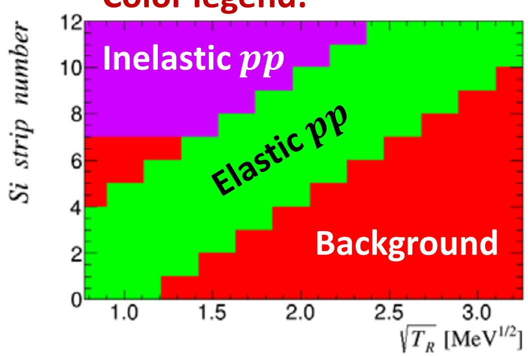
$\langle A_N \rangle^{\mathrm{beam}} = \langle A_N \rangle^{\mathrm{jet}}$?

Background subtraction:

- For elastic pp: $z_d - z_j = k\sqrt{T_R}$, $k \approx 18\ \mathrm{mm/MeV^{1/2}}$
- For inelastic pp scattering $p_b + p_j \to X + p_{j(R)}$

  $z_d - z_j = k\sqrt{T_R} \times \left(1 + m_p\Delta/E_{beam}\,T_R\right)$, $\Delta = M_X - m_p \geq m_\pi$
- For most backgrounds z_d and $\sqrt{T_R}$ are uncorrelated
- Some backgrounds require special consideration:
  (PSTP2017 Proceedings: https://pos.sissa.it/324/022/pdf)

Color legend:



$|\Delta P|_{\mathrm{bgr}} \sim 1\%$

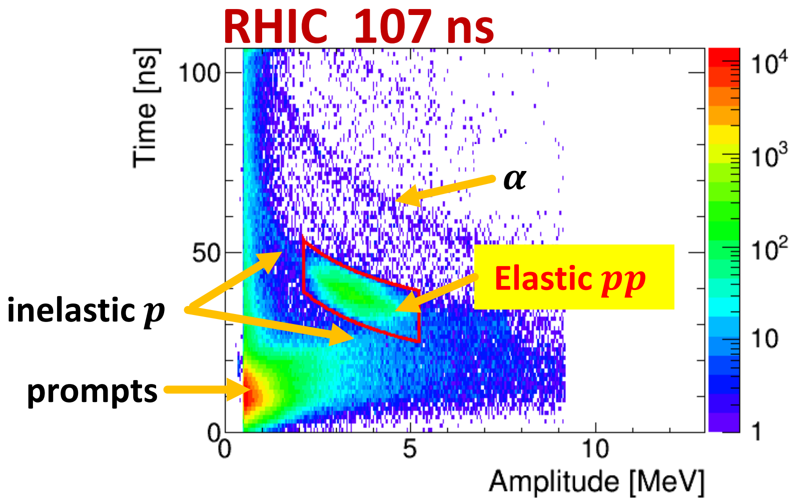
Since the background is routinely evaluated separately for
- **every Si detector (12 strips),**
- **every $\sqrt{T_R}$ bin,**
- **every combination of the jet and beam spins,**

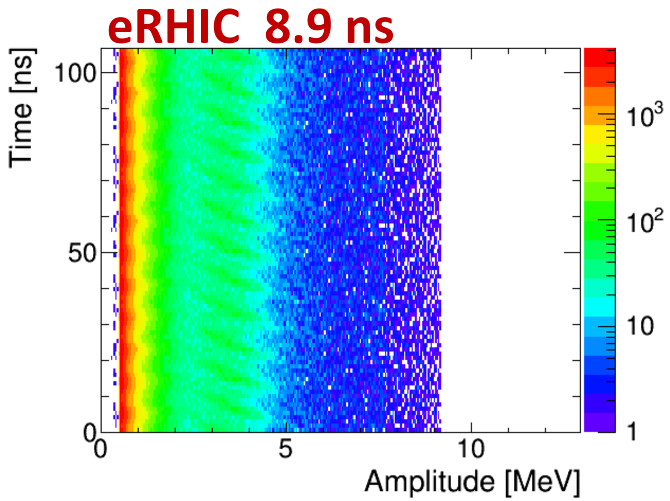
the background energy dependence and spin asymmetries, if any, are properly accounted in the subtraction.

➡ $\sigma_P^{syst}/P \lesssim 0.5\%$

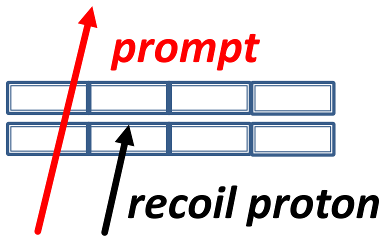
Could HJET be used at EIC ?

- The achieved at RHIC accuracy of the absolute polarization measurement well satisfies the EIC requirements.
- The proton beam energies and bunch intensities at EIC allows us to use HJET as is.
- However, the significant increasing of the bunch frequency may be an issue due to mixing prompts and elastic pp signals from different bunches.

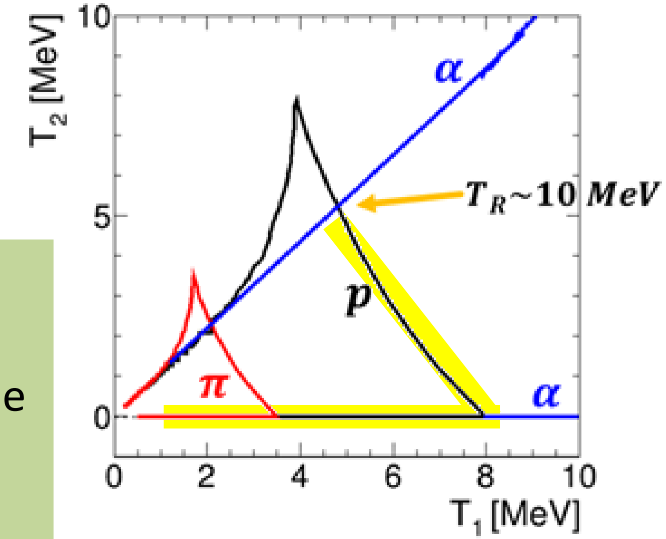




Two-layers Si detectors in HJET



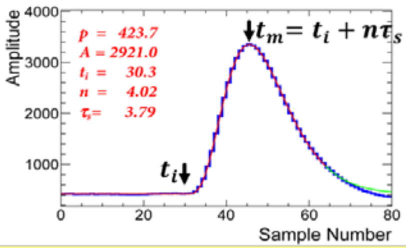
Correlation of the deposited energies in two Si layers



- The second layer can be used as veto to suppress prompts
- The background caused by low energy pions and alphas stopped in the first layer is expected to be small and may be suppressed using the standard background subtraction procedure.

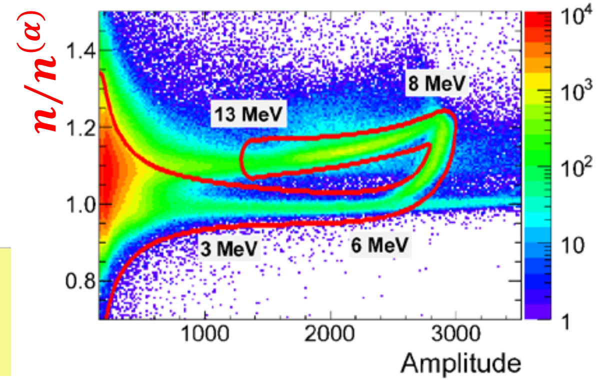
- **The prompts suppression by this method is not proved yet.**
- **The prompts rate is diluted by a factor 3-4 if JET is off, but we are not sure about the source of the remained 25-30% prompt events.**
- **A prototype of the double layer detector can be studied using Gold beam. (The recoil proton kinematics has only a weak dependence on the RHIC beam)**

Punch through events suppression using waveform shape analysis

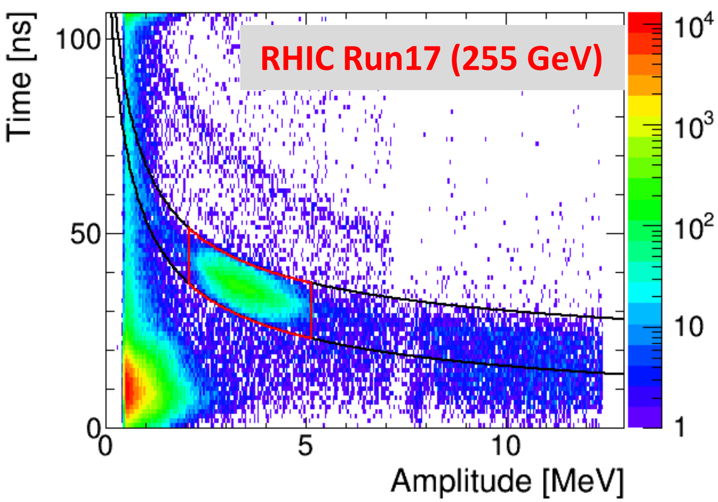


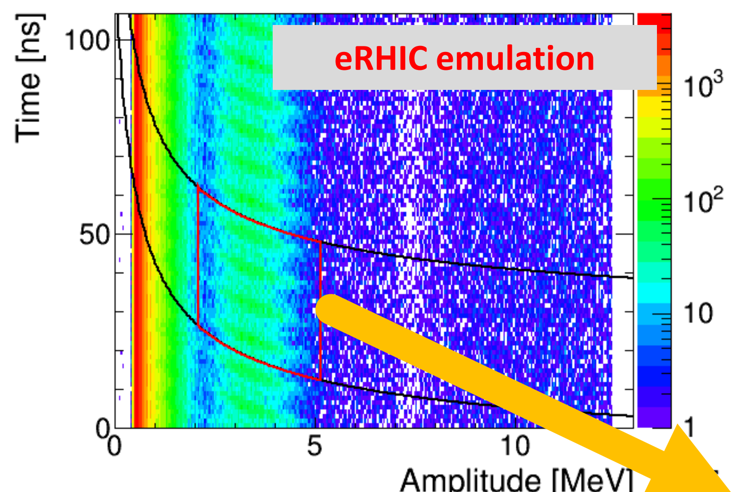
Signal parametrization:

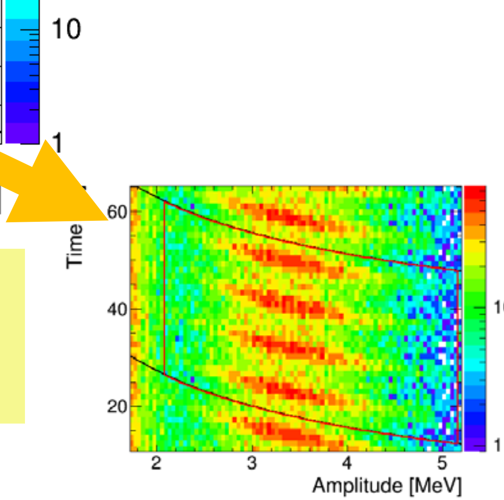
$$W(t) = p + A\,(t - t_i)^n \exp\left(-\frac{t - t_i}{\tau_s}\right)$$



- The waveform shape is not the same for stopped and punched through particles.
- This routinely used at RHIC to isolate elastic pp signals.
- The method is still workable with eRHIC bunch spacing.





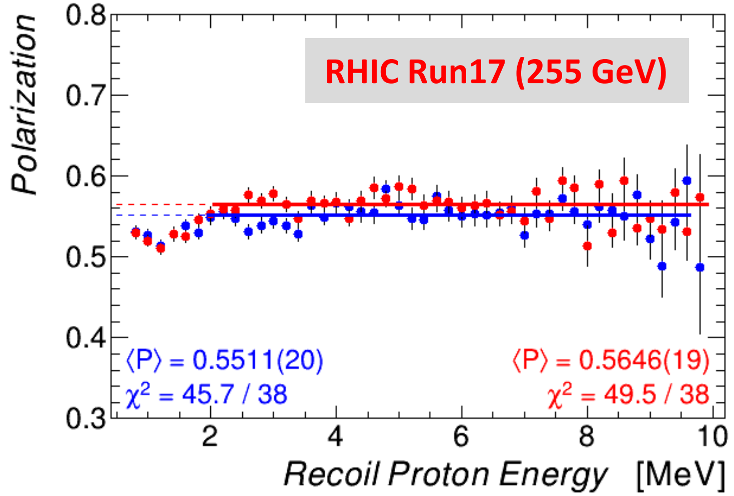


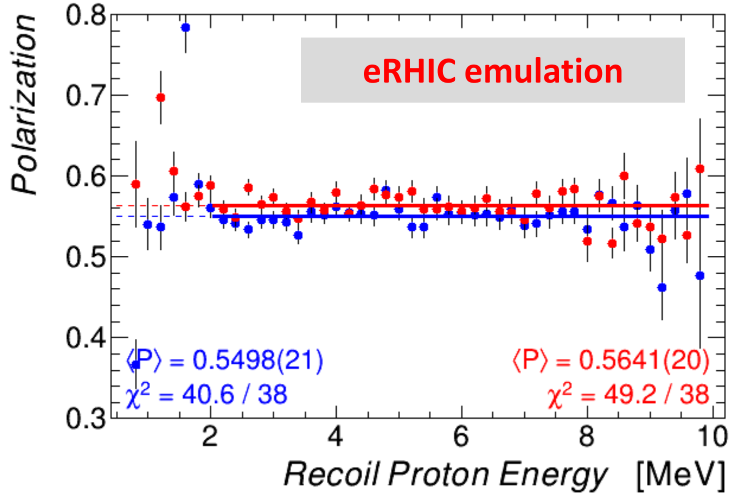
To emulate HJET performance at EIC (eRHIC), we used the Run17 data and for every event smeared the measured time with $\tau = 8.9$ ns step:

$$t \to t + (k + 0.5)\tau, \qquad k = -6, \dots, 5$$

Beam Polarization measurements. eRHIC vs RHIC.

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





- For recoil proton energy above 2 MeV, the EIC and RHIC results are well consistent.
- The EIC polarization is systematically shifted by only $|\Delta P/P| \lesssim 0.3\%$.
- A conservative estimate of the systematic uncertainties of the absolute polarization measurements at EIC is $\delta P_{\text{syst}}/P \lesssim 1\%$.

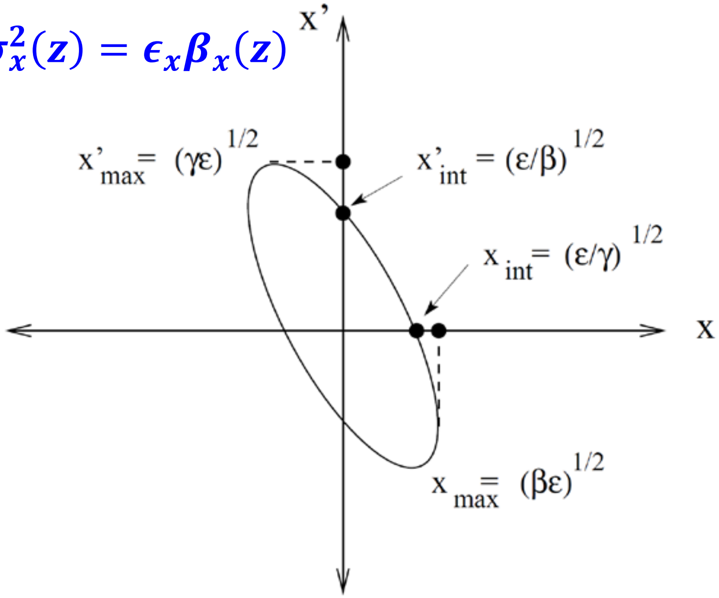
We are optimistic about possibility to use RHIC HJET at EIC.

Nonetheless, some improvements are still desirable:

- **Double layer detectors**
- **No magnetic field (unpolarized HJET?)**
- **Lower noise electronics**

Polarization Profile

$$\sigma_x^2(z) = \epsilon_x \beta_x(z)$$



The beam particles can be discriminated by the invariant values:

$$a^2 = x^2 + (\alpha x + \beta x')^2 = x^2 + \bar{x}'^2$$

$$P(a^2) = P_0 + P_1^{(x)} a_x^2 + P_1^{(y)} a_y^2 + \ldots$$

$$P(x,y) = \frac{P_0}{\sqrt{1+R_x}\sqrt{1+R_y}} \exp\left\{-R_x \frac{x^2}{2\sigma_x^2} - R_y \frac{y^2}{2\sigma_y^2}\right\}$$

$$\langle P \rangle_{\text{beam}} = \frac{P_0}{(1+R_x)(1+R_y)}$$

For fixed accelerator configuration (*optics and ramp scheme*) and for the measurements at the same *location* and *time after the injection*:

Measured by Ionization Profile Monitor — **Beam Optics**

$$R_x = \frac{\sigma_I^2}{\sigma_P^2} = \frac{\epsilon_x \beta_x}{\sigma_P^2} = c_x \epsilon_x$$

Beam optics and ramp scheme

- **The polarization profile parameters $R_{x,y}$ and zero emittance polarization P_0 are *location in the ring* independent.**
- **P_0 is expected to be *conserved* during the ramp, $P_0 = P_{\text{source}}$, <u>but this assumption is not experimentally confirmed yet</u>.**
- **$R_{x,y}$ are the emittances $\epsilon_{x,y}$ correlated.**

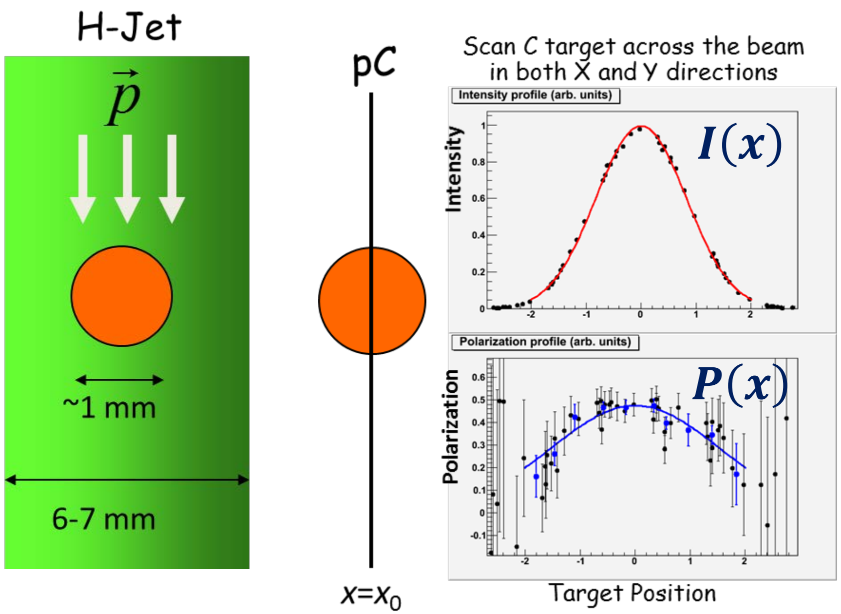
$$\langle P \rangle_{\text{beam}} = P_0/(1 + c_x\epsilon_x)(1 + c_y\epsilon_y) \approx P_0 - c\epsilon\,, \qquad \epsilon = (\epsilon_x + \epsilon_y)/2$$

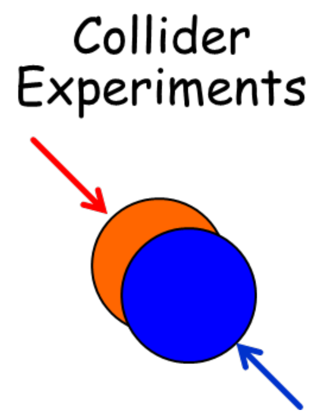
Collision average polarization

- HJET measures the beam average polarization $\langle P \rangle_{\text{jet}} \equiv \langle P \rangle_{\text{beam}}$.
- The Experiments need the collision average polarization $\langle P \rangle_{\text{coll}}$ which accounts the target density profile.
- Assuming that σ_I^2 is the same for both beams at collision

$$\langle P \rangle_{\text{coll}} / \langle P \rangle_{\text{jet}} = \frac{\sqrt{(1+R_x)(1+R_y)}}{\sqrt{\left(1+\frac{1}{2}R_x\right)\left(1+\frac{1}{2}R_y\right)}} \approx 1 + (R_x + R_y)/4,$$

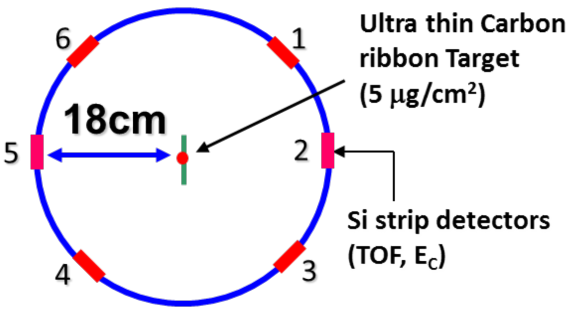
$$R = \sigma_I^2 / \sigma_P^2$$



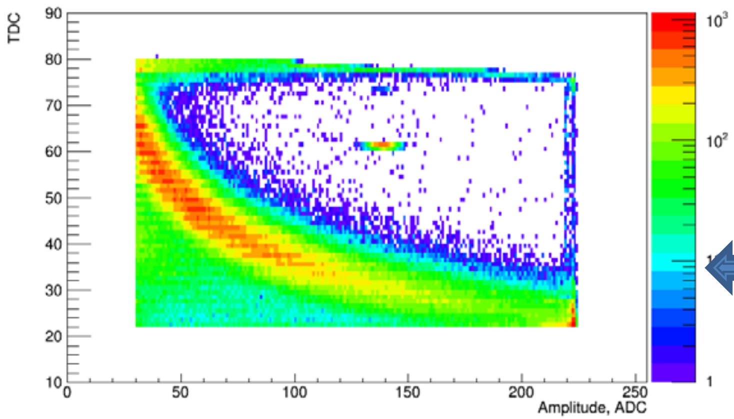


At RHIC, four pCarbon (pC) polarimeters are employed to measure the polarization profiles of both beams in x and y directions.

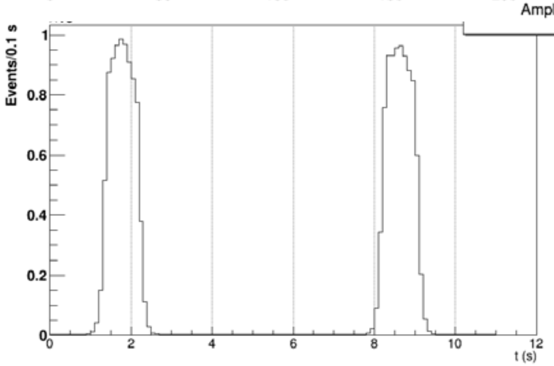
RHIC p-Carbon polarimeter



- 4 polarimeters, 2 per each beam.
- 6 detectors (72 Si strips total) in each polarimeter.
- Horizontal and vertical targets
- Relative polarization measurements.
- Beam Polarization is measured every 2-3 hours.
  - Polarization profile $R_{x,y} = R^{(0)}_{x,y} + \frac{dR_{x,y}}{dt}(t - t_0)$
  - Beam Polarization evolution $P = P^{(0)} + \frac{dP}{dt}(t - t_0)$
  - Spin Tilt measurements



Time – Amplitude distribution in a single Si strip.
The acquired events rate is ~ 500 kHz in the beam center.
The prompts are cut off at the WFD firmware level.



Event rate vs time (sec) in a sweep target measurement

- **Compared to HJET, the adoption of the RHIC pCarbon to EIC is more difficult task due to very high prompts rate.**
- **The investigation is continuing.**

Could $\langle P\rangle_{\text{coll}}$ be determined with no measurements of R?

$$\langle P\rangle_{\text{jet}} \equiv \langle P\rangle_{\text{beam}} = \frac{P_0}{(1+R_x)(1+R_y)} \approx \frac{P_0}{(1+R)^2}$$

$$\langle P\rangle_{\text{coll}} = \langle P\rangle_{\text{jet}} \frac{\sqrt{(1+R_x)(1+R_y)}}{\sqrt{\left(1+\frac{1}{2}R_x\right)\left(1+\frac{1}{2}R_y\right)}} \approx \frac{3\langle P\rangle_{jet} + P_0}{4}$$

$$\sqrt{(1+R_x)(1+R_y)} = (1+R)\sqrt{1-\frac{(R_x-R_y)^2}{4(1+R)^2}} \approx 1+R$$

where $R = (R_x+R_y)/2$

- P_0 is zero emittance polarization which is *assumed* to be preserved during the ramp, i.e. $P_0 = P_{\text{source}}$. *(At RHIC, $P_{\text{source}} \sim 80\%$ and can be measured with accuracy $\sigma_P \lesssim 0.5\%$.)*
- If so ,the collision average polarization could be derived from the values of the $\langle P\rangle_{\text{jet}}$ and $P_0 = P_{\text{source}}$. The P_0 uncertainties are suppressed by factor 4.
- **The hypothesis $P_0 = P_{\text{source}}$ is not experimentally proved yet.**

- More commonly, $\langle P\rangle_{\text{jet}} \leq P_0 \leq P_{\text{source}}$ which may be interpreted as

$$\langle P\rangle_{\text{coll}} = \langle P\rangle_{\text{jet}} + \Delta_P/2 \pm \Delta_P/\sqrt{12}\,, \quad \text{where } \Delta_P = \left(P_{\text{source}} - \langle P\rangle_{\text{jet}}\right)/4$$

- **In eRHIC proposal, $\langle P\rangle_{\text{beam}} \sim 80\%$ and $P_{\text{source}} \sim 85\%$ $\Rightarrow$ $\Delta_P \sim 1\%$.**
  Consequently, the effect of the polarization profile is negligible. Similarly for JLEIC.
- **Nonetheless, experimental evaluation of the polarization profile at EIC is important for better monitoring of the proton beam polarization.**

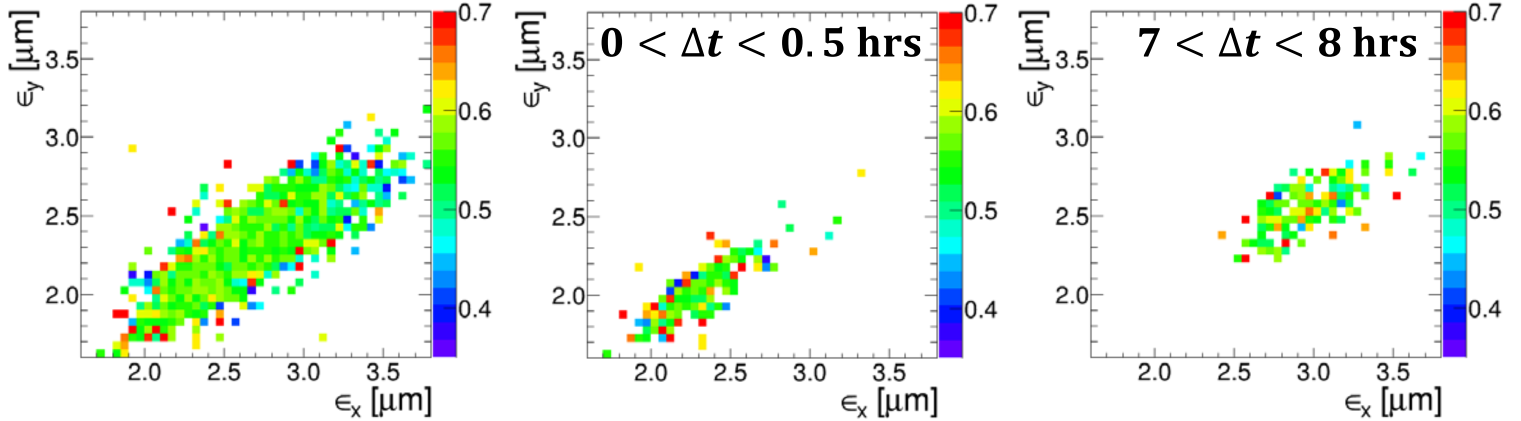
HJET data analysis (Fills 20624-20933, 255 GeV)

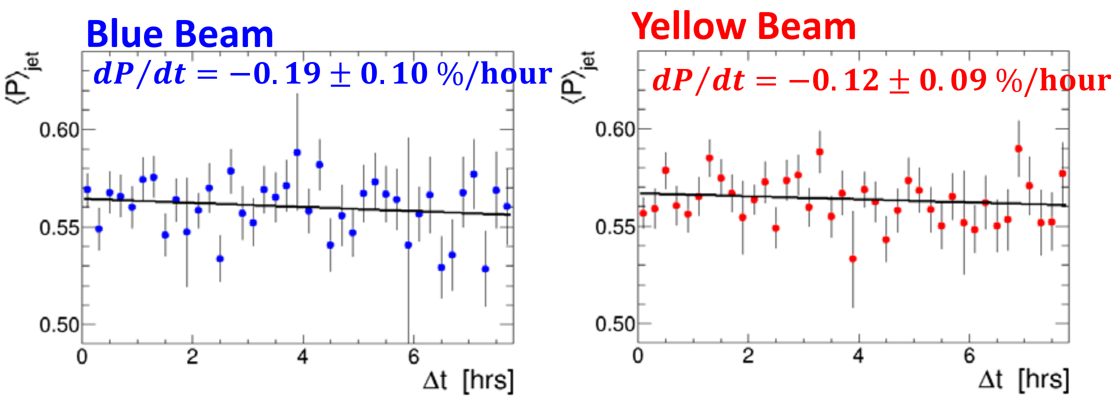
For each Jet cycle (5 min) and bunch spin, a dataset of 8 Si counts and 4 emittances (IPM) was determined.

$$\langle P \rangle_{jet} = P(\epsilon_x, \epsilon_y, \Delta t)$$

Δt is time after the ramp

The Run average polarization $\langle P \rangle_{jet}$ dependence on x, y emittances (blue beam)





This estimate of the polarization decay estimate is consistent with p-Carbon measurements, but has about a factor 2 larger uncertainty.

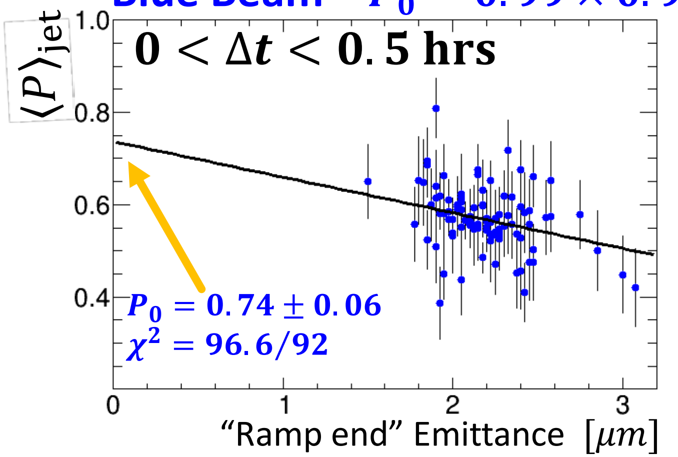
An evaluation of the P_0 from HJET data (20624-20933)

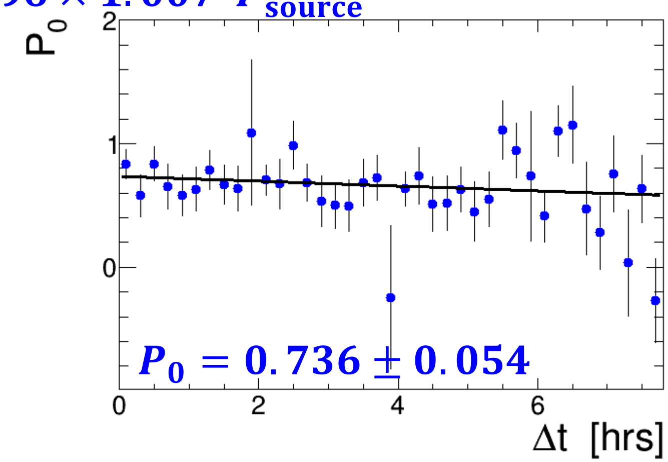
$$\langle P \rangle_{jet} = \frac{P_0}{1 + c\epsilon}$$

Spin tilt at injection

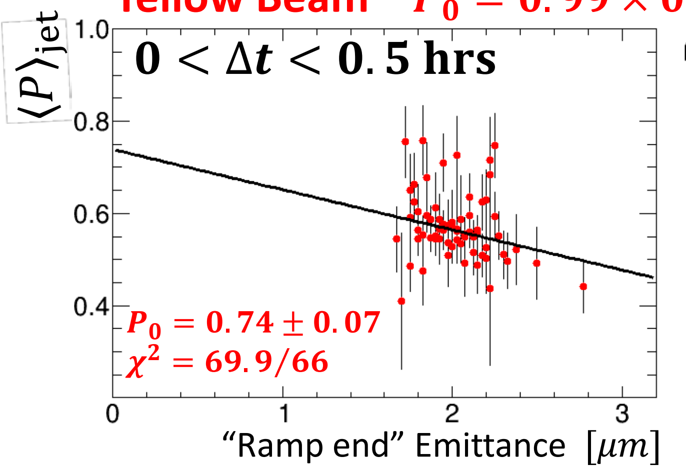
AGS RHIC **Background** *(no background subtraction in this study)*

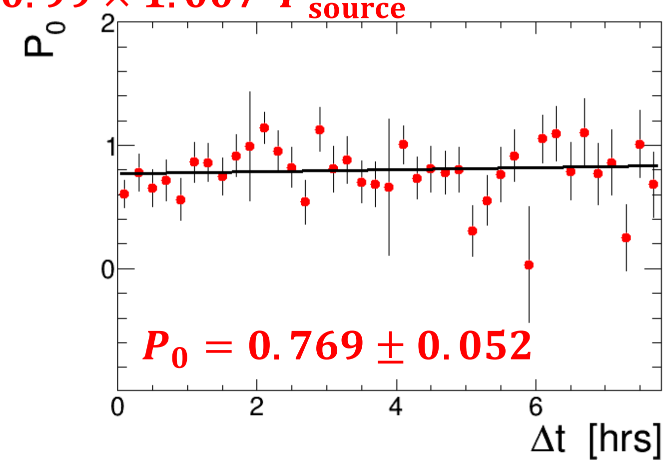
Blue Beam $P_0 = 0.99 \times 0.96 \times 1.007 \ P^{(\text{eff})}_{\text{source}}$





Yellow Beam $P_0 = 0.99 \times 0.99 \times 1.007 \ P^{(\text{eff})}_{\text{source}}$





$P_{\text{source}} \sim 80\%$

$P^{(\text{eff.})}_{\text{source}} = (77.4 \pm 3.9)\%$

$R = 0.16 \pm 0.03$

$\delta \langle P \rangle_{\text{coll}} = \pm 1\%$

The result is consistent with the assumptions:

$R \propto \epsilon$ **and** $P_0 = P_{\text{source}}$

However, *uncertainties are not small*. Some effects:

- Non-linear dependence on R
- Different dependence of R on ε for x and y
- Longitudinal polarization profile (seen in Run 17)

were not considered .

More study based on available and future RHIC data might be important for EIC polarimetry.

Could HJET duplicate p-Carbon at EIC?

Main pCarbon measurements	
Polarization decay dP/dt	YES[1)]
Spin tilt	YES[2)] if unpolarized HJET with no holding magnet
Evaluation of R (or P_0)	YES?[3)] If the discussed above method can be used at EIC

1) After factor 3 increasing of the total beam intensity at eRHIC, the statistical uncertainty of the polarization measurement at HJET will be the same as at pCarbon (for 3 measurements per store). Unpolarized HJET can provide even can improve the accuracy.
2) At unpolarized HJET, 45 degree detectors can be installed, which provides a possibility for the spin tilt measurement.
3) The HJET data evaluation of P_0 gave reasonably good result, but
   - The extrapolation from $\epsilon \sim 2.3 \pm 0.3$ to $\epsilon = 0$ is strongly dependent on the assumption $R = c\epsilon$ and, currently, cannot be considered as reliable.
   - For a "perfect accelerator" there should not be fill-to-fill variations of the emittance and, thus, the method will not work.

How p-Carbon can be used in eRHIC

- If the $R_{x,y} = R(\varepsilon_{x,y})$ can be properly calibrated, the emittance measurements can be used to monitor polarization profile.
- For the calibration, pCarbon can be used as in eRHIC in special (calibration) short time fills with 107 ns bunch spacing
  - The very high rate prompts can be eliminated as in RHIC.
  - This method does not require extrapolation to $\epsilon \to 0$.
  - The statistical accuracy may be significantly improved compared to RHIC

- Such a calibration $R_{x,y} = R(\varepsilon_{x,y})$ can be studied using available RHIC polarized proton data of 2015 (100 GeV) and 2017 (255 GeV).
- Similar analysys using AGS pCarbon data should also be done.
- A more detailed study, including special tests, can be done in the anticipated RHIC pp Runs in 2021, 2023, 2025..

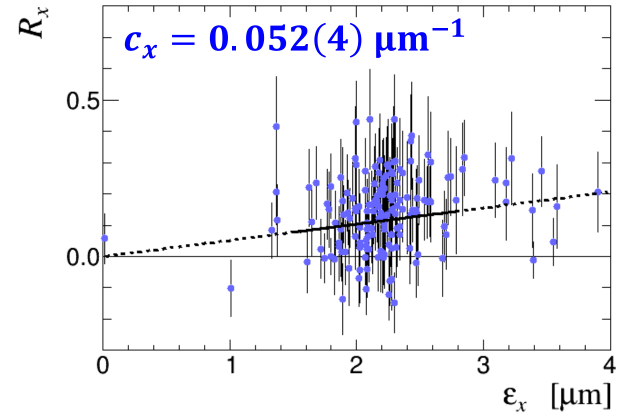
Summary

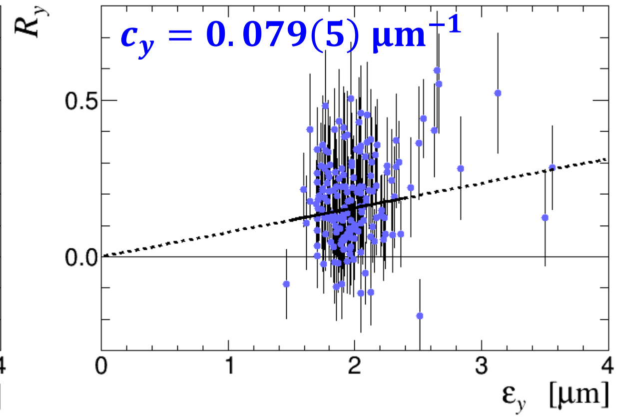
- The Polarized Atomic Hydrogen Gas Jet Target (HJET) polarimeter at RHIC shows a reliable performance providing the RHIC beam polarization measurements with low systematic uncertainties of $\sigma_P^{syst}/P \lesssim 0.5\%$.
- The projection of HJET performance to EIC suggests that it satisfies the EIC requirement for proton beam absolute polarization measurement, $\sigma_P^{syst}/P \lesssim 1\%$, and also can partially duplicate the pCarbon polarimeter functions.
- Nonetheless, some improvements of HJET are desirable:
  - Double layer detectors
  - No magnetic field (unpolarized HJET?)
  - Lower noise electronics
- A possibility to evaluate the zero emittance polarization P_0 using HJET data (255 GeV) and the emittance measurements of the was studied.
- The evaluated value of P_0 is consistent with the polarization at the source P_{source} though the experimental uncertainties of the measurement are not inconsiderable.
- A study of the correlation between the polarization profile and emittance might be helpful for EIC polarimetry.

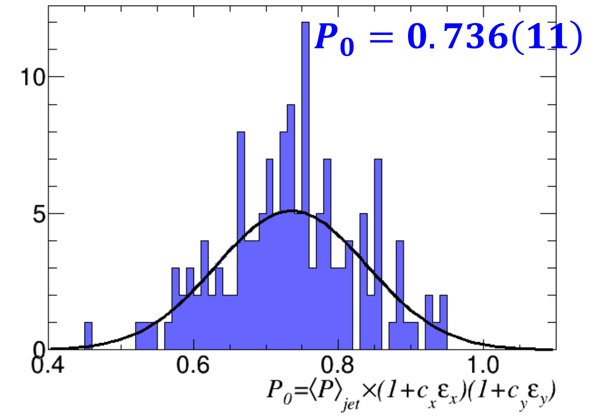
Backup

Preliminary Results for $R_{x,y}(\epsilon_{x,y})$

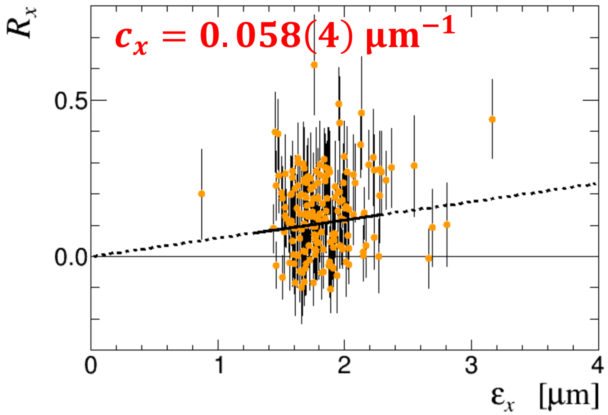
pp 255 GeV Blue Beam

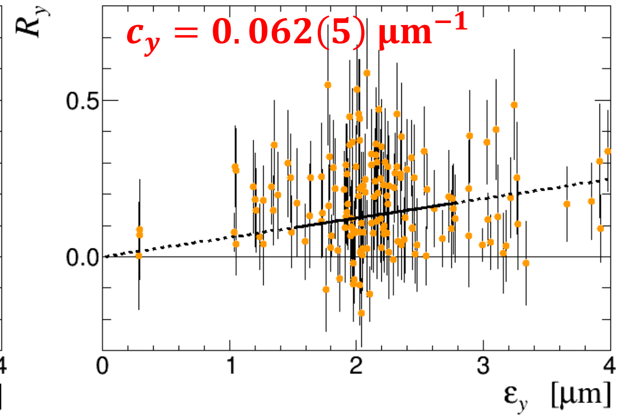


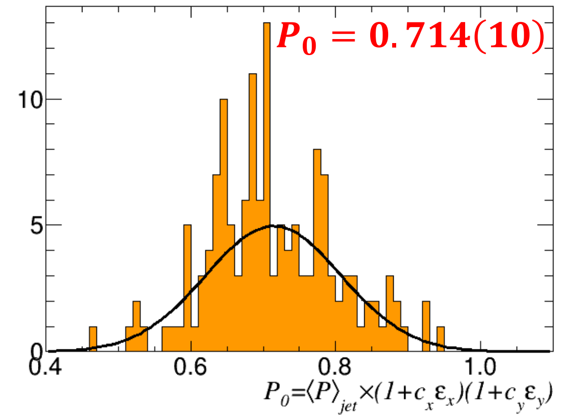




pp 255 GeV Yellow Beam







Evoluation of P_{source}
(if P_0 is preserved)

$$P_{source} = 76.9 \pm 1.1\%$$

$$P_{source} = 72.3 \pm 1.0\%$$

Absolute $^3\mathrm{He}$ polarimeter at eRHIC

- Polarized $^3\mathrm{He}$ beam is under consideration for EIC.
- Since analyzing power for elastic $^3\mathrm{He}$-$^3\mathrm{He}$ scattering is about -0.78 of the elastic pp, a polarized $^3\mathrm{He}$ gas target (similar to HJET) can be employed for absolute polarization measurement of the $^3\mathrm{He}$ beam.
- However, there might be an issue with inelastic

$$^3\mathrm{He} + {}^3\mathrm{He} \to p + d + {}^3\mathrm{He} \qquad (\Delta M = 4.5\ \mathrm{MeV})$$

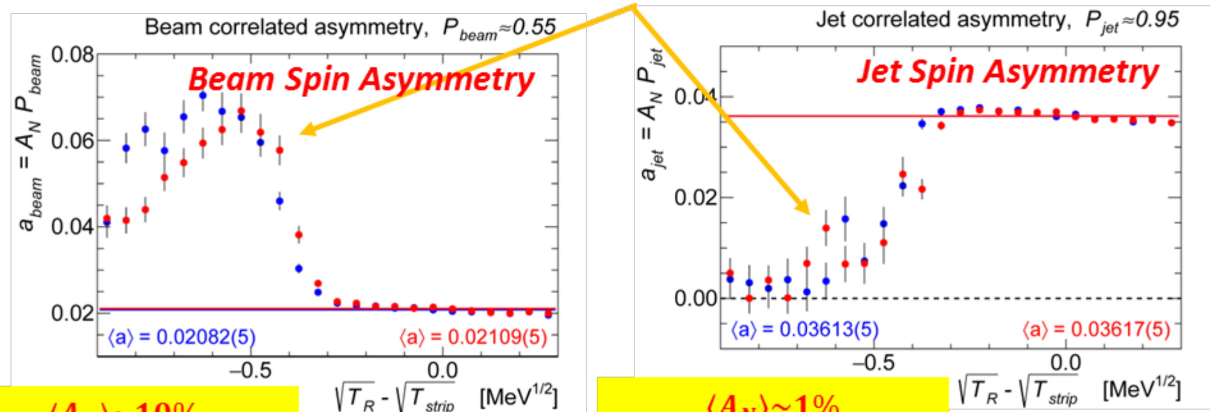
scattering:
  - If beam $^3\mathrm{He}$ dissociates then the beam jet spin analyzing power might be very different resulting in a wrong measurement of the beam polarization
  - If target $^3\mathrm{He}$ dissociates then recoil protons will deteriorate the recoil $^3\mathrm{He}$ signals.
- *If zero emittance polarization is well controlled* then high density unpolarized HJET can be used to measure $^3\mathrm{He}$ beam polarization:
  - The relative beam polarization can be monitored by the recoil proton asymmetry
  - The measured polarization can be normalized by evaluation of the P_0 (as it was done at HJET) and comparing the result with P_{source}.

Inelastic effects at HJET (255 GeV)

$$p + p \rightarrow p + X$$
$$(\Delta M = m_\pi = 135\ \text{MeV})$$

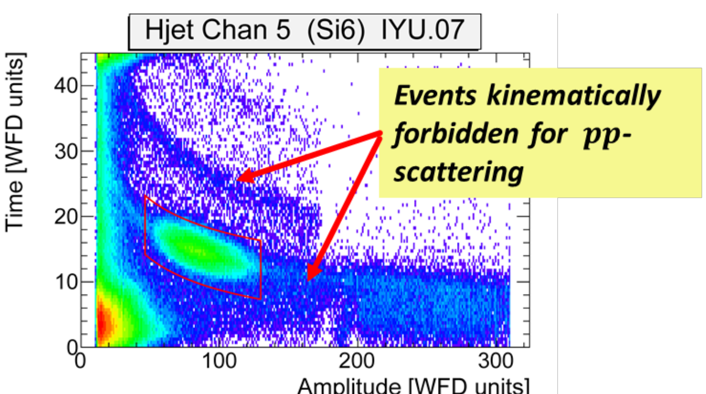
$\langle A_N \rangle_{elastic} \sim 4\%$

Inelastic contribution to the measured asymmetry



$\langle A_N \rangle \sim 10\%$ for $p_b^{\uparrow} + p_j \rightarrow X + p_j$

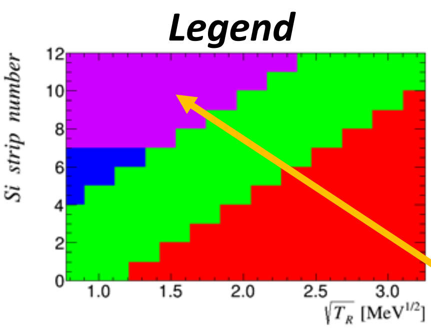
$\langle A_N \rangle \sim 1\%$ for $p_b + p_j^{\uparrow} \rightarrow X + p_j$



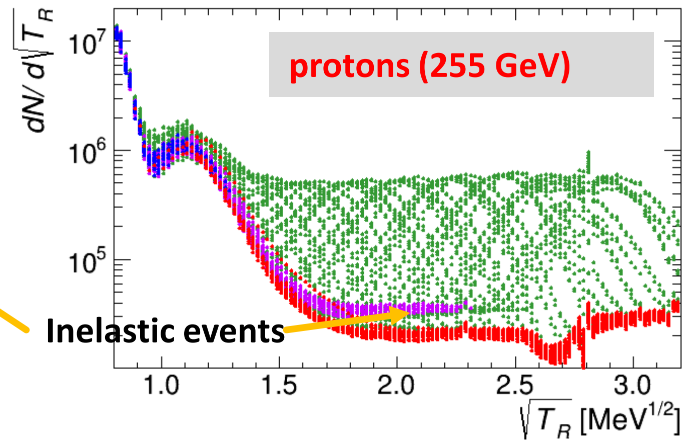
The Jet is contaminated by a small amount of O, N, … nuclei . The proton beam scattering pA on the Jet and beam gas nuclei manifests itself by detection events kinematically forbidden for pp scattering.

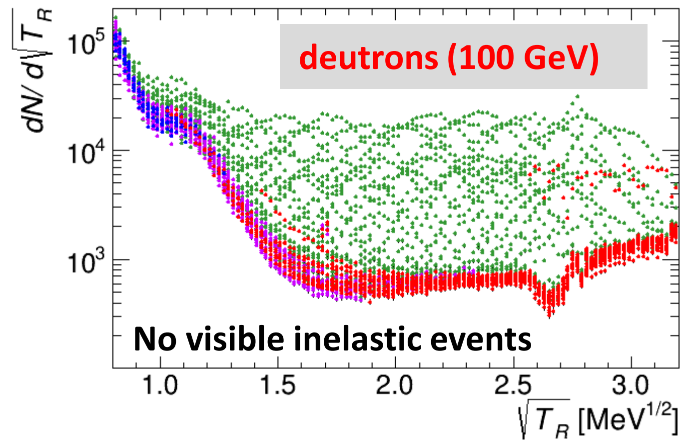
Search for inelastic events for 100 GeV deuterium beam

Superposition of all Si strips $dN/d\sqrt{T_R}$ distributions



Inelastic events





No essential contribution of inelastic events $dp^{\uparrow} \rightarrow Xp$ was found.