eRHIC polarimetry Meeting
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Kinematics constraints on the eRHIC polarized ^{3}He *target design.*

A.A. Poblaguev
Brookhaven National Laboratory

BROOKHAVEN NATIONAL LABORATORY

Missing Mass

$$M_X^2 = \left(p_{\mathrm{beam}} + p_{\mathrm{target}} - p_{\mathrm{recoil}}\right)^2$$

$$M_X^2 = M^2 - 2(E+m)T_R + 2\sqrt{E^2 - M^2}\sqrt{2mT_R + T_R^2}\,\sin\theta_R$$

For elastic pp scattering:

$$\tan\theta_R = \sqrt{\frac{T_R}{2m_p}}\sqrt{\frac{E_p + m_p}{E_p - m_p - T_R}}$$

For inelastic scattering $p + p \to (p + \pi + \ \dots) + p$

$$M_X = M + \Delta, \qquad \Delta \geq m_\pi$$

$$\sin\theta_R \to \sin\theta_R \times \left[1 + \frac{m_p\left(\Delta + \Delta^2/2m_p\right)}{\left(E_p + m_p\right)T_R}\right]$$

Kinematics dependence on the Beam + Target

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

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

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

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

$$E_p = E_{\text{beam}} \times \frac{Am_p}{M_A} \approx E_{\text{beam}}$$

$$\Delta^* = \Delta \times (1 + \Delta/2m_{\text{beam}})$$

$\mathbf{E}_{\text{beam}}$ is given in GeV/nucleon units

E_p is the jet proton energy in the beam frame

Kinetic Energy and TOF *of the recoil particles*

presented at SPIN16

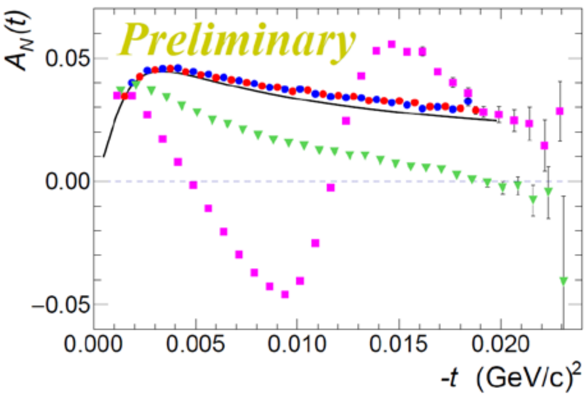


FIG. 13. Preliminary results for $p^{\uparrow}p$ (●) and ● for blue and yellow beams, respectively), $p^{\uparrow}$Al (▼), and $p^{\uparrow}$Au (■) analyzing powers measured with 100 GeV/n beams in RHIC Run15.

For the CNI recoil target polarimetry, the most attractive are momentum transfers of about

$$-t = \text{few} \times 10^{-3}\ \text{GeV}^2$$

$$T_R = \frac{-t}{2m_R} = 0.5\ \text{MeV} \times \frac{-t}{0.001\ \text{GeV}^2} \times \frac{m_p}{m_R}$$

$$\text{TOF} = \frac{m_R}{\sqrt{-t}}\frac{L}{c} = 0.9\ \text{ns} \times \frac{L}{1\ \text{cm}} \times \sqrt{\frac{0.001\ GeV^2}{-t}} \times \frac{m_R}{m_p}$$

A clone of the pCarbon with Au ($m_R/m_p = 197$) wire or Xe ($m_R/m_p \sim 131$) jet targets has no perspectives.

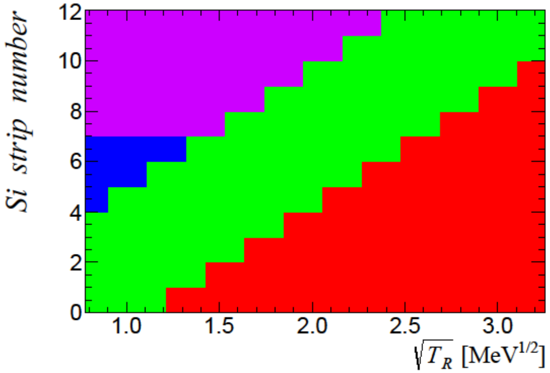
Alternative usage of the Gold wire or Xenon jet targets in

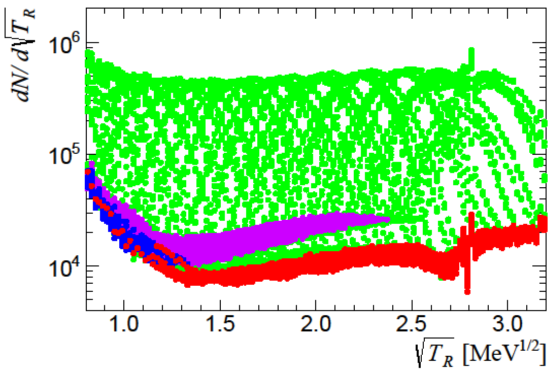
- measurement at non-CNI large $|t|$ (lower cross-section, no suppression of inelastic scattering, unknown analyzing power),
- measurement of the beam scattering asymmetry (different experimental technique)

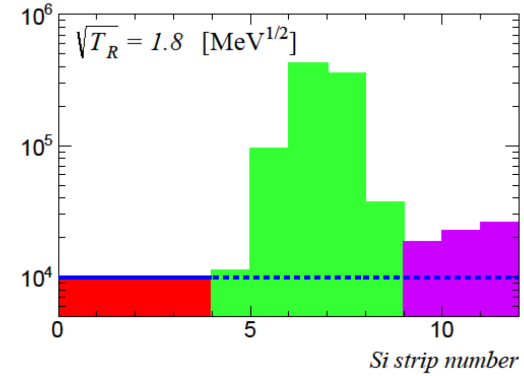
are not considered here.

Inelastic scattering

Inelastic event isolation for 255 GeV proton beam:



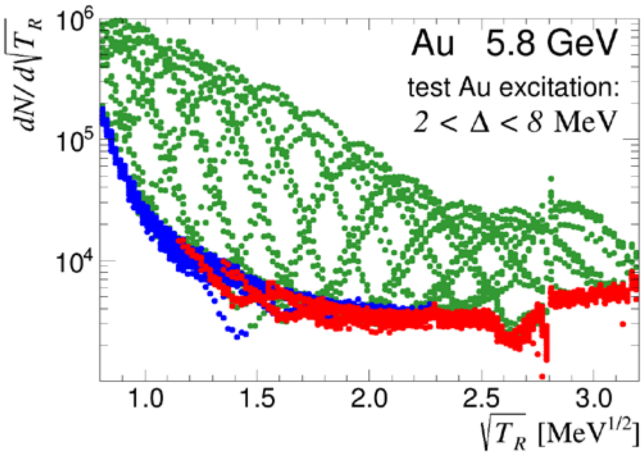


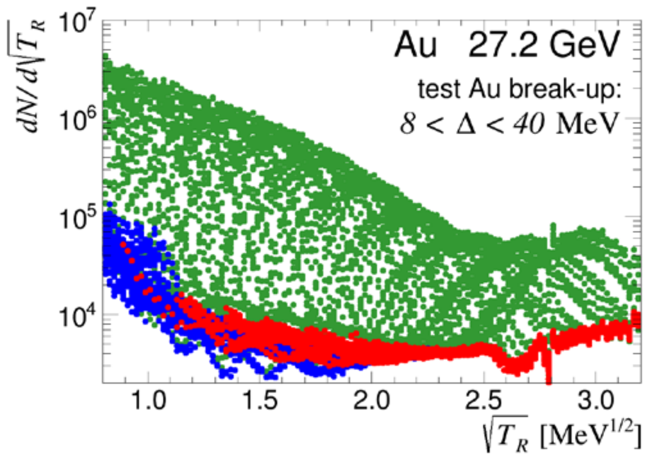


Evaluation of the inelastic rate (relative to elastic peak) for the Gold beams:

Au excitation: ~ 0.002
Au break-up < 0.001

For the $2 < T_R < 6$ MeV range, it was evaluated $\langle\Delta\rangle \sim 0.7$ MeV, but the method is not proved yet.





Inelastic background in gold beam scattering on the jet proton **is almost not seen!**

Why inelastic scattering of the gold beam is not observed at HJET

Incoherent proton-nucleus scattering

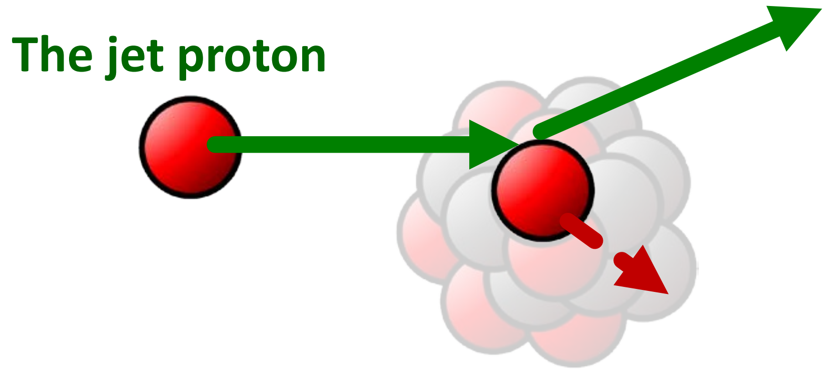
If recoil proton with energy T_R is detected in the beam ion scattering at HJET proton, then considering this event as (elastic) proton scattering on mass m^*,

$$m_p \leq m^* \leq M_A,$$

in the ion, one finds:

$$\left[1 + \frac{m_p^2/m^*}{E_p}\right] = \left[1 + \frac{m_p^2/M_A}{E_p} + \frac{m_p \Delta}{E_p T_R}\right]$$

$$\Delta = \left(\frac{m_p}{m^*} - \frac{m_p}{M_A}\right) T_R \leq \left(1 - \frac{m_p}{M_A}\right) T_R < \boldsymbol{T_R}$$



- For the beam nucleus scattering on the jet, the missing mass cannot exceed the detected recoil proton energy, $\Delta \leq \boldsymbol{(1 - m_p/M_A) T_R}$.
- For the $^3\mathrm{He}$ beam, $\Delta \leq \boldsymbol{2T_R/3}$
- Pion or heavier hadron production in the collision were not considered.
- Nucleon motion in the nucleus was not considered. It may alter the conclusion.

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

Helion $\left({}_{2}^{3}\mathrm{He}\right)$ ***beam***

$$\boldsymbol{m_h = m_p + m_d + \Delta_h\,,\quad \Delta_h = 5.5\ \mathrm{MeV}}$$

If in the helion beam scattering at the jet, the recoil proton energy is $\boldsymbol{T_R < 3\Delta_h/2 = 8.2\ \mathrm{MeV}}$ (this is almost full energy range available in the measurement) then the scattering is elastic!

For designing the helion jet polarimeter, it is critically important to verify that scattering is elastic. For that, a dedicated measurement at RHIC can be used:

- Fill RHIC with (unpolarized) $^{3}\mathrm{He}$ beam
  - **single beam** (to reduce background),
  - **10 GeV/n** (to have the same $\Delta_{\mathrm{min}}/E_{\mathrm{beam}}$ ratio as for 255 GeV inelastic scattering
  - Few days of running.
- **The magnetic field OFF** at HJET.

!

How well the inelastic

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

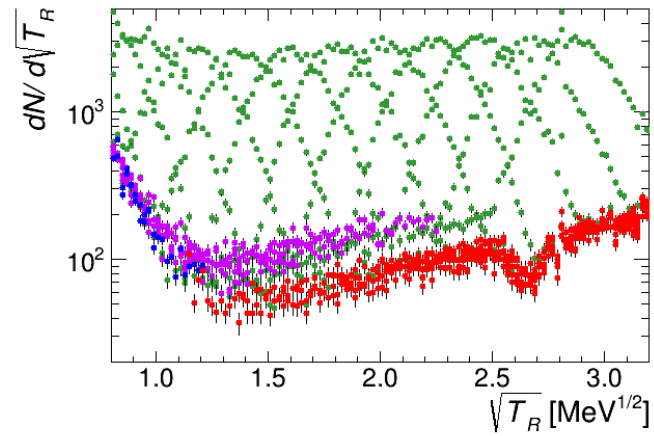
background rate can be evaluated ?

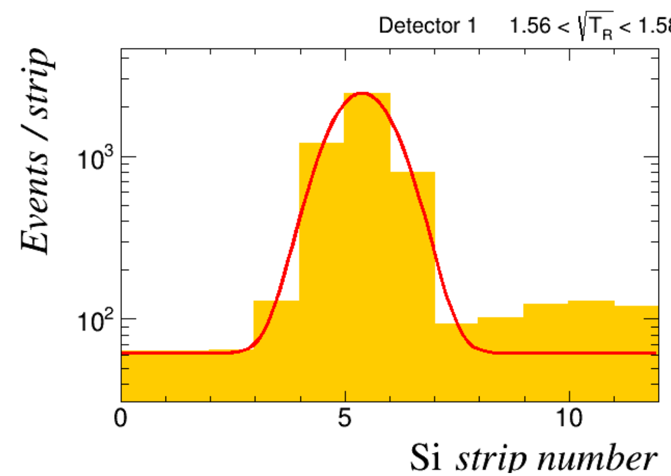
$p + p \rightarrow (p + \pi + \ ...) + p$

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

^{3}He *analyzing power in* $h^{\uparrow}p$ *and* $h^{\uparrow}h$ *elastic scattering*

Neglecting ρ, δ_C, and r_5, the analyzing power can be well approximated by:

$$A_N = \frac{\kappa\sqrt{-t_c}}{m_p} \times \frac{\sqrt{t_c/t}}{(t_c/t)^2+1}$$

where $\kappa = \mu/Z - m_p/m$, $t_c = -8\pi\alpha Z Z'/\sigma_{\text{tot}}$

- A_N has maximum of $A_N^{\max} = \left(3^{3/4}/4\right) \times \kappa\sqrt{-t_c}/m_p$ at $t = \sqrt{3}t_c$
- For elastic $p^{\uparrow}p$ (100 GeV): $\kappa^p = 1.793$, $t_c^{pp} = -1.86 \times 10^{-3}$ GeV^2
- For elastic $h^{\uparrow}p$ and $h^{\uparrow}h$: $\kappa^h/\kappa^p = -0.78$, $t_c^{hp}/t_c^{pp} \sim 0.74$, $t_c^{hh}/t_c^{pp} \sim 0.55$,

Nuclear-nuclear total cross sections:

Ignoring absorption:

$\sigma_{\text{tot}}^{pA}/\sigma_{\text{tot}}^{pp} = A$, $\sigma_{\text{tot}}^{AA}/\sigma_{\text{tot}}^{pp} = A^2$

The absorptions for large A,

$\sigma_{\text{tot}}^{pA}/\sigma_{\text{tot}}^{pp} = A^{2/3}$, $\sigma_{\text{tot}}^{AA}/\sigma_{\text{tot}}^{pp} = A^{4/3}$

For small A (d, He3):

$\sigma_{\text{tot}}^{pp} = 38.4$, $\sigma_{\text{tot}}^{pn} = 38.9$, $\sigma_{\text{tot}}^{pd} = 73.2$

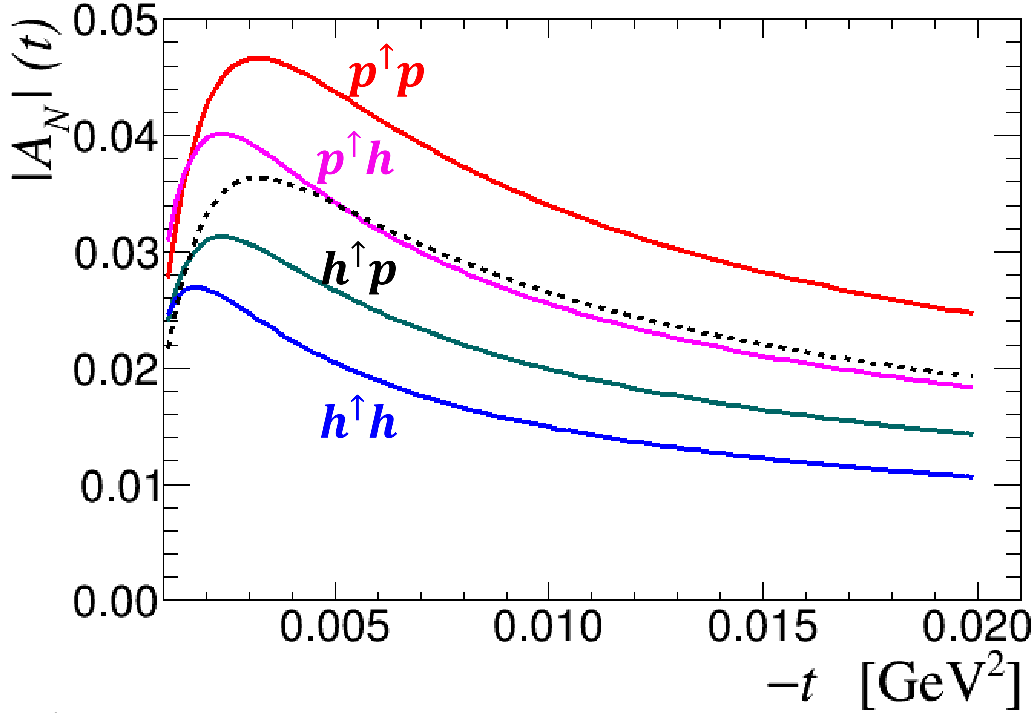
$\Rightarrow$ $f = \sigma_{\text{tot}}^{pd}/\left(\sigma_{\text{tot}}^{pp} + \sigma_{\text{tot}}^{pp}\right) \approx 0.95$

$\boldsymbol{\sigma_{\text{tot}}^{ph}/\sigma_{\text{tot}}^{pp} = f^2 A_h \approx 2.7,}$

$\boldsymbol{\sigma_{\text{tot}}^{hh}/\sigma_{\text{tot}}^{pp} = f^4 A_h^2 \approx 7.2}$

For helion:

$\boldsymbol{f^2 A_h / A_h^{2/3} \approx 1.3}$



^{3}He *analyzing power in* $h^\uparrow p$ *and* $h^\uparrow h$ *elastic scattering*

Extrapolating the theory developed for elastic pp scattering to polarized helion-proton scattering, one expects:

$$\boldsymbol{A_N(t) = A_N^{\mathrm{QED}}(t) \times \alpha_5 \times (1 + \beta_5\, t/t_c)}$$

- $\boldsymbol{A_N^{QED}}$ is analyzing power due to interference of the electromagnetic spin-flip and hadronic non-flip amplitudes. It supposed to be known from QED

  if σ_{tot}^{hp}, ρ^{hp}, B^{hp}, and δ_C^{hp} are already determined.
- $\boldsymbol{\alpha_5}$ and $\boldsymbol{\beta_5}$ are constants depending on the hadronic spin flip amplitude r_5:
  $\alpha_5 \approx 1 - 2\,\mathrm{Im}\,r_5,\ \beta_5 \approx -2\,Re\,r_5$
- We do not need to know the helion beam polarization at eRHIC to determine $Re\,r_5$

Can theory predict $\boldsymbol{\mathrm{Im}\,r_5}$ (with sufficient accuracy) for $\boldsymbol{h^\uparrow p}$ if the following is known:

✓ $\boldsymbol{p^\uparrow p}$:	$Re\,r_5$	$\mathrm{Im}\,r_5$	**Measured at HJET**
✓ $\boldsymbol{p^\uparrow h}$:	$Re\,r_5$	$\mathrm{Im}\,r_5$	**To be measured at HJET with helion beam**
✓ $\boldsymbol{h^\uparrow p}$:	$Re\,r_5$		**To be measured at HJET with polarized helion beam**

!

If Yes, the absolute average polarization of the helium-3 beam at eRHIC can be measured using only Hydrogen Jet.

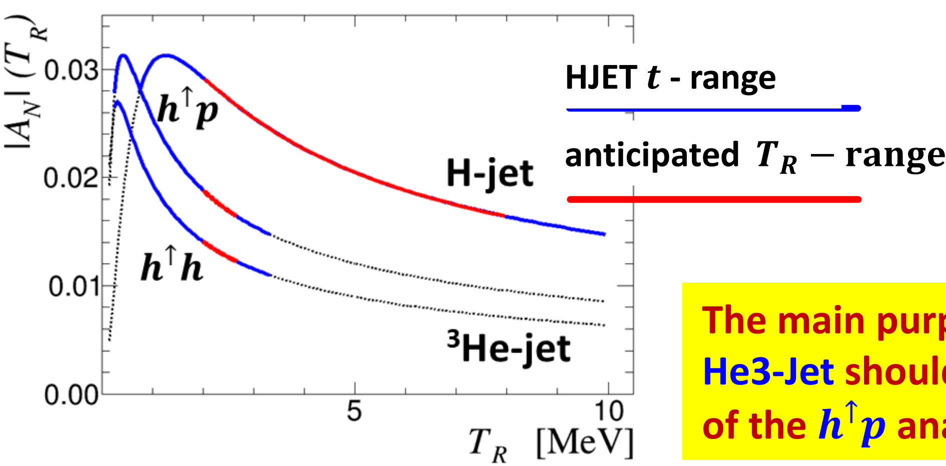
The polarized He3 target

To begin with, I will consider He3 Jet assuming
- HJET recoil spectrometer geometry,
- RHIC bunch spacing,
- and disregarding that He3 is very rare and expensive.

The total global market is measured in mere kilos per year – selling for thousands of dollars per litre.

Anticipated recoil energy cuts:
- Detector z-size should not be reduced to keep background subtraction
- TOF => $T_R > 2\ \mathrm{MeV}$ $(\mathbf{He3})$
- Beam He3 breakup => $T_R < 8\ \mathrm{MeV}$ $(\mathbf{H})$
  $T_R < 2.7\ \mathrm{MeV}$ $(\mathbf{He3})$
- "Prompts" => $T_R > 2\ \mathrm{MeV}$ $(\mathbf{H\ \&\ He3})$

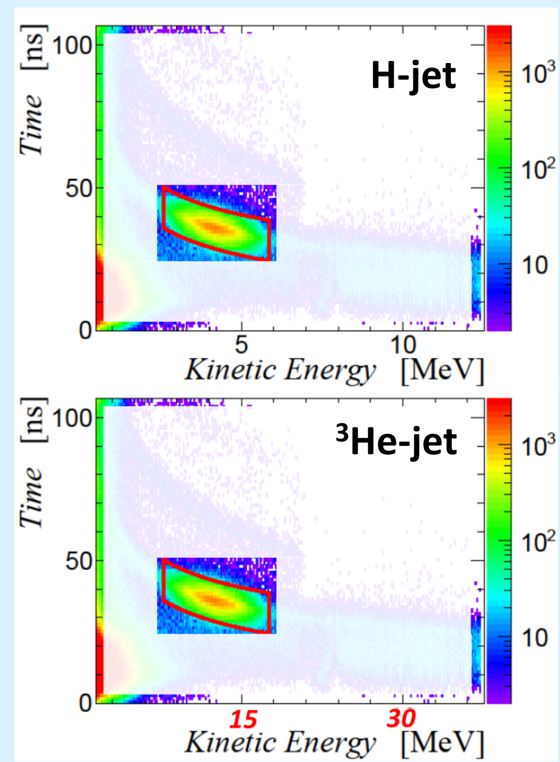
Real cuts may be better, but it is not proved.



The main purpose of the He3-Jet should be calibration of the $h^\uparrow p$ analyzing power

$$(z_R - z_{\mathrm{jet}}) \times \mathbf{TOF} = L^2/c$$

For a Si strip, the elastic He3 TOF will be as for proton, but the energy will be factor 3 scaled.



Optimization of the He3 *detector thickness*

Stopping energy (MeV) in Si

	$500\ \mu m$	$100\ \mu m$	$35\ \mu m$
π	3.5	1.4	0.8
p	8.1	3.1	1.6
d	9.3	3.6	1.8
h	30.6	11.8	**6.1**
α	32.4	12.9	**6.4**

- Recoil He3 can be separated from the background pions, protons, deuterons (including prompts) if thin, $35\ \mu\mathrm{m}$, Si detectors can be used.
- This will not affect α-calibradtion (Gd and Am)

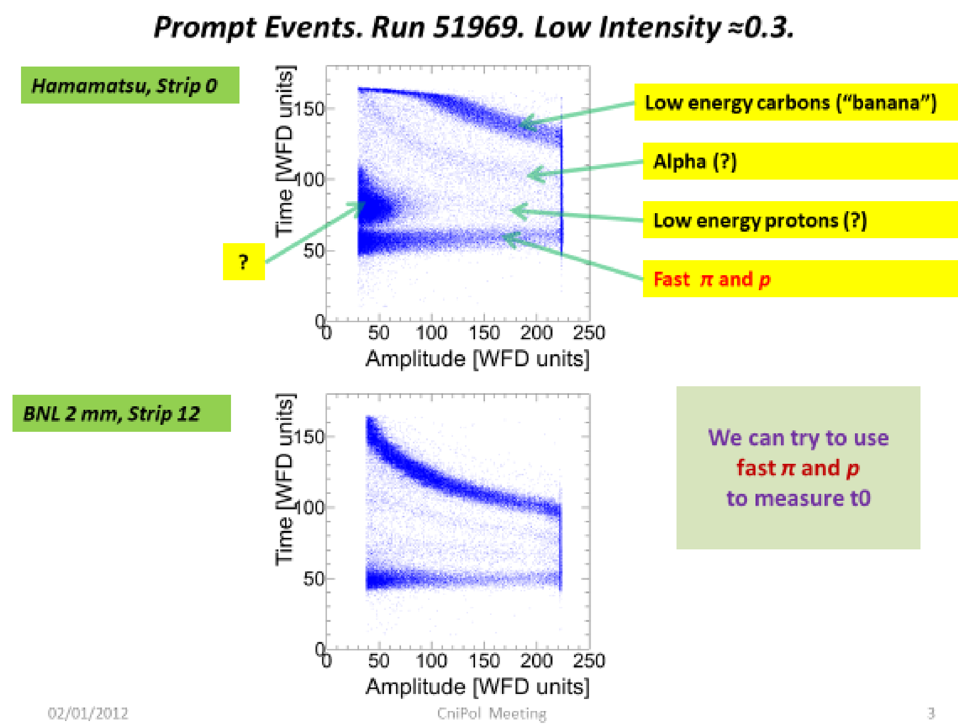
- In such an optimization we should keep in mind:
    - noise in the detector
    - punch through helions (double layer detectors?)

Are such measurements really background free?

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?**

!

Summary

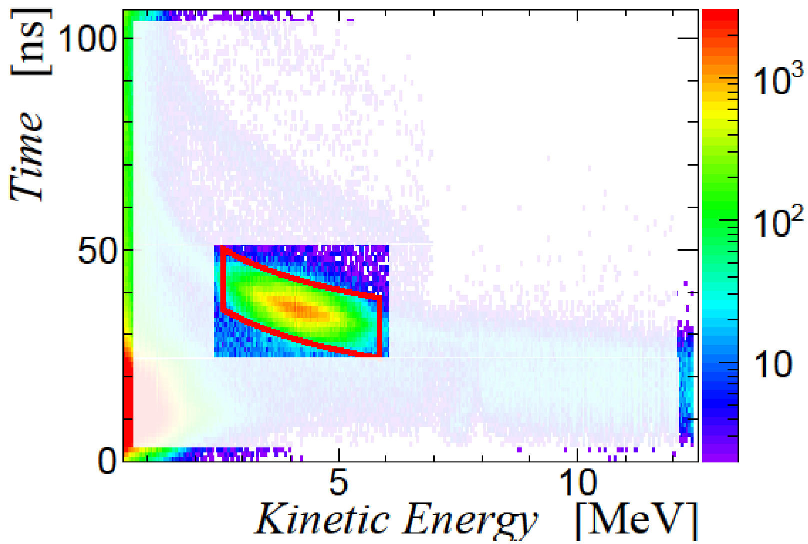
- For the He3 beam, **I guess**, only elastic recoil protons can be detected in HJET. (Strong suppression of the beam He3 breakup).
- **I think**, that HJET should be a primary polarimeter to measure absolute polarization of the He3 beam in elastic $h^{\uparrow}_{\text{beam}} p_{\text{jet}}$ scattering
  - Very reliable and reproducable performance during many years at RHIC
  - Low statistical errors (with unpolarized HJET)
  - Well controlled and very low (< 1%) systematic errors
  - To normalized analyzing power, the following can be tried
    - Theory, using on the $p^{\uparrow}_{\text{beam}}\ p^{\uparrow}_{\text{jet}}$ measurements
    - He3 jet using elastic $p^{\uparrow}_{\text{beam}}\ h^{\uparrow}_{\text{jet}}$ (before He3 Run) or $h^{\uparrow}_{\text{beam}}\ h^{\uparrow}_{\text{jet}}$ (during He3 run) scattering
- Polarized He3 target is needed even if HJET can be calibrated using theory. Significant optimization of the detectors (geometry, Si thickness will be needed.

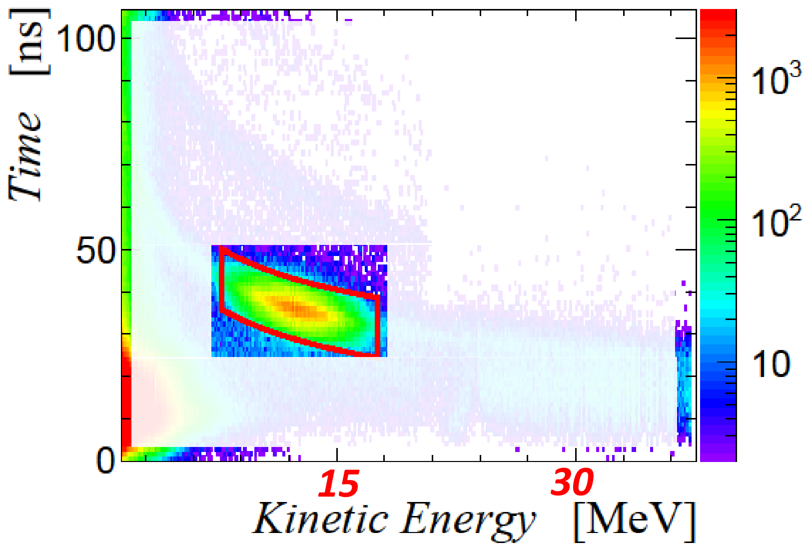
Answers on the following questions are critically important for a conceptual design of the absolute He3 polarimeter:

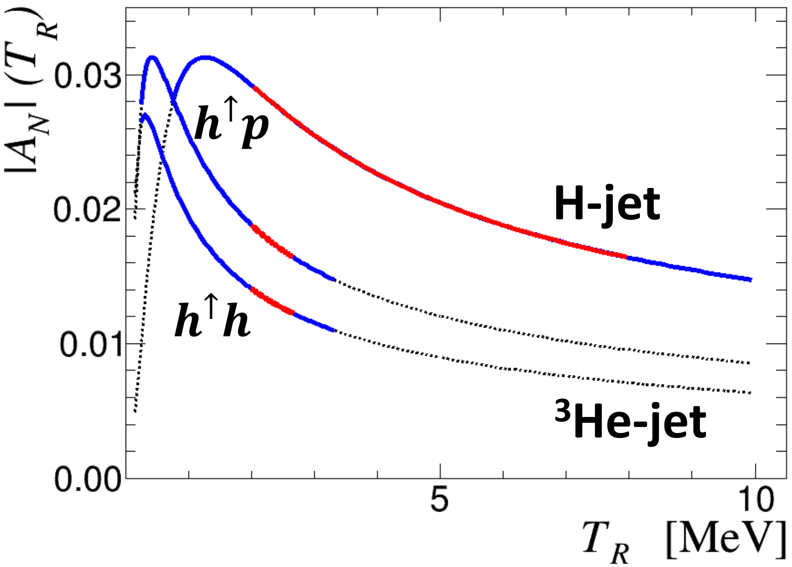
- Is inelastic (beam He3 breakup) scattering is strongly suppressed in the jet measurements.
- How intense are recoil proton and deuteron backgrounds due to target He3 breakup.
- How well theory can predict analyzing power for elastic $h^{\uparrow}p$ scattering at 100 GeV

The answers on first two questions can be found empirically at RHIC.

Backup


Time [ns]
100
50
0
5
10
Kinetic Energy [MeV]
10^3
10^2
10


Time [ns]
100
50
0
15
30
Kinetic Energy [MeV]
10^3
10^2
10


$|A_N|\ (T_R)$
0.03
0.02
0.01
0.00
5
10
T_R [MeV]
$h^{\uparrow}p$
H-jet
$h^{\uparrow}h$
^{3}He-jet