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Can the EIC ^{3}He beam polarization be precisely measured by HJET ?

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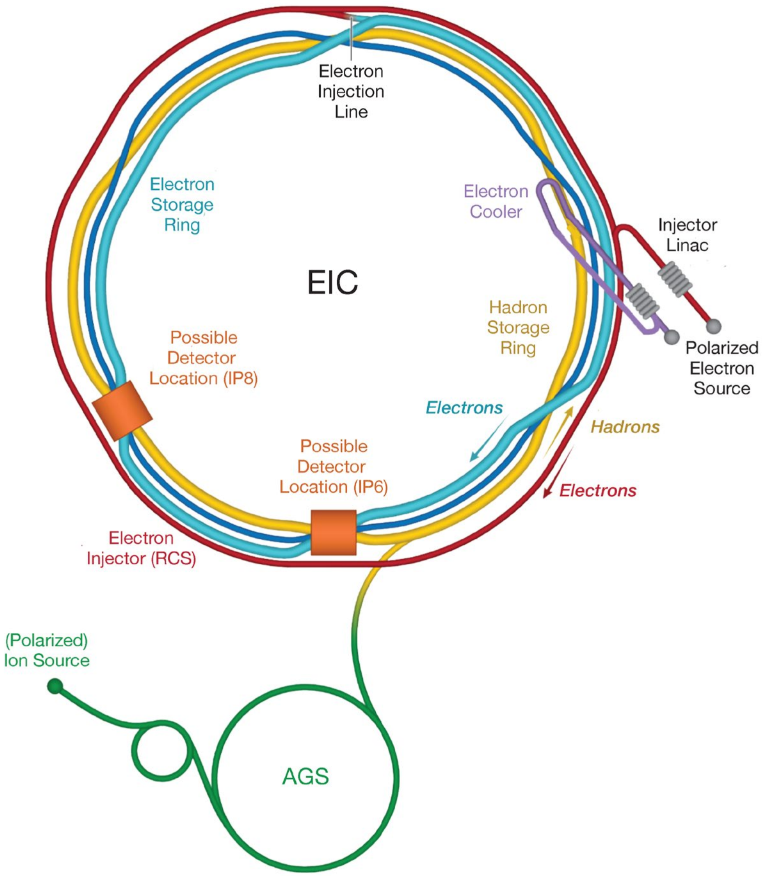
Hadronic polarimetry at the EIC



High energy, 40-275 GeV polarized proton and helion ($^3He^{\uparrow}$) beams are planned at the future Electron Ion Collider.

The requirement for the EIC beam polarimetry:

$$\sigma_P^{syst}/P \lesssim 1\%$$

Compared to RHIC, there are new challenges for the hadronic beam polarimetry at EIC

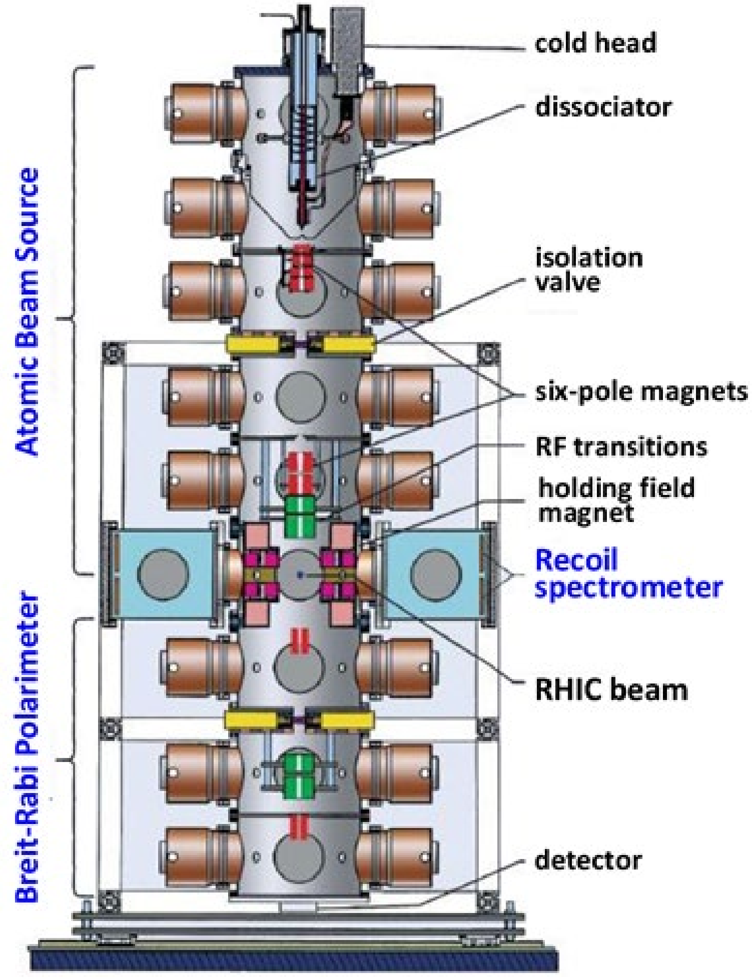
- Much shorter, 10 ns bunch spacing (107 ns at RHIC)
- $^3He^{\uparrow}$ beam

- **A complete analysis of the beam polarization includes measurement of the polarization profile, polarization decay time, …**
- **The main goal of this presentation is to discuss the RHIC Hydrogen Jet Target (HJET) feasibility to measure the $^3He^{\uparrow}$ beam averaged absolute polarization at EIC.**

The Polarized Atomic Hydrogen Gas Jet Target (HJET)

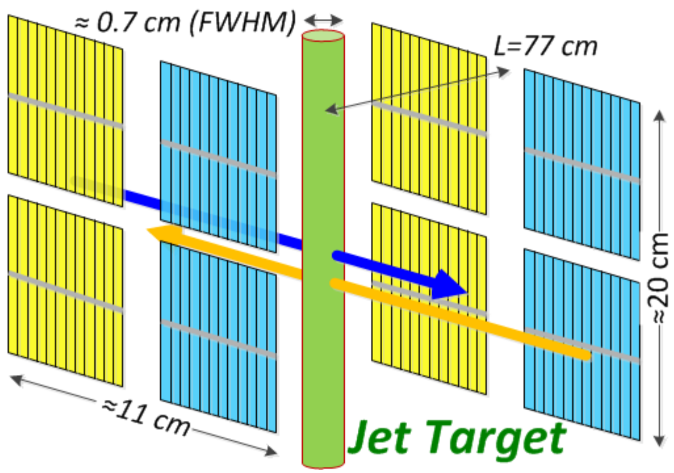
A. Zelenski et al., Nucl. Instrum. Meth. A **536**, (2005)

- 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.

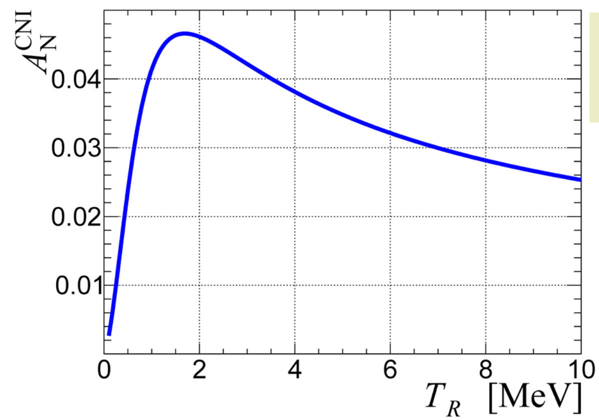


- The target with no walls or windows
  - ✓ Continuous beam polarization measu-rement with no impact on the RHIC experiments.
  - ✓ The recoil protons can be precisely measured in the energy range of 0.6 – 10 MeV (the CNI analyzing power maximum)
- The beam polarization can be related to the atomic Hydrogen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

The HJET recoil spectrometer



Analyzing power $A_N^{CNI}(t)$ (*leading order approximation*) as function of the recoil proton energy $T_R = -t/2m_p$



B. Z. Kopeliovich and L. I. Lapidus, Sov. J. Nucl. Phys. 19, 114 (1974)

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

$$\kappa_p = \mu_p - 1 = 1.793$$

$$T_c = 4\pi\alpha/m_p\sigma_{tot} \approx 1\ \mathrm{MeV}$$

The beam $(\uparrow\downarrow)$ and target $(\pm)$ single spin asymmetries are concurrently measured In the $0.5 < T_R < 10$ MeV recoil energy range.

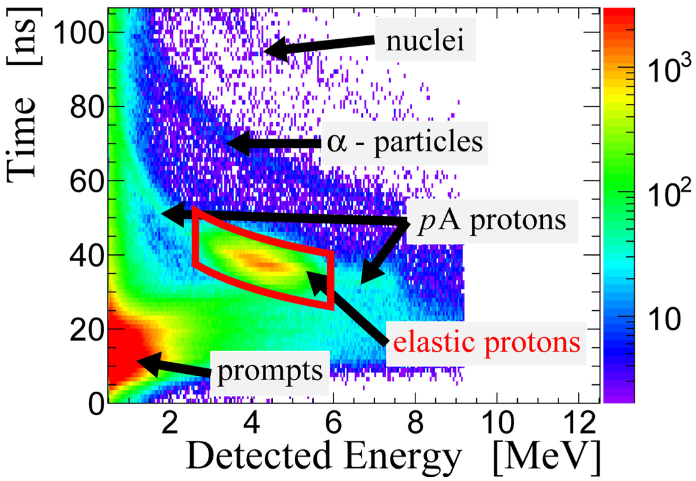
$$a_{beam} = \langle A_N \rangle P_{beam} \Rightarrow \frac{\sqrt{N_R^\uparrow N_L^\downarrow} - \sqrt{N_R^\downarrow N_L^\uparrow}}{\sqrt{N_R^\uparrow N_L^\downarrow} + \sqrt{N_R^\downarrow N_L^\uparrow}}$$

$$a_{jet} = \langle A_N \rangle P_{jet} \Rightarrow \frac{\sqrt{N_R^+ N_L^-} - \sqrt{N_R^- N_L^+}}{\sqrt{N_R^+ N_L^-} + \sqrt{N_R^- N_L^+}}$$

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

The beam polarization can be precisely determined with no detailed knowledge of the analyzing power

Isolation of the elastic pp events



For the elastic proton beam scattering,

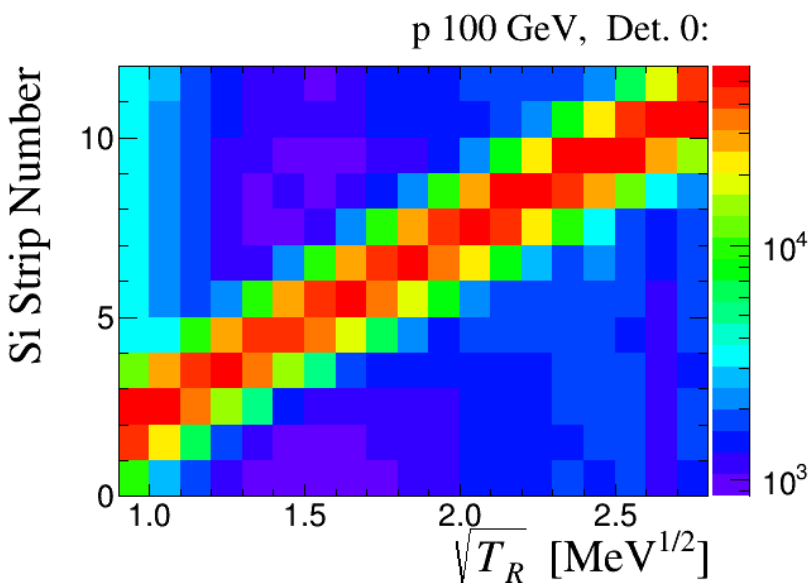
- The recoil angle θ_R can be discriminated by the Si strip number ($\Delta z = 3.75\ \mathrm{mm}$)

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

- **The energy range,** $0.5 < T_R < 10\ \mathrm{MeV}$, is defined by the detector geometry

- Elastic pp scattering can be identified by the strict correlation between z_{det} and $\sqrt{T_R}$.
- Two most important backgrounds are
  - Beam gas hydrogen (aka molecular hydrogen)
  - $p\mathrm{A} \to pX$, proton beam scattering on some nuclei in the jet or around. The breakup protons are detected.

In ***basic approximation***, the background proton rates depend on the recoil energy T_R but not on the recoil angle θ_R.



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:

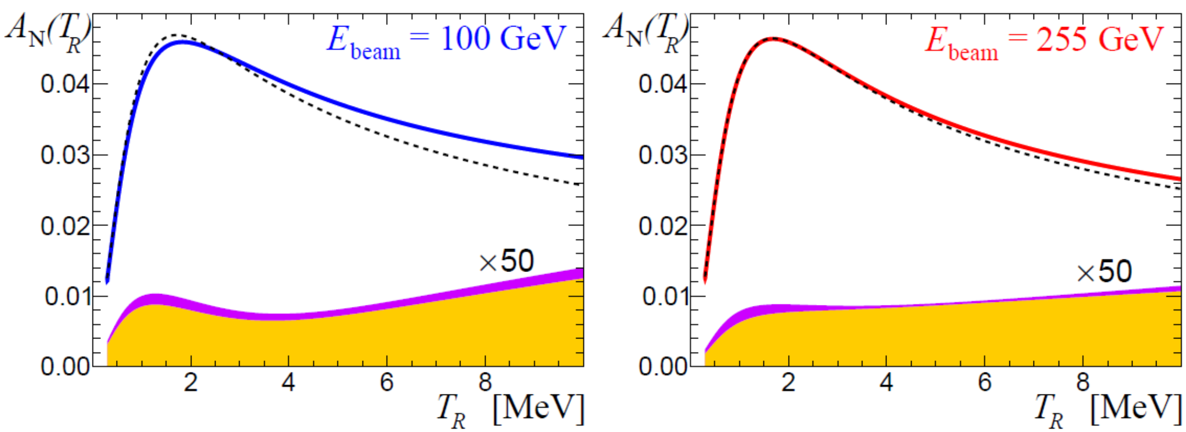
Typically, for 8 hour store (Run 17, 255 GeV):

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

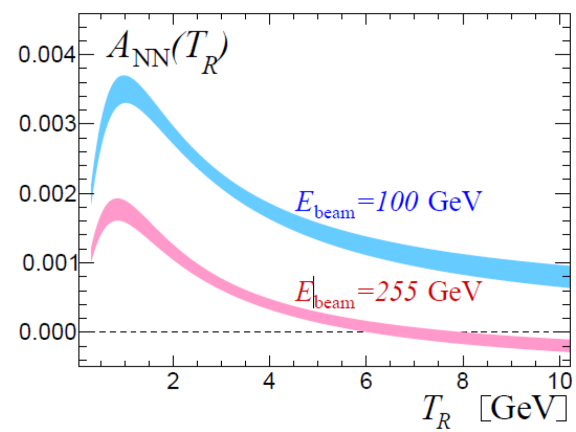
$$\sigma_P^{\mathrm{syst}}/P_{\mathrm{beam}} \lesssim 0.5\%$$

Elastic *pp* analyzing powers:

Single Spin



Double Spin



- The filled areas specify 1σ experimental uncertainties, stat.+syst., scaled by x50 for A_N.
- The dashed curves correspond to the leading order approximation $A_N^{CNI}(T_R)$
- The analyzing powers can be extrapolated to other beam energies

Polarized $^3He^{\uparrow}$ (helion) gas target

!

The $^3He^{\uparrow}$ beam polarization can be measured with, actually, no knowledge of the helion-helion analyzing power $A_N^{hh}(t = -2m_h T_R)$

$$\boldsymbol{P_{\text{beam}} = P_{\text{target}} \times \left(a_{\text{beam}}/a_{\text{target}}\right)}$$

?

- Can the $^3He^{\uparrow}$ target polarization be controlled with precision much better than 1% ?
- The recoil *helion* kinematics

$$T_R \propto t/m_h, \quad \vartheta_R \propto (T_R/m_h)^{1/2}, \quad \text{ToF} \propto (T_R/m_h)^{-\frac{1}{2}}$$

significantly differs from the proton one. This may affect the systematic uncertainties in the measurements.
- Breakup of the target ^3He may contaminate the elastic data
- Breakup of the beam ^3He may alter the elastic $a_{\text{beam}}/a_{\text{target}}$ ratio used to determine the beam polarization.
- Since the EIC bunch spacing, ~ 10 ns, will be much smaller than at RHIC, ~ 107 ns, the prompts may essentially degrade the systematic uncertainties in the beam polarization measurements.

Possibility to overcome the potential problems listed are currently under consideration by the BNL polarimetry group.

Can we use polarized hydrogen target (HJET) ?

!

Due to frequent HJET operations in the RHIC ion beams (d, O, Al, Ru, Zr, Au), including wide range 3.85-100 GeV of the Au beam energies, we already have good understanding of the HJET performance in the EIC $^3He^{\uparrow}$ beam polarization measurement.

?

- To determine the $^3He^{\uparrow}$ beam polarization,

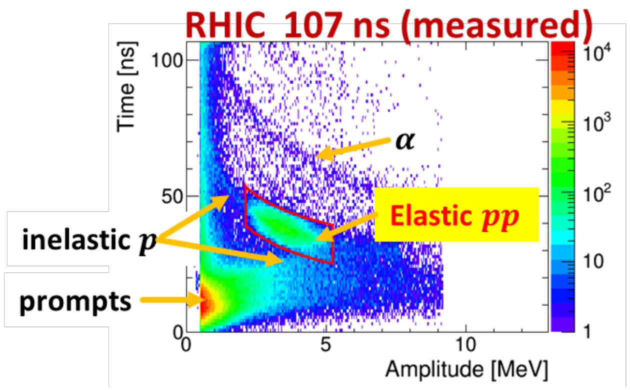
$$\boldsymbol{P_{\text{beam}} = P_{\text{jet}} \times \left(a_{\text{beam}}/a_{\text{jet}}\right) \times A_N^{ph}/A_N^{hp}}$$

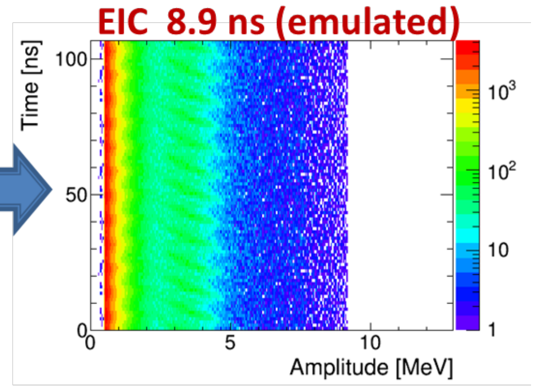
  we need to know the ratio of the $p^{\uparrow}h$ and $h^{\uparrow}p$ analyzing powers
- Breakup of the beam ^3He may alter the elastic $\boldsymbol{A_N^{ph}/A_N^{hp}}$ ratio used to determine the beam polarization.
- Since the EIC bunch spacing, $\sim 10\ \text{ns}$, will be much smaller than at RHIC, $\sim 107\ \text{ns}$, the prompts may essentially degrade the systematic uncertainties in the beam polarization measurements.

Common concerns for the Hydrogen and Helion targets.

The anticipated "bunch spacing" problem at EIC.

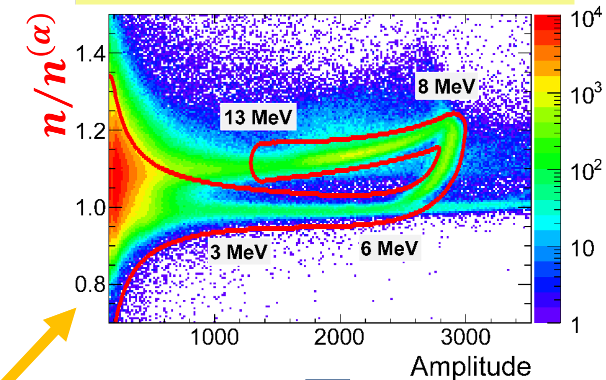
Significant increasing of the bunch frequency, **107 ns → 10 ns**, at EIC may be an issue due to mixing prompts and elastic pp signals from different bunches.

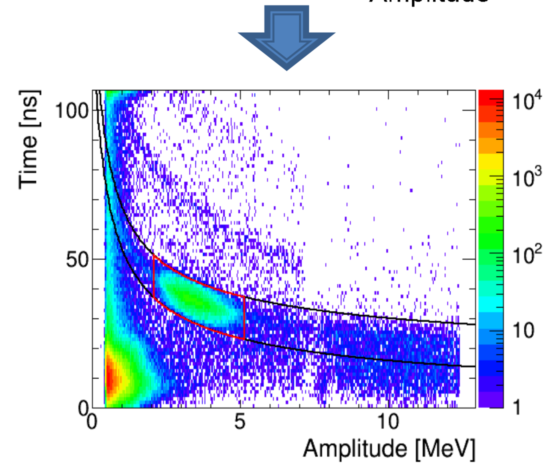




Signal parametrization:

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





Guessing that prompts are fast, punch through, particles (e.g pions) emitted in the beam scattering, one can consider two methods to solve the problem:

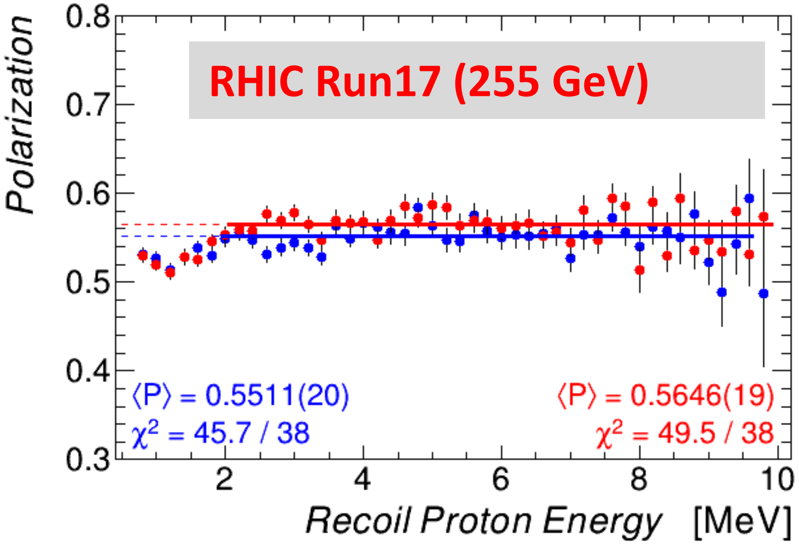
- **suppress prompts analyzing the signal wave form shapes (this method is routinely used in the RHIC data analysis)**
- **veto prompts using double layer detectors**

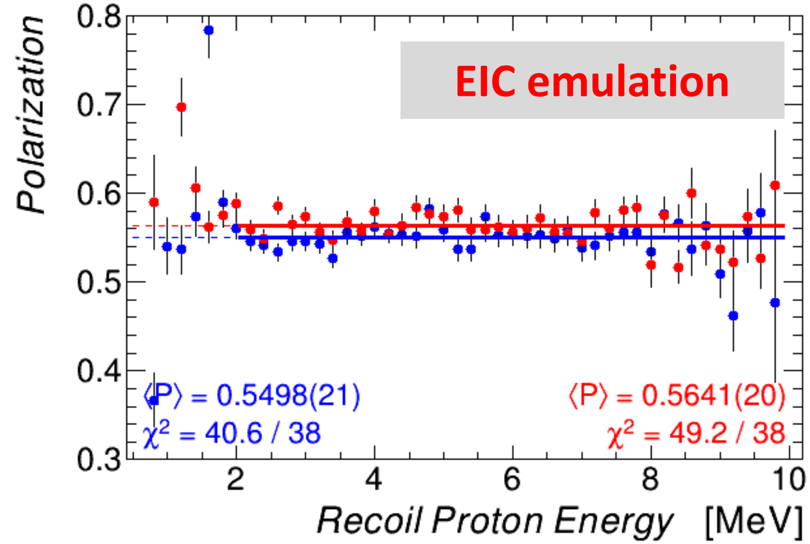
Proton Beam Polarization measurements. EIC vs RHIC.

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):

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 $|\Delta P/P| \lesssim 0.3\%$.
- The estimate of the systematic uncertainties in the absolute polarization measurements at EIC is $\delta P_{syst}/P \lesssim 0.6\%$.

The emulation corresponds to worser condition of the measurements than it is expected at EIC:

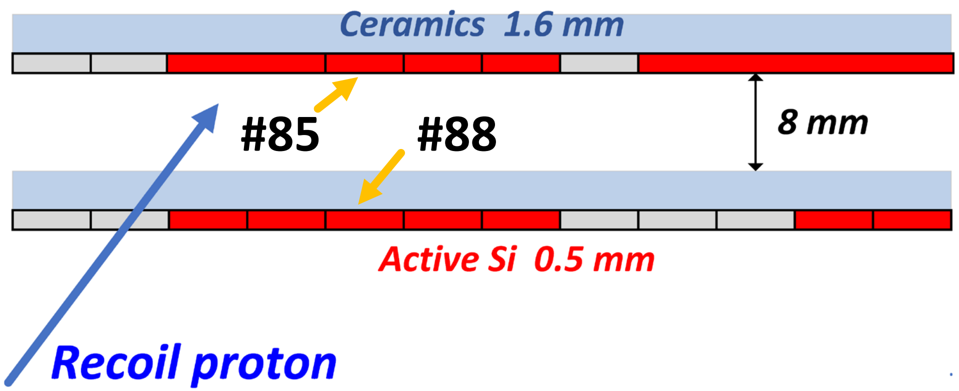
- The background rate will be factor 2 lower (only one proton beam)
- The bunch spacing will be larger, 10.1 ns vs 8.9 ns
- The bunch length will be much shorter.
- However, the beam current will be × 3 larger

Prototype of a double-layer detector for HJET

The prototype was assembled using available components (not an optimized design):

- **1.6 mm of ceramics between layers**
- **~10 mm gap between layers**

One of 8 HJET detectors was replaced by the prototype.



- **The goal was to veto punch-through $\pi, p, d, \alpha, \ldots$.**
- **Only signals with deposited energy <1 MeV (which corresponds to the momentums 100-500 MeV/c) were studied . The extra ceramics must not be the problem for that.**
- **The detector was tested in 5.76 GeV/n Au beam (Run 2020)**
- **The prompts rate in the second layer was 30-40% compared to the first one.**
- **The prompts veto efficiency was evaluated as $\lesssim$10-20%.**

Preliminary (non-proved) conclusion: ***The prototype does not work as expected.***
The un-vetoed events may be characterized by

- Time of flight corresponding speed of light
- The wave form shape is similar to that of stopped particles in the Si strip.

Currently, we have no realistic model for such events.

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

For elastic scattering in the CNI region, the analyzing power is defined by the interference of the *spin-flip* $\phi_5(s,t)$ and *non-flip* $\phi_+(s,t)$ amplitudes

$$A_N(s,t) = -2\,\mathrm{Im}(\phi_5^*\phi_+)/|\phi_+|^2$$

$\phi = \phi^{\text{had}} + \phi^{\text{em}} e^{i\delta_C}$ (hadronic and electromagnetic components)

$T_R = -t/2m_p$ (recoil proton kinetic energy, $T_R < 10\ \text{MeV}$)

$\phi_5^{\text{em}}\,\mathrm{Im}\,\phi_+^{had}$ $\phi_+^{\text{em}}\,\mathrm{Im}\,\phi_5^{had}$ $\mathrm{Re}\,\phi_5^{\text{had}}\,\mathrm{Im}\,\phi_+^{had}$

$$A_{\mathrm{N}}(T_R) = A_{\mathrm{N}}^{\mathrm{nf}}(T_R) \times \left(\kappa_h - 2I_5^{hp} - 2R_5^{hp}\,T_R/T_c\right)$$

$$A_{\mathrm{N}}^{\mathrm{nf}}(T) = \sqrt{\frac{2T_R}{m_p}} \times \frac{T_c/T_R}{(T_c/T_R)^2 - 2(\rho+\delta_C)\,T_c/T_R + 1}$$

$\left|\phi_+^{had}\right|^2 \propto d\sigma/dt$

$\kappa_h = \mu_h/Z_h - m_p/m_h = -1.398$
$T_c = 4\pi\alpha/m_p\sigma_{\text{tot}}^{hp} \approx 0.7\ \text{MeV}$
$\rho + \delta_C \approx -0.05$
$|r_5| = |R_5 + iI_5| = \mathcal{O}(1\%)$

- **Some small corrections are omitted here**
- **Since helion spin is mostly carried by the constituent neutron, the $h^{\uparrow}p$ value of r_5 can be related to the $p^{\uparrow}p$ one, measured at HJET**

Can r_5^{hp} and r_5^{ph} be determined from the measured r_5^{pp} ?

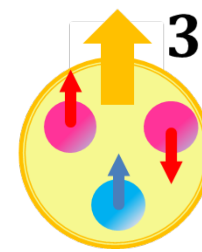
In the HJET measurements ⟶

$$P_{\text{beam}} = P_{\text{jet}} \frac{a_N^{\text{beam}}}{a_N^{\text{jet}}} \times \frac{\kappa_p - 2I_5^{ph} - 2R_5^{ph}\, T_R/T_c}{\kappa_h - 2I_5^{hp} - 2R_5^{hp}\, T_R/T_c}$$

$\kappa_p = 1.973, \qquad \kappa_h = -1.398$

Since $|r_5| \lesssim 2\%$, a **10% theoretical accuracy** in evaluation of the r_5^{hp} and r_5^{hp} is more than sufficient for a precision measurement of the P_{beam}

- r_5 for $p^{\uparrow}A$ and $p^{\uparrow}p$ scattering is the same: $r_5^{ph} = r_5^{pp} \times (1 \pm 5\%)$
  B. Kopeliovich and T. Trueman, Phys. Rev. **D 64**, 034004 (2001)
- Since a helion spin is carried by the neutron: $r_5^{hp} = r_5^{pp}/3$



$^3\text{He}^{\uparrow}$

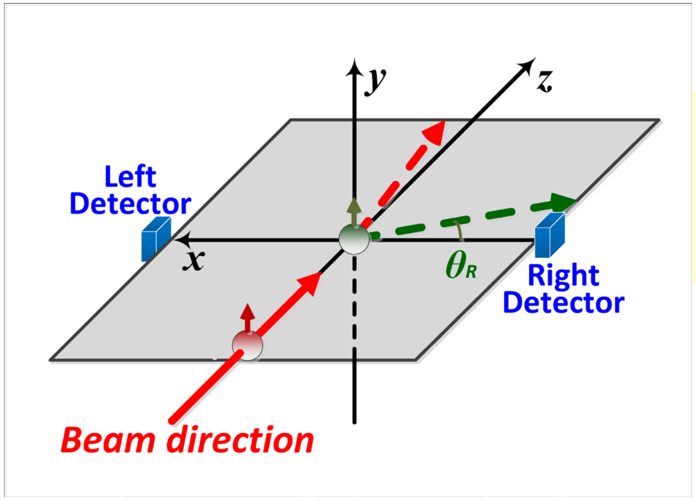
Some possible corrections to the estimate done should be considered

- The neutron polarization in a ^{3}He is about 88%: $r_5^{hp} \to 0.27 r_5^{pp}$
- The $p\ ^3$He scattering is given by pure isoscalar $(I = 0)$ exchange, i.e. $r_5^{pn} = r_5^{pp}$
  "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)

Precision measurement of the helion beam polarization can be done by HJET if the *pp* hadronic spin-flip amplitudes are known

$$P_{\text{beam}} = P_{\text{jet}} \frac{a_N^{\text{beam}}}{a_N^{\text{jet}}} \times \frac{\kappa_p - 2I_5^{pp} - 2R_5^{pp}\, T_R/T_c}{\kappa_h - 0.54 I_5^{pp} - 0.54 R_5^{pp}\, T_R/T_c}$$

The recoil proton kinematics



For an ion A beam, the jet proton recoil angle is

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

- Beam energy E_{beam} is given in GeV/nucleon units
- $\Delta = m_A^* - m_A$ (if inelastic scattering)

For the elastic scattering:

$(\theta_R^h - \theta_R^p)/\theta_R^p = -2m_p/3E_{\text{beam}} \approx 0.6\%$ (for 100 GeV beam)

(no much difference between helion and proton beams)

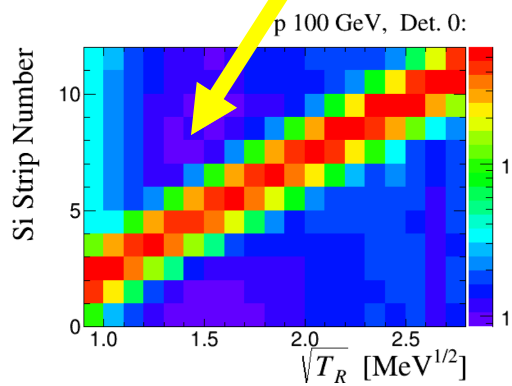
For the inelastic scattering

proton beam: $\Delta > \mathbf{135\ MeV}$ (pion production)

helion beam: $\Delta > \mathbf{5.5\ MeV}$ (the ^{3}He breakup)

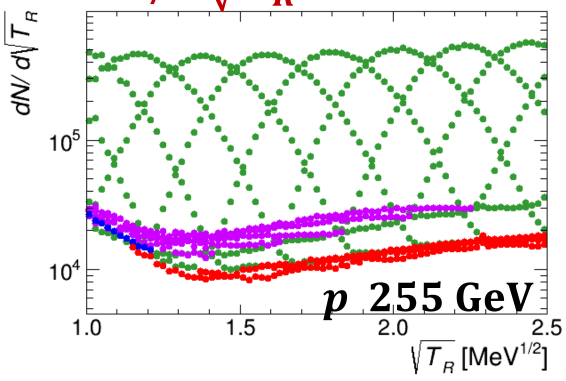
The $\Delta_{\min}(T_R E_{\text{beam}}) < \Delta < \Delta_{\max}(T_R E_{\text{beam}})$ range, for which inelastic events can isolated in the HJET detector is defined by the jet width ($\Delta_{\min}$) and the detector length along z-axis ($\Delta_{\max}$)

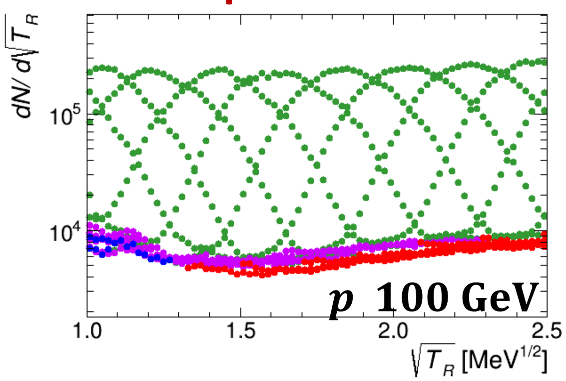
Possible inelastic data area



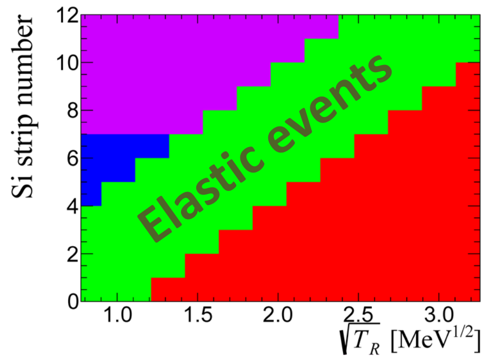
Isolation of the inelastic events at HJET (one detector)

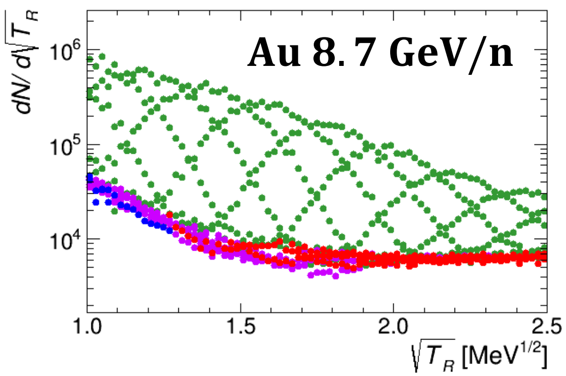
$dN/d\sqrt{T_R}$ distributions for all Si strips in a detector





Color legend





The result depends on the Δ/E_{beam} ratio

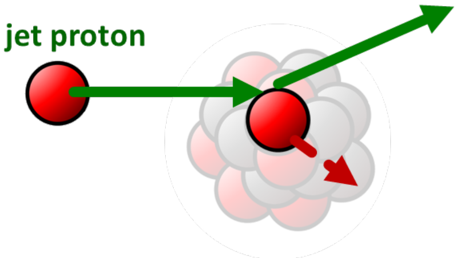
- $p \to \pi + X$ (255 GeV)
  Inelastic events are well isolated (~4%)
- $p \to \pi + X$ (100 GeV)
  Inelastic events are seen only in strip 12
- $\mathrm{Au} \to A_1 + A_2 + ..$ (8.7 GeV/n)
  No evidence of the breakup, even though the $\Delta > 10$ MeV events can be observed.
- Using 3.85 GeV/n Au beam, the breakup fraction was evaluated as $\sigma_{qel}/\sigma_{el} = 0.20 \pm 0.12\%$ ($1.7 < T_R < 4.4$ MeV and $4 < \Delta < 8$ MeV)

In the HJET measurements $\left(|t| \lesssim 0.01\ \mathrm{GeV}^2\right)$ with Au beam, elastic data contamination by the breakup events is very small and there is no evidence of the breakup events beyond the elastic peak.

Estimate of the ^{3}He *breakup fraction*

For incoherent proton-nucleus scattering, simple kinematical consideration gives:

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



p_x^* is the target nucleon transverse momentum in A
For an event detected at HJET, Δ is small and the breakup is strongly suppressed by the phase space).

For the deuteron beam, extrapolation to the full range in Δ gives:

$$\sigma_{qel}^{pd}/\sigma_{el}^{pd} = 5.1 \pm 1.4\% \quad [2.8 < T_R < 4.2 \text{ MeV}]$$

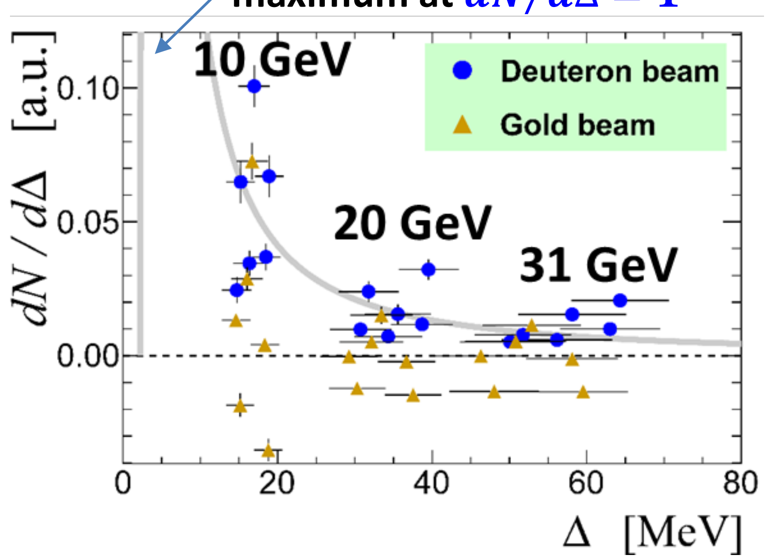
(statistical error only)

Recalculation for the 100 GeV helion beam:

$$\sigma_{qel}^{ph}/\sigma_{el}^{ph} = 2.4 \pm 0.4\% \quad [1 < T_R < 10 \text{ MeV}]$$

A simple model based on Eq. above was used to evaluate ^{3}He *breakup fraction* using 2016 HJET data acquired in *dAu* Runs

maximum at $dN/d\Delta = 1$



Obvious concerns about confidence of the estimate done:

- **The data analysis was based on a naive and unjustified model.**
- **Only small part of full $dN/d\Delta$ distribution was available for analysis.**
- **The result of the deuteron beam measurement was extrapolated to the ^{3}He beam.**

Breakup rate for ^{6}Li (based on old, 1966, measurement)

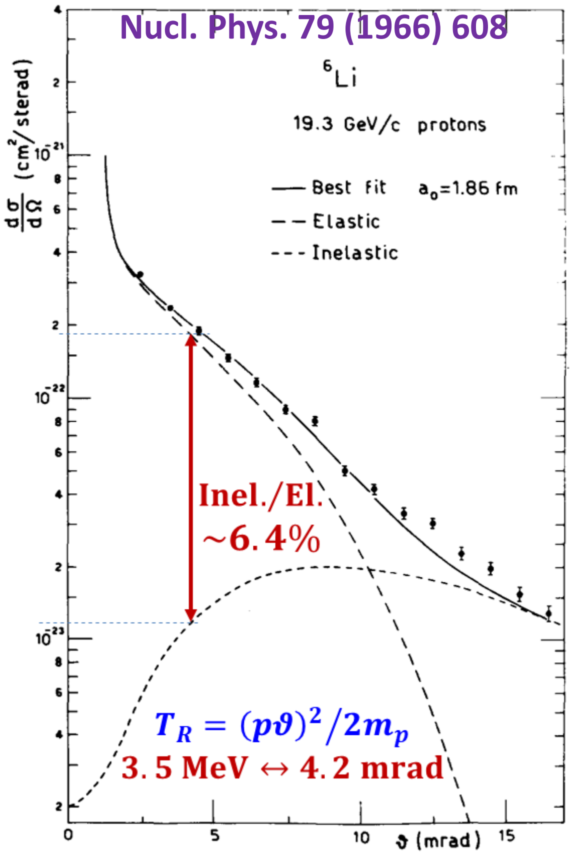


Fig. 1. The experimental data of ref. [4] on the scattering of 19.3 GeV/c protons by ^{6}Li are shown together with the result of the best fit. Elastic and inelastic contributions are shown separately.

Experimental results on elastic+breakup $d\sigma/dt$ for a 19.3 GeV/c proton beam scattering on ^{6}Li were fit by R.J Glauber and Matthiae, Nucl. Phys. B21 (1970) 135

For equivalent $T_R = 3.5$ MeV ($\vartheta = 4.2$ mrad):

$$\left.\frac{d\sigma}{dt}\right|_{\text{breakup}} / \left.\frac{d\sigma}{dt}\right|_{\text{elastic}} = 6.4\% \; (^6\text{Li})$$

Assuming the following breakup channels,

- ${}^6_3\text{Li} + 6.1\text{ MeV} \to {}^5_3\text{Li} + n,$
- ${}^6_3\text{Li} + 4.8\text{ MeV} \to {}^5_2\text{He} + p,$
- ${}^6_3\text{Li} + 1.6\text{ MeV} \to \alpha + d,$
- ${}^6_3\text{Li} + 17\text{ MeV} \to h + t,$

one can **extrapolate the HJET deuteron beam result**:

$$\left.\frac{d\sigma}{dt}\right|_{\text{breakup}} / \left.\frac{d\sigma}{dt}\right|_{\text{elastic}} = 7.0 \pm 1.7\%$$

!

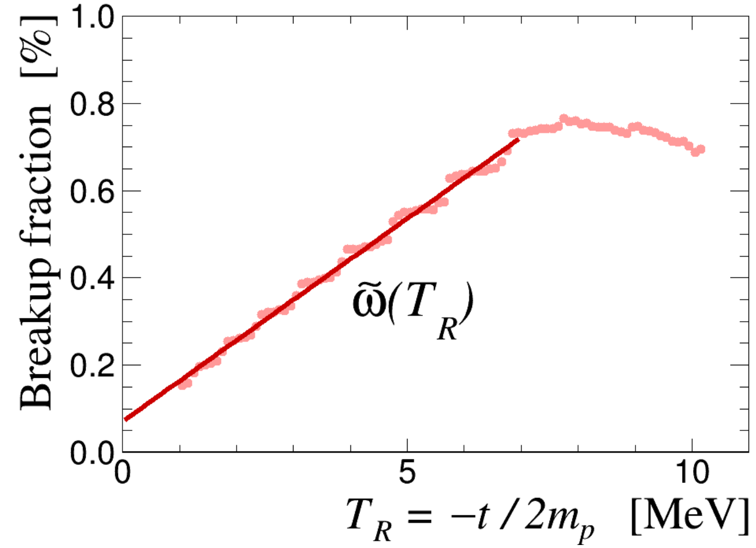
- **^{6}Li breakup rate extrapolated from the HJET deuteron measurements is excellent agreement with Glauber's analysis of p ^{6}Li scattering experiment.**
- **The consistency by order of magnitude could be interpreted as good agreement.**

Does the breakup affect the ^{3}He *beam polarization measurement*

For the $\phi_5^{\mathrm{em}}\phi_+^{had}$ interference, the breakup can be approximated by a correction to the hadronic non-flip amplitude $\phi_+^{had} \to \phi_+^{had} \times [1 + \tilde{\omega}(T_R)]$

$$P_{\mathrm{beam}} = P_{\mathrm{jet}} \frac{a_N^{\mathrm{beam}}}{a_N^{\mathrm{jet}}} \times \frac{\kappa_p \times [1 + \tilde{\omega}(T_R)] - 2I_5^{ph} - 2R_5^{ph}\, T_R/T_c}{\kappa_h \times [1 + \tilde{\omega}(T_R)] - 2I_5^{hp} - 2R_5^{hp}\, T_R/T_c}$$

Since $|r_5| = |R_5 + iI_5| \sim 0.02$ and $|\tilde{\omega}^{max}(T_R)| < 1\%$,
the breakup corrections **are canceled** in this ratio.



The related systematic uncertainty are very small

$\sigma_P^{\mathrm{breakup}}/P \lesssim 1.6|r_5|\,\tilde{\omega}^{max} \sim 0.03\%$

$\tilde{\omega}(T_R) \propto \sqrt{\sigma_{qel}^{ph}/\sigma_{el}^{ph}}$

The breakup related systematic errors remains negligible even if the breakup rate was underestimated by order of magnitude.

How to measure ^{3}He beam polarization in HJET

HJET performance in the helion beam is about the same as in the proton one.

^{3}He beam polarization can be measured for $T_R > 2\ \mathrm{MeV}$

(for $T_R > 0.5\ \mathrm{MeV}$ if the prompts will be suppressed)

$$P_{\mathrm{beam}}^{meas}(T_R) = P_{\mathrm{jet}}\,\frac{a_N^{\mathrm{beam}}}{a_N^{\mathrm{jet}}} \times \frac{\kappa_p - m_p^2/m_h E_{\mathrm{beam}} - 2I_5^{pp} - 2R_5^{pp}\,T_R/T_c}{\kappa_h - m_h/E_{\mathrm{beam}} - 0.54 I_5^{pp} - 0.54 R_5^{pp}\,T_R/T_c}$$

$$= P_{\mathrm{beam}} \times (1 + a\,T_R/T_c)$$

measured must be $a = 0$ QED corrections $T_c \approx 0.7\ \mathrm{MeV}$

Expected systematic uncertainties: $\sigma_P^{\mathrm{syst}}/P = 0.6\%_{\mathrm{meas}} \oplus 0.5\%_{r_5} \oplus 0.2\%_{\mathrm{theor}}$

Evaluated using real HJET data, are well justified

Should be verified

Summary

The presented analysis leads to an optimistic conclusion:

the HJET can be readily used to measure ^{3}He beam polarization at EIC with the required precision, $\boldsymbol{\sigma_P^{syst}/P \lesssim 1\%}$

However, to prove small systematic uncertainties, more solid studies might be needed:

- Extended theoretical analysis:
  - The relation between hp and pp hadronic spin-flip amplitudes $r_5^{pp} \to r_5^{hp}$ and $r_5^{pp} \to r_5^{ph}$
  - The hp breakup cross-section $d\sigma^{hp}/dtd\Delta$
- Experimental study:
  - a proton-proton $A_N^{pp}(t, E_{\text{beam}})$ for each ^3He beam energy E_{beam} used,
  - evaluation of the $d\sigma^{hp}/dtd\Delta$ using low energy, 5-10 GeV helion beam (~1 day run),
  - a possibility of the breakup vetoing by a forward detector
  - understanding the nature of the prompts
- Experimental technique:
  - more accurate study of the wave-form shape dependence on the recoil proton energy
  - HJET with no holding field magnet

Main Takeaway

The upgraded HJET is currently considered for the proton beam absolute polarization measurement at EIC.

The HJET ability to measure EIC's $^3\mathrm{He}$ beam polarization at EIC with the required precision $\boldsymbol{\sigma_P^{syst}/P \lesssim 1\%}$ depends mostly on how well small, the $^3\mathrm{He}$ beam related, systematic corrections to the measurements can be evaluated by the theory.

Thus,
the Polarized Atomic Hydrogen Gas Jet Target (HJET) is an ideal candidate to be a "Plan B" for the $^3\mathbf{He}$ beam absolute polarimetry at EIC

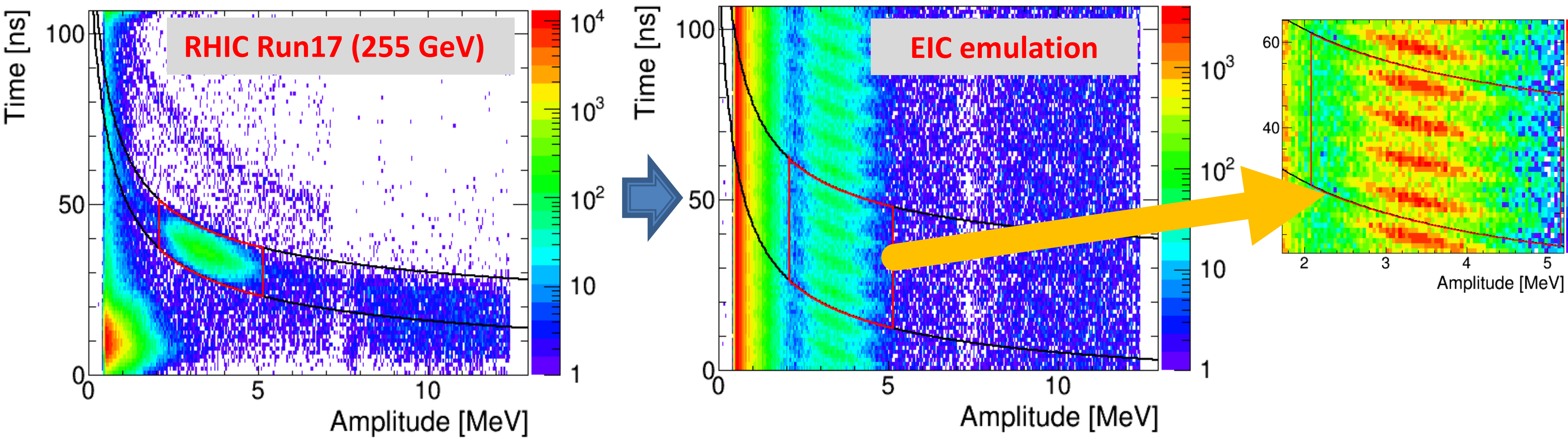
Backup

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):

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

$\boldsymbol{t' \Rightarrow t' - 2\tau/3\,,\ t',\ t' - 2\tau/3}$ [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**.

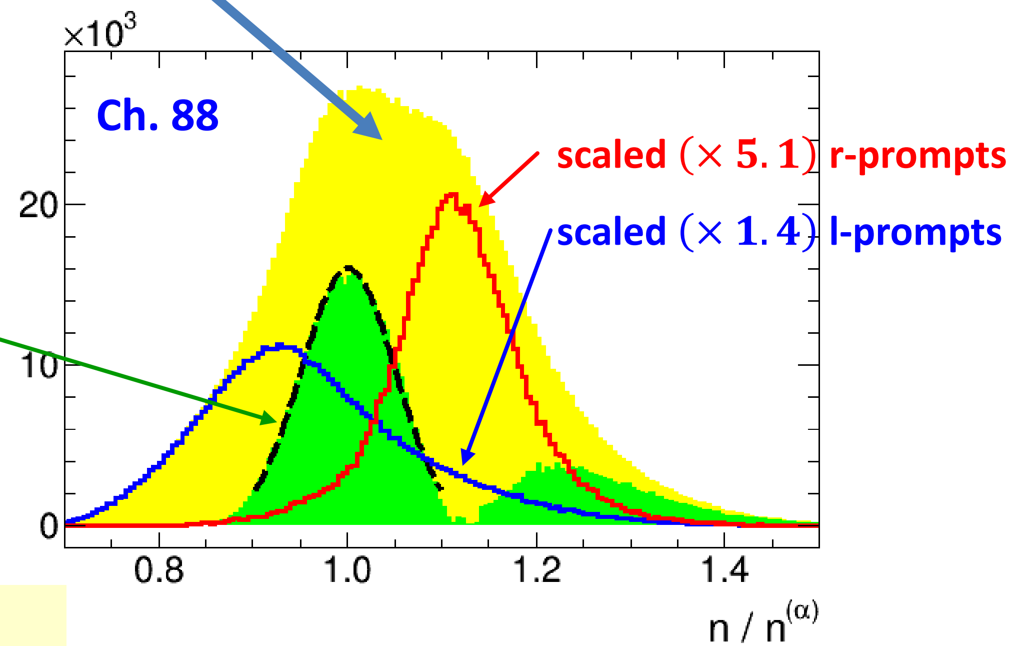
The emulation gives worse condition of the measurements than it is expected at EIC:

- 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.

Fills 25121-25153 (Au, *5.76* GeV/*n*)

Analysis of the prompts $n/n^{(\alpha)}$ distributions

- **The l-prompts and r-prompts distribution were scaled as much as possible (to avoid negative rates)**
- **The residual distribution peak is consistent with a stopped particle distribution**

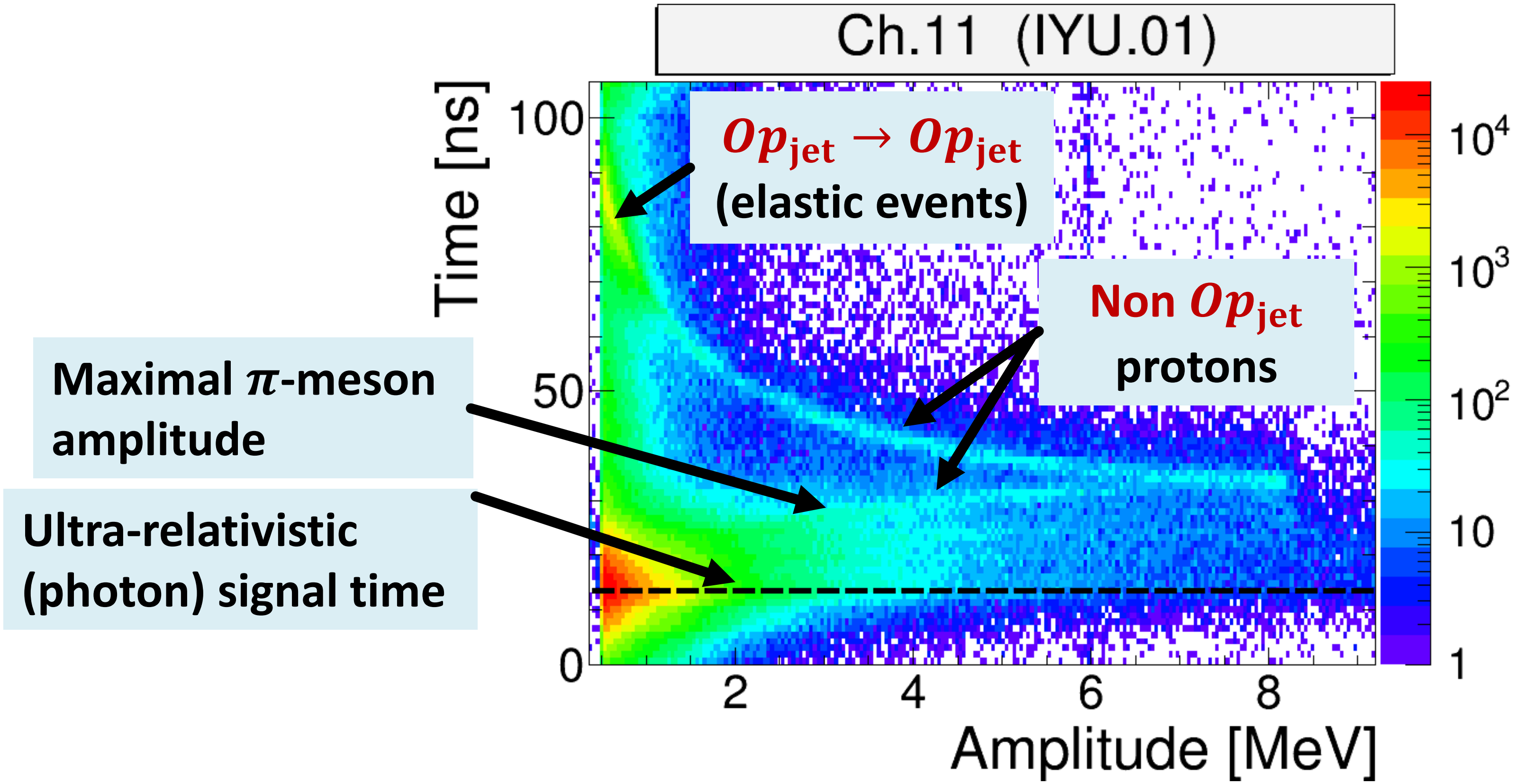


Event fractions:

- **l-prompts 33%** **(coincidences in Si strips of the same layer)**
- **r-prompts 36%** **(coincidences between the layers)**
- **residual 31% (24%+7%)**

The prompt data contains significant contribution of the stopped like events.

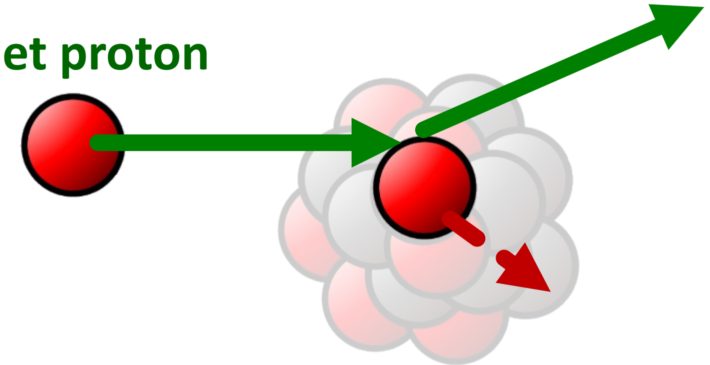
Time – amplitude of the prompts events



- The punch through protons are well identified by continuation of the stopped proton line.
- Protons and pions are not the dominant component of the prompt events
- Significant part of the prompt signals has measured time of flight consistent with the speed of light particle.

Why is Au *breakup 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 $\boldsymbol{\Delta < 50\ \mathrm{MeV} \ll M_A}$ **(breakup is strongly suppressed by phase space).**

If $f(p_x, \sigma)dp_x$ is the nucleon momentum distribution in a nucleus then, in HJET measurements,

$$dN(T_R, \Delta)/d\Delta \propto F(T_R, \Delta) \times \Phi(\Delta)$$

$$F(T_R, \Delta) = \mathrm{f}(\Delta - \Delta_0, \sigma_\Delta), \quad \Delta_0 = \left(1 - m_p/M_A\right)T_R, \quad \sigma_\Delta = \sigma\sqrt{2T_R/m_p}$$

For the $h + p \to (p + d)_h + p$ breakup, the phase space factor is equal to

$$\Phi(\Delta) = \frac{\sqrt{2m_p m_d}}{4\pi m_h} \times \sqrt{\frac{\Delta - \Delta_{\mathrm{thr}}^h}{m_h}}, \qquad \Delta_{\mathrm{thr}}^h = m_p + m_d - m_h = 5.5\ \mathrm{MeV}$$

The effective amplitude

$$\phi(t) \to \phi(t) + \int d\Delta\ \tilde{\phi}(t,\Delta)$$

($\phi(t)$ and $\tilde{\phi}(t,\Delta)$ do not interfere)

The effective breakup amplitude

$\tilde{\phi}(t,\Delta) = \phi(t) \times k(t,\Delta)$

$k(t,\Delta)$ is "the decay" amplitude

$$\left|\phi_+^{\mathrm{had}}\right|^2 \to \left|\phi_+^{\mathrm{had}}\right|^2 \times [1 + \omega(t)]$$

$$\omega(t) = \int d\Delta\ |k(t,\Delta)|^2 F(t,\Delta)\Phi(\Delta)$$

$$= \langle |k(t,\Delta)|^2 \rangle \omega_\Phi(t)$$

$$\mathrm{Im}\ \phi_5^{\mathrm{em}}\phi_+^{\mathrm{had}} \to \kappa \times [1 + \tilde{\omega}(t)]$$

$$\tilde{\omega}(t) = \int d\Delta\ \mathrm{Re}[\tilde{\kappa}/\kappa \times k(t,\Delta)]\ F(t,\Delta)\Phi(\Delta)$$

$$|\tilde{\omega}(t)| \le \sqrt{\omega(t)\omega_\Phi(t)}$$

The breakup corrections to A_N are the same for $p^\uparrow h$ and $h^\uparrow p$, if neglect r_5 !

(the uncorrelated corrections are of about $\sim r_5\tilde{\omega}$)

For the $A \to A_1 + A_2$ breakup,

$$\Phi(\Delta) = \frac{\sqrt{2m_1m_2}}{4\pi m_A} \times \sqrt{\frac{\Delta - \Delta_{\mathrm{thr}}^A}{m_A}} \propto m_A^{-1}$$ (or $\propto m_A^{-1/2}$ if $m_1 \approx m_2$)

A model to describe helion and/or deuteron breakup

$$\left.\frac{dN(T_R,\Delta)}{d\Delta}\right|_{\text{breakup}} = \left.\frac{dN(T_R,\Delta)}{d\Delta}\right|_{\text{elastic}} \times \left|k((T_R,\Delta))\right|^2 F(T_R,\Delta)\,\Phi(\Delta)$$

$k(T_R,\Delta)$ is the ratio of the breakup and elastic amplitudes

The model used is based on the following approach:

- $k(T_R,\Delta) = \text{const}$
- $F(T_R,\Delta)$ **is derived from one of the momentum distribution functions:** $f_G(p_x,\sigma),\ f_{BW}(p_x,\sigma),\ f_H(p_x,\sigma)$, **considering σ as an adjustable parameter.**

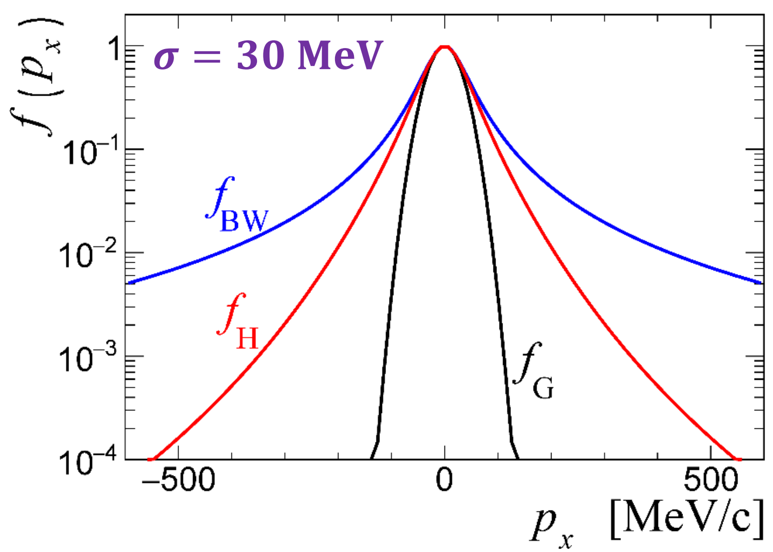
$f_G(p_x,\sigma) \propto \exp(-p_x^2/2\sigma^2)/\sqrt{2\pi}\sigma$

$f_{BW}(p_x,\sigma) \propto \pi^{-1}\sqrt{2}\sigma/(p_x^2+2\sigma^2)$

$f_H(p_x,\sigma = 30\text{ MeV})$ is expected to be a nucleon momentum distribution function for the deuteron.

All three functions have the same behavior around $p_x = 0$:

$$f(p_x,\sigma) = f(p_x,\sigma)\times[1-p_x^2/2\sigma^2]$$



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- Experimental technique:
  - more accurate study of the wave-form shape dependence on the recoil proton energy
  - HJET with no holding field magnet

An improved/upgraded (if needed) HJET is considered for the proton beam polarimetry at EIC. For such a polarimeter, a feasibility to measure $^3\mathrm{He}$ beam polarization at EIC with the required precision is mostly defined by a theoretical possibility to adequately evaluate small systematic corrections in the measurements.

Therefore, **HJET can be considered as ideal "Plan B" for the ^3He beam polarimetry at EIC**