CniPol Meeting
5 September 2019

H-Jet Polarimeter. From RHIC to eRHIC.

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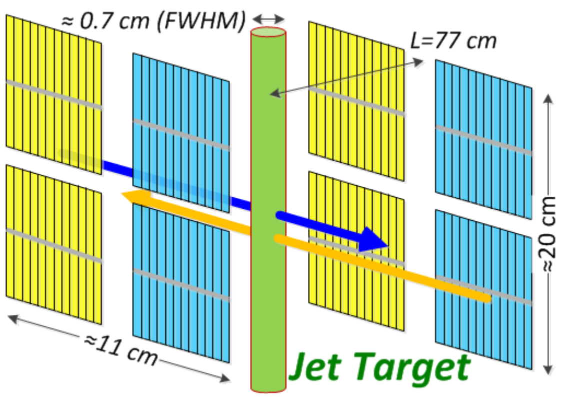
Polarized proton beams at IEC (eRHIC)

	Energy, GeV	Bunch Intensity, E10	Number of Bunches	Emittance RMS, μs
eRHIC (proposed)				
p	275	18.7	290 / 360	2.2
p	275	27.6*	290* / 360	1.6
p	100	27.6*	290* / 360	1.9
p	100	18.8*	290* / 360	2.6
p	41	4.5*	290* / 360	2.6
He3	**?**	**?**	**?**	**?**
** each bunch is longitudinally split into 4 after the ramp*				
RHIC				
p	255	16.5	111 / 120	2.1
p	100	22.5	111 / 120	4.0

Since polarized proton beams at eRHIC are similar to that of the RHIC, the polarimetry methods developed for RHIC can be helpful for eRHIC.

A very good experience with HJET polarimeter at RHIC



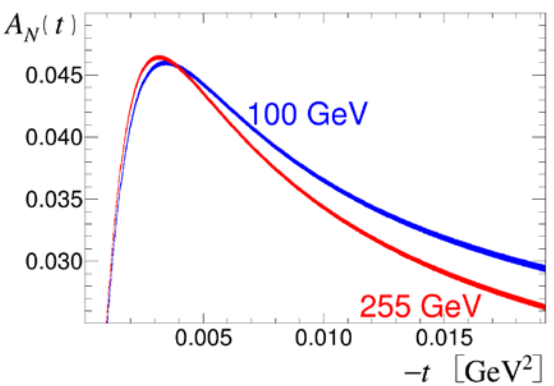
The absolute beam average polarization is determined by measuring jet and beam correlated asymmetries:

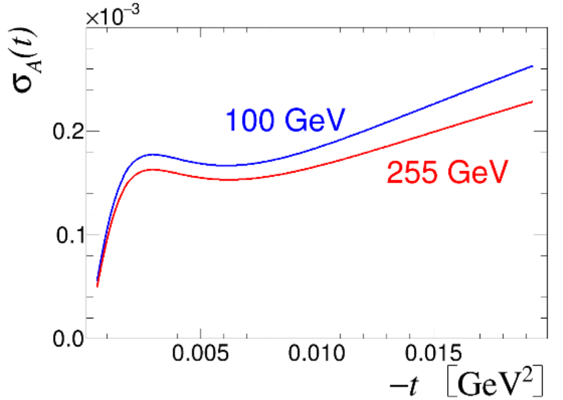
$$a_{jet} = \langle A_N \rangle P_{jet} \qquad a_{beam} = \langle A_N \rangle P_{beam}$$

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

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 41 and 275 GeV

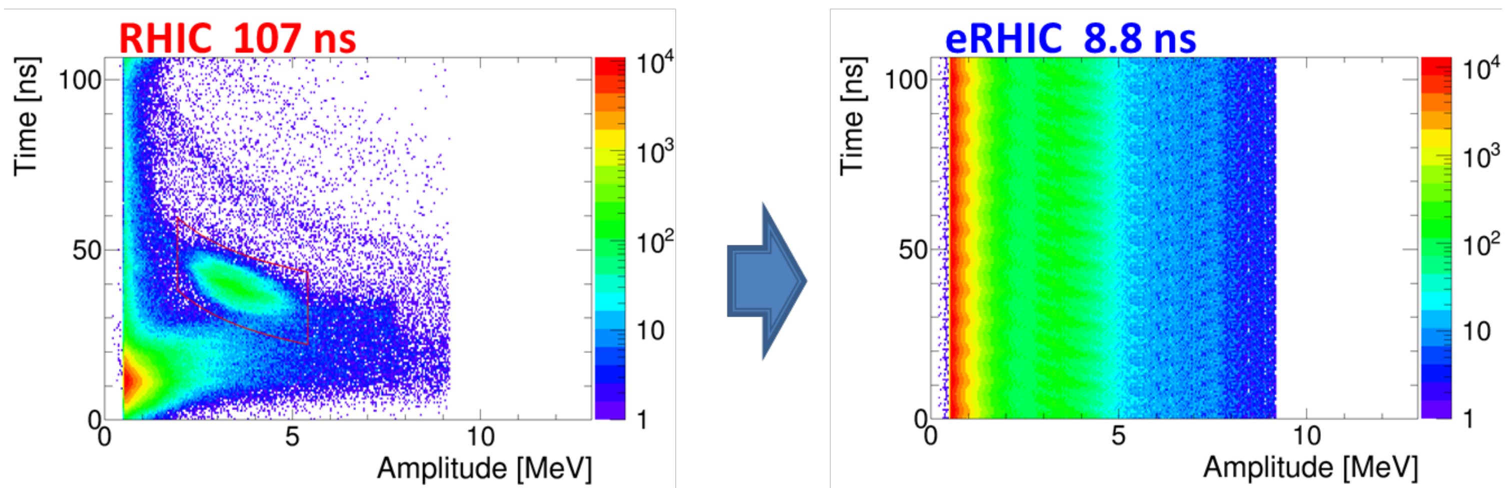
Employing of unpolarized Jet with up to 100-fold density could strongly improve the statistical accuracy of the polarization measurements:

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

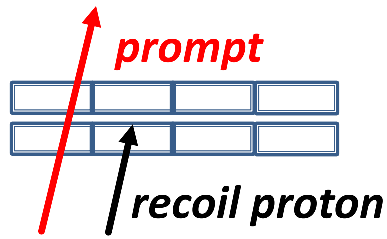
Polarization decay and spin tilt can also be precisely measured.

Could HJET be used at EIC (eRHIC) ?

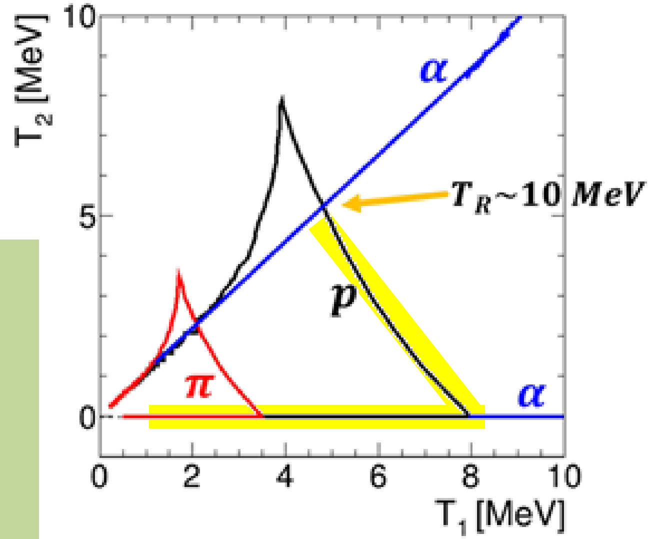
- **The achieved accuracy of the absolute polarization measurement well satisfies the EIC (eRHIC) requirements for hadron polarimetry.**
- **The proposed for EIC beam energies and bunch intensities allows us to use HJET as is.**
- **However, the 12-fold increasing of the bunch frequency can crucially degrade the HJET performance due to mixing prompts and elastic pp signals from different bunches.**



Two-layers Si detectors in HJET



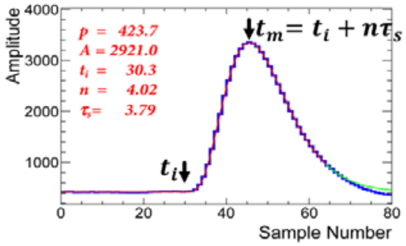
Correlation of the deposited energies in two Si layers



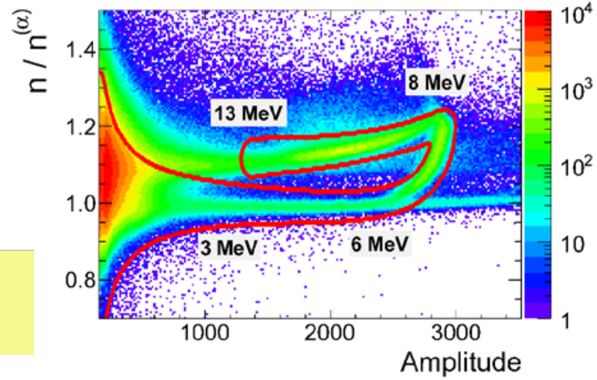
- The second layer can be used as veto to suppress prompts
- The background caused by low energy pions and alphas stopped in the first layer is expected to be small and may be suppressed using the standard background subtraction procedure.

- **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)**

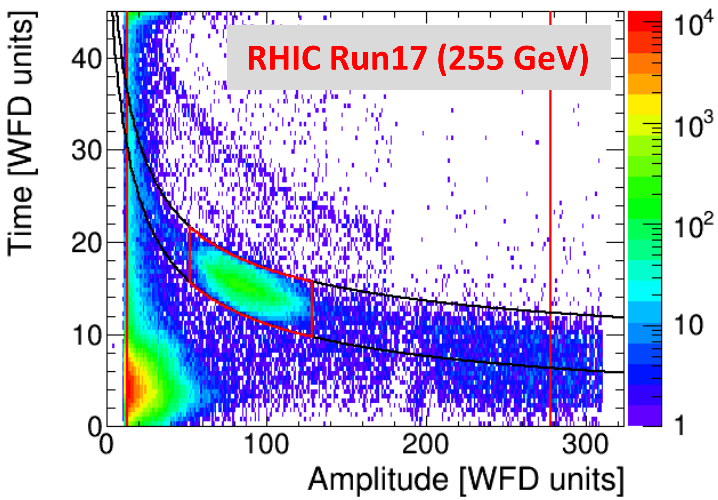
! Punch through events suppression using waveform shape analysis

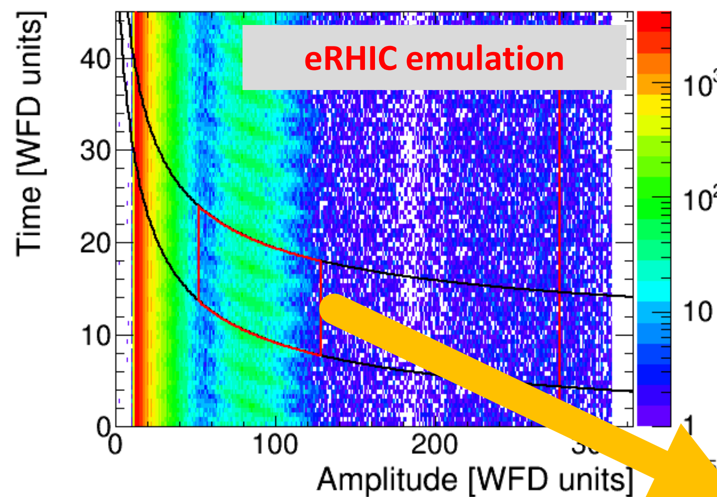


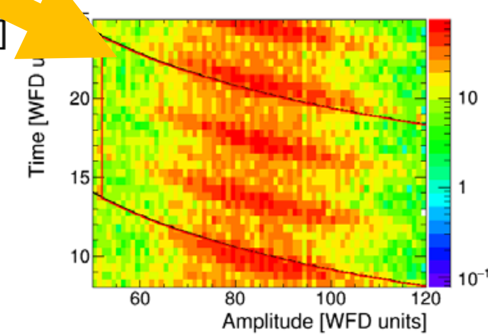
Signal parametrization: $W(t) = p + A\,(t - t_i)^n \exp\left(-\frac{t-t_i}{\tau_s}\right)$



- **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.**





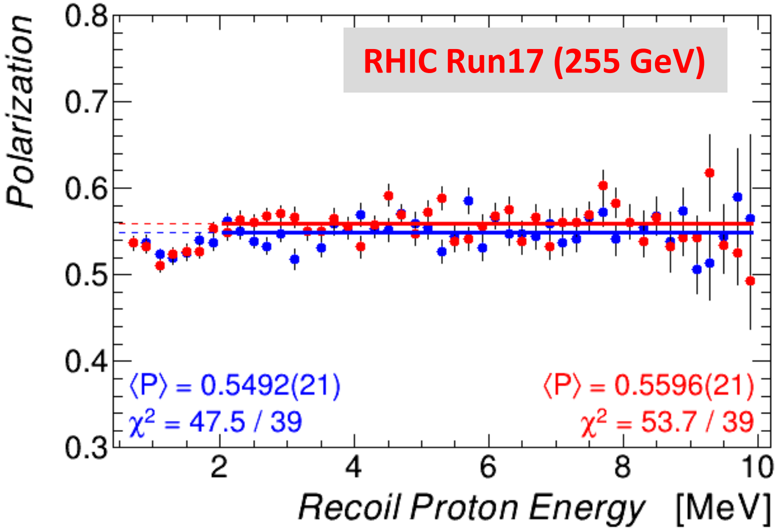


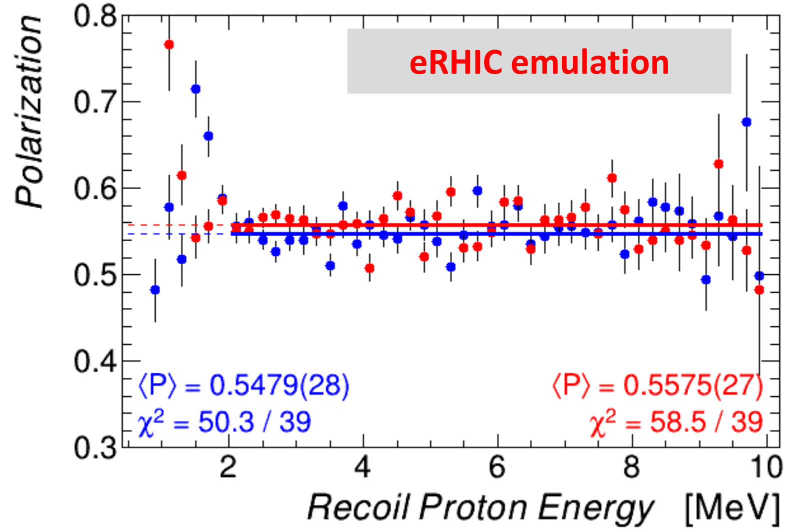
To emulate HJET performance at eRHIC, we used the Run17 data and for every event smeared the measured time with $\tau = 8.7$ ns step:

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

Beam Polarization measurements. eRHIC vs RHIC.

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





- **For recoil proton energy above 2 MeV, the eRHIC results are well consistent with RHIC.**
- **The eRHIC polarization is systematically shifted by $\Delta P/P \sim 0.3\text{-}0.4\%$.**
- **A conservative estimate of the systematic uncertainties of the absolute polarization measurements at eRHIC is $\delta P_{syst}/P < 1\%$.**

The RHIC HJET polarimeter is ready for eRHIC.
Nonetheless, some improvements are still desirable:

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

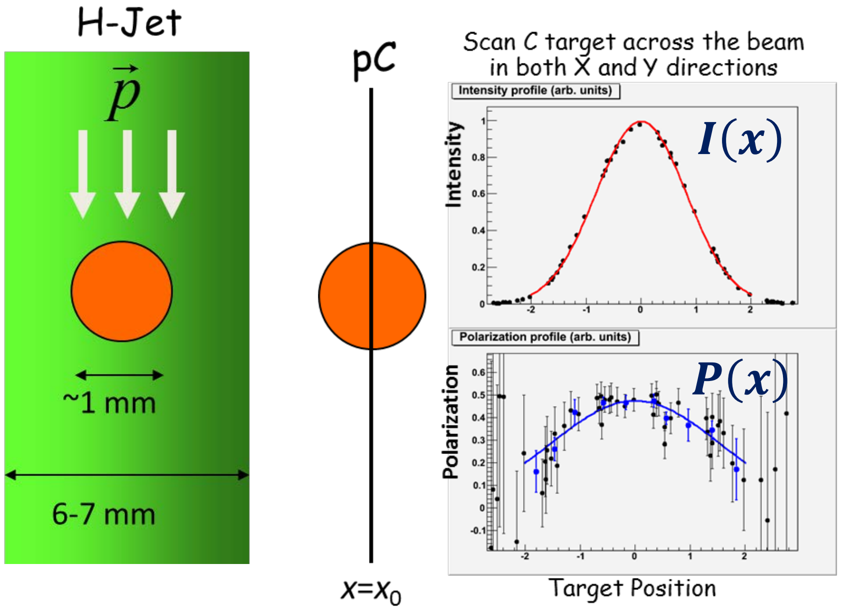
Polarization Profile

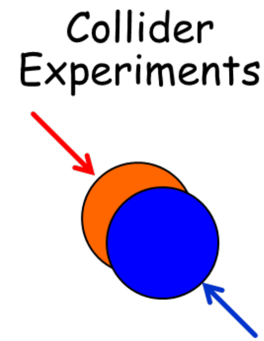
- If polarization changes across the beam, the average polarization seen by Polarimeters and Experiments (in collision) is different
- At RHIC, pCarbon polarimeters are used to determine polarization profiles:

Intensity: $I(x,y) \propto \exp\left(-x^2/2\sigma_x^2 - y^2/2\sigma_y^2\right)$

Polarization: $P(x,y) \propto \exp\left(-R_x\, x^2/2\sigma_x^2 - R_y\, y^2/2\sigma_y^2\right)$

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





$$\langle P\rangle_{exp}/\langle P\rangle_{HJET} = 1 + \left(R_x + R_y\right)/4$$

- **Due to very high rate of prompts the p-Carbon polarimeter can not be used at eRHIC.**
- **There will be a permanent veto signal in double layer detectors.**

Could $\langle P \rangle_{exp}$ be determined without p-Carbon?

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

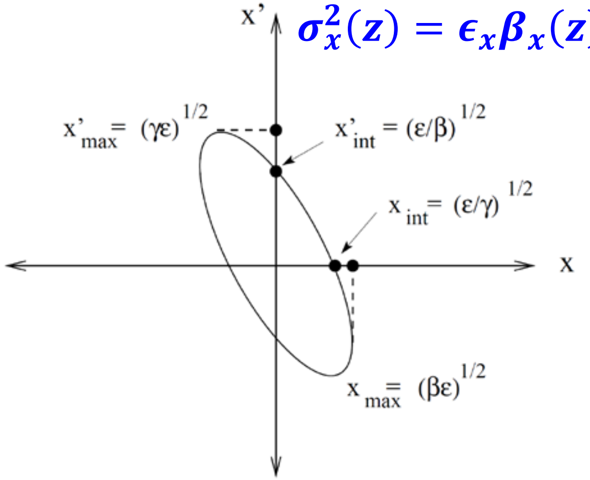
$$\langle P \rangle_{exp} = \langle P \rangle_{jet} \frac{\sqrt{(1+R_x)(1+R_y)}}{\sqrt{\left(1+\frac{1}{2}R_x\right)\left(1+\frac{1}{2}R_y\right)}} \approx \frac{3\langle P \rangle_{jet} + P_0}{4}$$

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

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

- P_0 is zero emittance polarization which is supposed to be preserved during acceleration, $P_0 = P_{source}$
- If so ,the collision average polarization could be derived from the values of the $\langle P \rangle_{jet}$ and $P_0 = P_{source}$. The P_0 uncertainties are suppressed by factor 4.
- The hypothesis $P_0 = P_{source}$ is not experimentally proved yet

! A possible method of experimental evaluation of the P_0



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

Measured by IPM

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 acceleration schema

$$\langle P \rangle_{jet} = P_0 - c_x\epsilon_x - c_y\epsilon_y \approx P_0 - c\varepsilon$$

$$\epsilon = (\epsilon_x + \epsilon_y)/2$$

- P_0 can be determined by study dependence of the $\langle P \rangle_{jet}$ on ϵ
- The correlation $R = c\epsilon$ may be ramp schema dependent
- The σ_P^2 can variate during the store. The study should be done using "ramp end" emittance ϵ_0.

Beam Polarization in Run 17

The RHIC Fills used in this analysis.

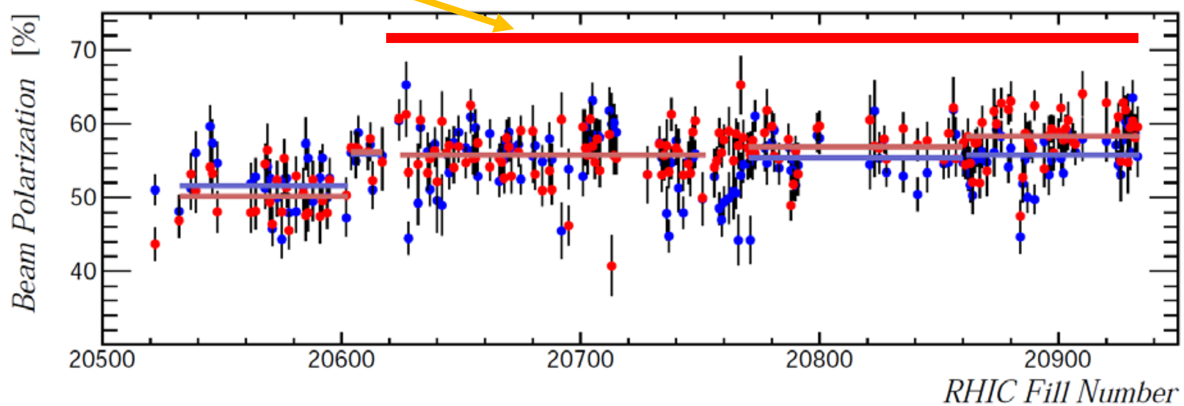


Figure 24: Monitoring of the RHIC store average absolute polarization of the proton beams in Run 2017. Only statistical errors are shown.

RHIC Fills	Blue Beam	Yellow Beam	Running Conditions[10, 11]
20537–20603	51.7 ± 0.5	50.2 ± 0.5	AGS Single Harmonic
20604–20617	55.9 ± 0.9	56.2 ± 0.9	AGS Dual Harmonic
20624–20753	55.8 ± 0.3	55.8 ± 0.3	slower Ramp
20770–20860	55.6 ± 0.3	56.8 ± 0.4	D' Lattice only in Blue beam
20861–20935	55.4 ± 0.4	58.3 ± 0.3	
Run 2017 average	54.9	56.1	

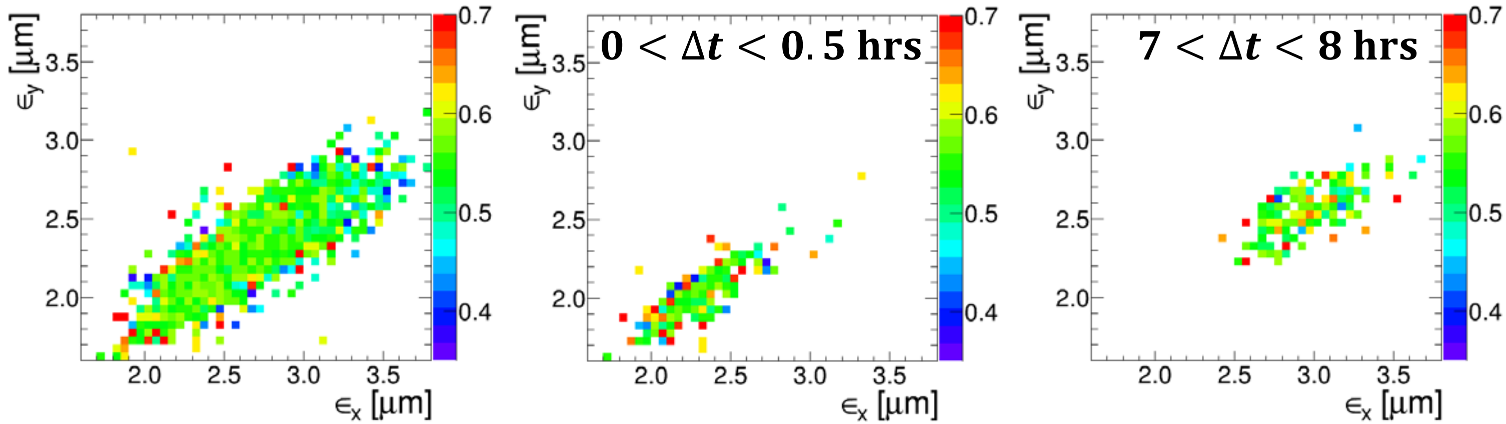
Table 2: The average beams polarizations depending on the running conditions. The shown errors are statistical uncertainties in determination of the interval average polarization.

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

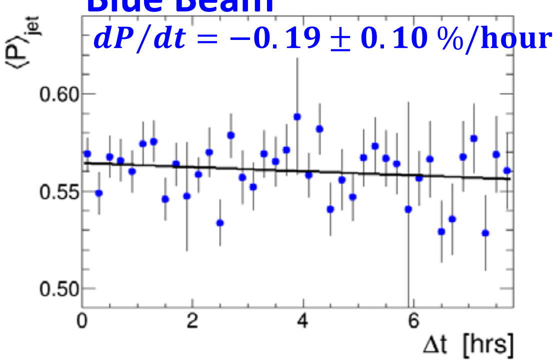
- **For each Jet cycle, a dataset of 8 Si counts and 4 emittances (IPM) were determined.** ⇨ $\langle P \rangle_{jet} = P(\epsilon_x, \epsilon_y, \Delta t)$

Δt is time after the ramp

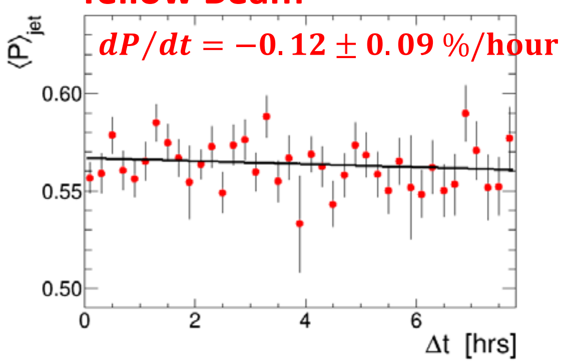
The Run average polarization $\langle P \rangle_{jet}$ dependence on x, y emittances (blue beam)



Blue Beam



Yellow Beam

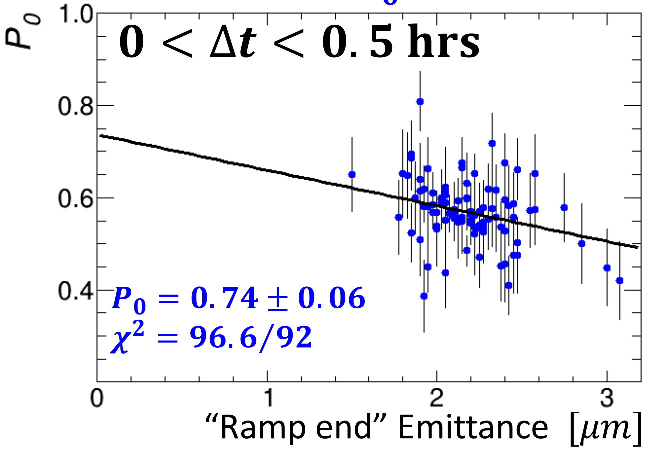


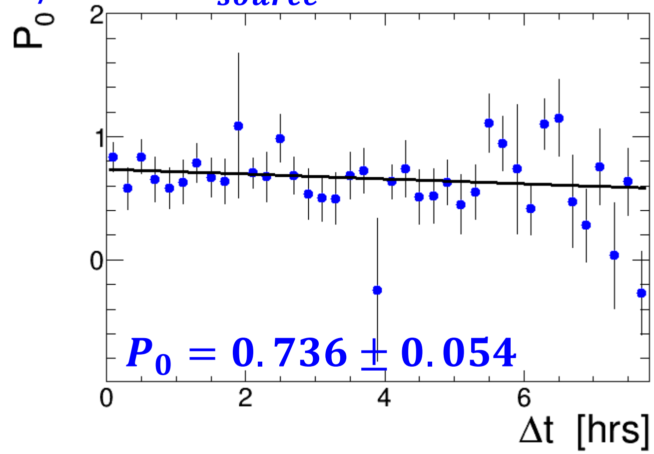
This Polarization decay estimate is consistent with p-Carbon measurements, but has about a factor 2 larger uncertainty.

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

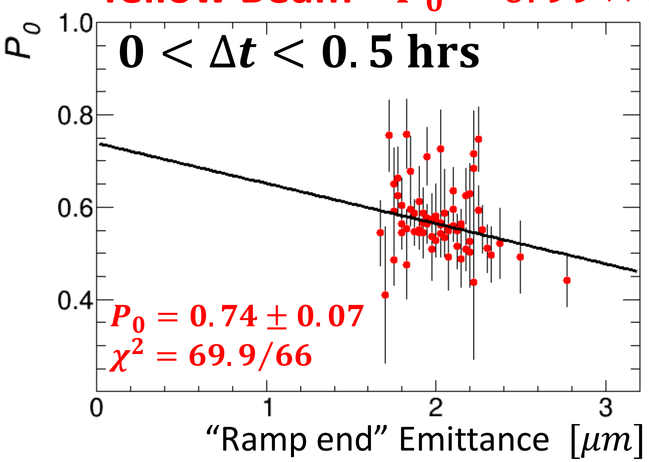
AGS RHIC Background

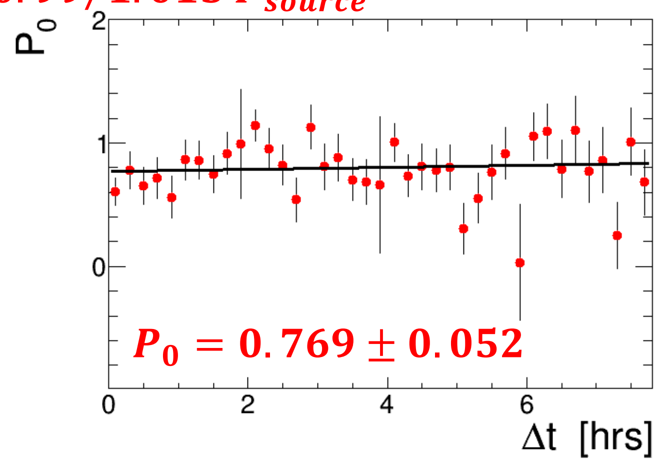
Blue Beam $P_0 = 0.99 \times 0.96/1.015\ P_{source}$





Yellow Beam $P_0 = 0.99 \times 0.99/1.015\ P_{source}$





$R = 0.16 \pm 0.03$

$P_{src} = (76 \pm 4)\%$

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

The result is consistent with the assumptions:

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

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 using available and future data might be critically important for EIC (eRHIC) polarimetry.

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Could HJET substitute p-Carbon at eRHIC?

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 eRHIC

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 better accuracy than pCarbon.**
2) **At unpolarized HJET, 45 degree detectors can be installed, which provide spin tilt measurements.**
3) **In the method discussed above, the fluctuations of the emittance are very important to evaluate P_0. However,**
   - **Depending on the source of the fluctuations, they may violate the assumption $R = c\epsilon$ the method is based on. In this case $P_0^{\text{meas}} \leq P_0 \leq P_{\text{source}}$ (which, nonetheless, also might be an acceptable solution).**
   - **The emittance fluctuations at eRHIC may be insufficient to achieve desirable accuracy of the P_0.**

!

How p-Carbon can be used in eRHIC

- The correlation between beam average polarization (HJET) and beam emittance (IPM) suggests that $R_{x,y} = R(\varepsilon_{x,y})$.
- If such a dependence is (somehow) calibrated then the IPM can be used to monitor the polarization profile of the eRHIC beam and, thus, to control the collision average polarizations of the eRHIC polarized proton beam.
- The RHIC pCarbon polarimeter can be employed to calibrate $R(\varepsilon_{x,y})$ at eRHIC in dedicated short fills:
  - Fill eRHIC with 107 ns bunch spacing
  - Ramp
  - Split (8.7 ns spacing) each bunch into 4
  - Polarization profile measurements using pCarbon (as in RHIC)
  - Beam dump
- A similar study of the $R(\varepsilon)$ at AGS pCarbon, potentially, might provide an estimate of the bunch-to-bunch variation of the polarization of at eRHIC.

- The possibility of the 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).
- A more detailed study, including special tests, can be done in the anticipated RHIC pp Runs in 2021, 2023, 2025.
- The final goal of these studies should be understanding of the dependences of the $P_0(\epsilon)$ and $R_{x,y}(\epsilon)$ on the polarization at source P_{source} and accelerator configuration. If this goal will be achieved, we can get evaluation of the collision average polarization for Hellium-3 and deuterium beams without direct measurements at eRHIC.

What else can be done with available data ?

- A similar study using Run 15 (100 GeV) data
- More accurate study of the $R = c\varepsilon$ correlation (separately for x and y coordinates) using RHIC p-Carbon.
- The $R = c\varepsilon$ study at AGS. Potentially, this might provide an estimate of the bunch-to-bunch variation of the polarization of at RHIC.
- Could other measured beam parameters (e.g. bunch intensities) be helpful in the evaluation of P_0?

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Projection to eRHIC

- **The unpolarized HJET can significantly improve the statistical uncertainties of the evaluation of P_0.**
- **For precise estimate of the P_0 the ramp-to-ramp fluctuations of the emittance are very helpful.**
- **If they will be very small then:**
  - ***If it will be proved* that $P_0 = P_{source}$ then the polarization profile can be derived from the HJET measurement $R = \sqrt{P_0/\langle P\rangle_{jet} - 1}$ and, consequently, the collision average polarization can be determined**
    $$\langle P\rangle_{exp} = \langle P\rangle_{jet} \times (1+R)/(1+R/2)$$
  - **A part of stores (10% ?) can be filled with enlarged emittance beams.**
  - **The p-Carbon can be used (exactly like in RHIC) in a special short stores (just to measure polarization profile R) filled with 111 bunches.**
- **The *unpolarized* HJET seems to be a critically important component of the eRHIC polarimetry**

Absolute ^{3}He polarimeter at eRHIC

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

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

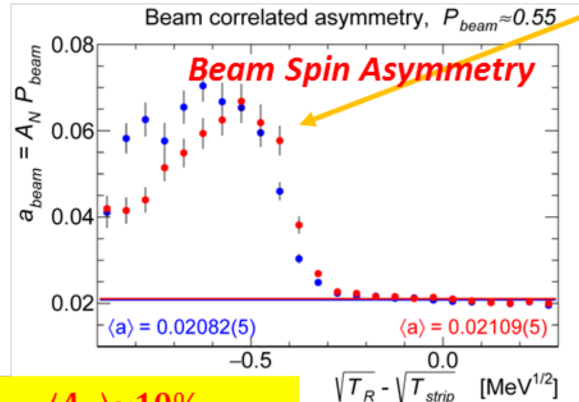
scattering:
  - If beam ^{3}He dissociates then the beam jet spin analyzing power might be very different resulting in a wrong measurement of the beam polarization
  - If target ^{3}He dissociates then recoil protons will deteriorate the recoil ^{3}He signals.
- *If zero emittance polarization is well controlled* then high density unpolarized HJET can be used to measure ^{3}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)

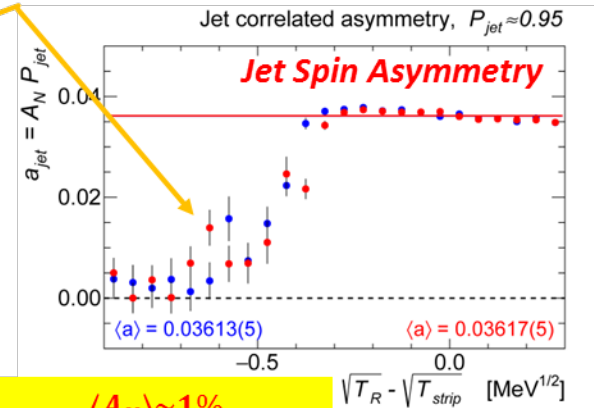
$p + p \to p + X$
$(\Delta M = m_\pi = 135\ \text{MeV})$

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

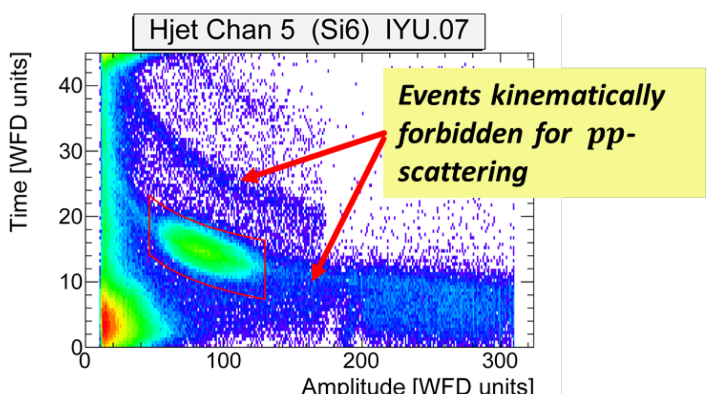
Inelastic contribution to the measured asymmetry



$\langle A_N \rangle \sim 10\%$
for $p_b^\uparrow + p_j \to X + p_j$



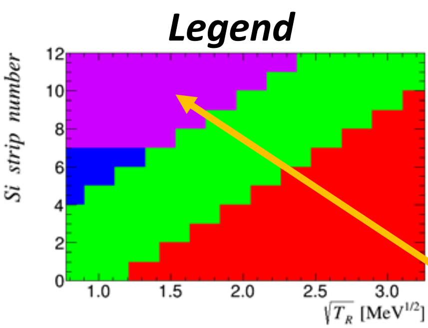
$\langle A_N \rangle \sim 1\%$
for $p_b + p_j^\uparrow \to X + p_j$

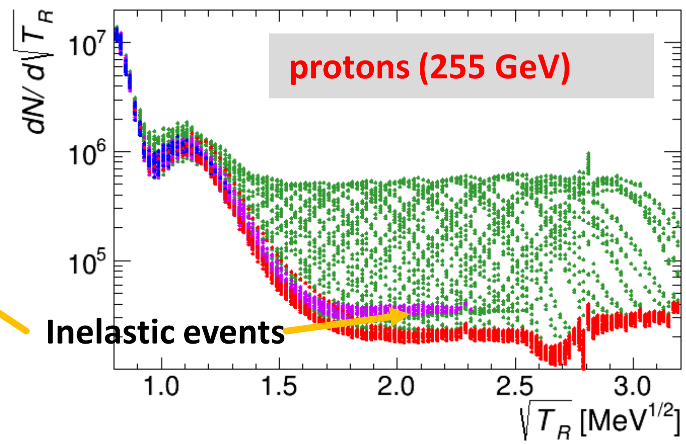


The Jet is contaminated by a small amount of O, N, … nuclei. The proton beam scattering pA on the Jet and beam gas nuclei manifests itself by detection events kinematically forbidden for pp scattering.

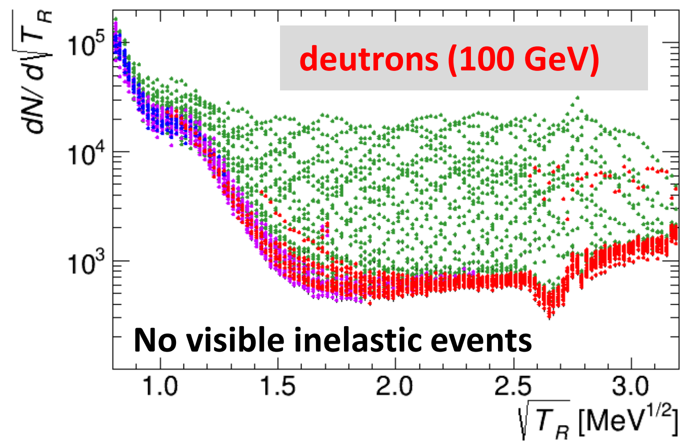
⁉ Search for inelastic events for 100 GeV deuterium beam

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

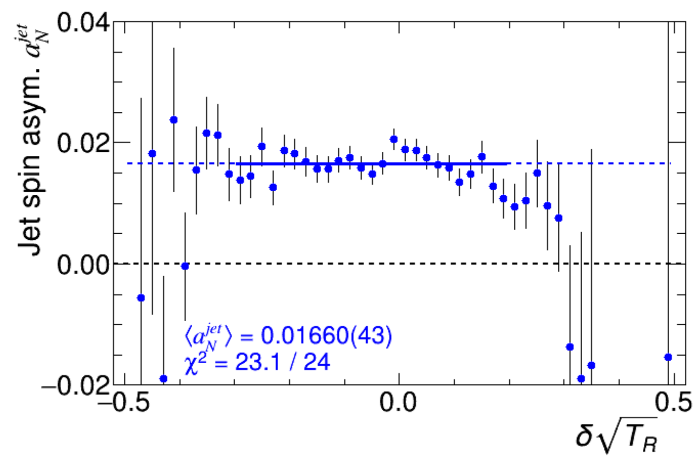




Inelastic events



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



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Summary

- A possibility to evaluate the zero emittance polarization P_0 using HJET data (255 GeV) and IPM measurements of the beam emittances was studied.
- The method was confirmed within uncertainties of the measurements and the determined value of P_0 is consistent with the polarization at source (if known corrections) are applied.
- However more study is still needed.
- Preliminary conclusion:
  - understanding of the P_0 evolution during the ramp and store and
  - employing of high intensity unpolarized hydrogen jet target

  is crucially important for the eRHIC hadronic polarimetry.
- *Alternative solutions for EIC hadronic polarimetry (not used at RHIC) where not considered here.*