Polarimetry at EIC

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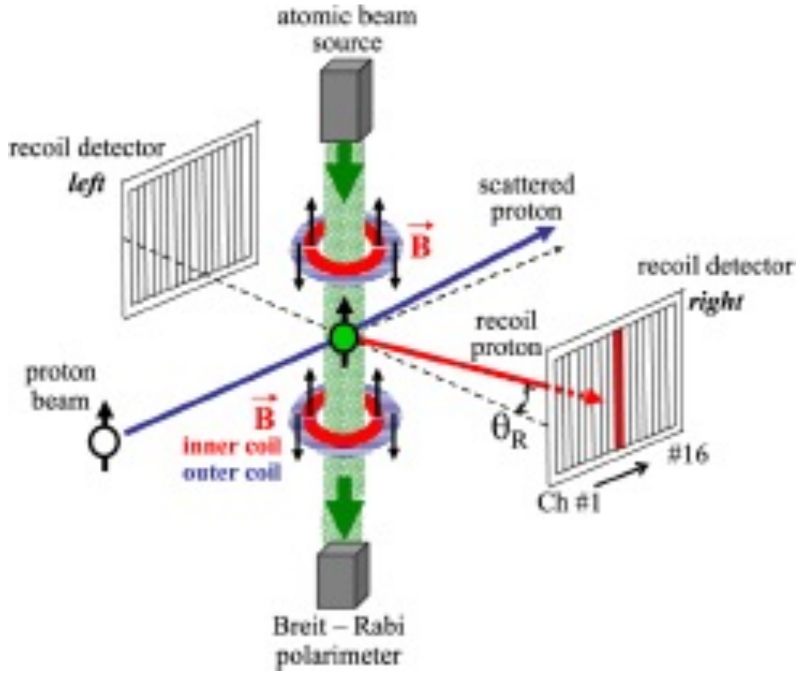

CFNS Summer School on the Physics of the Electron Ion Collider

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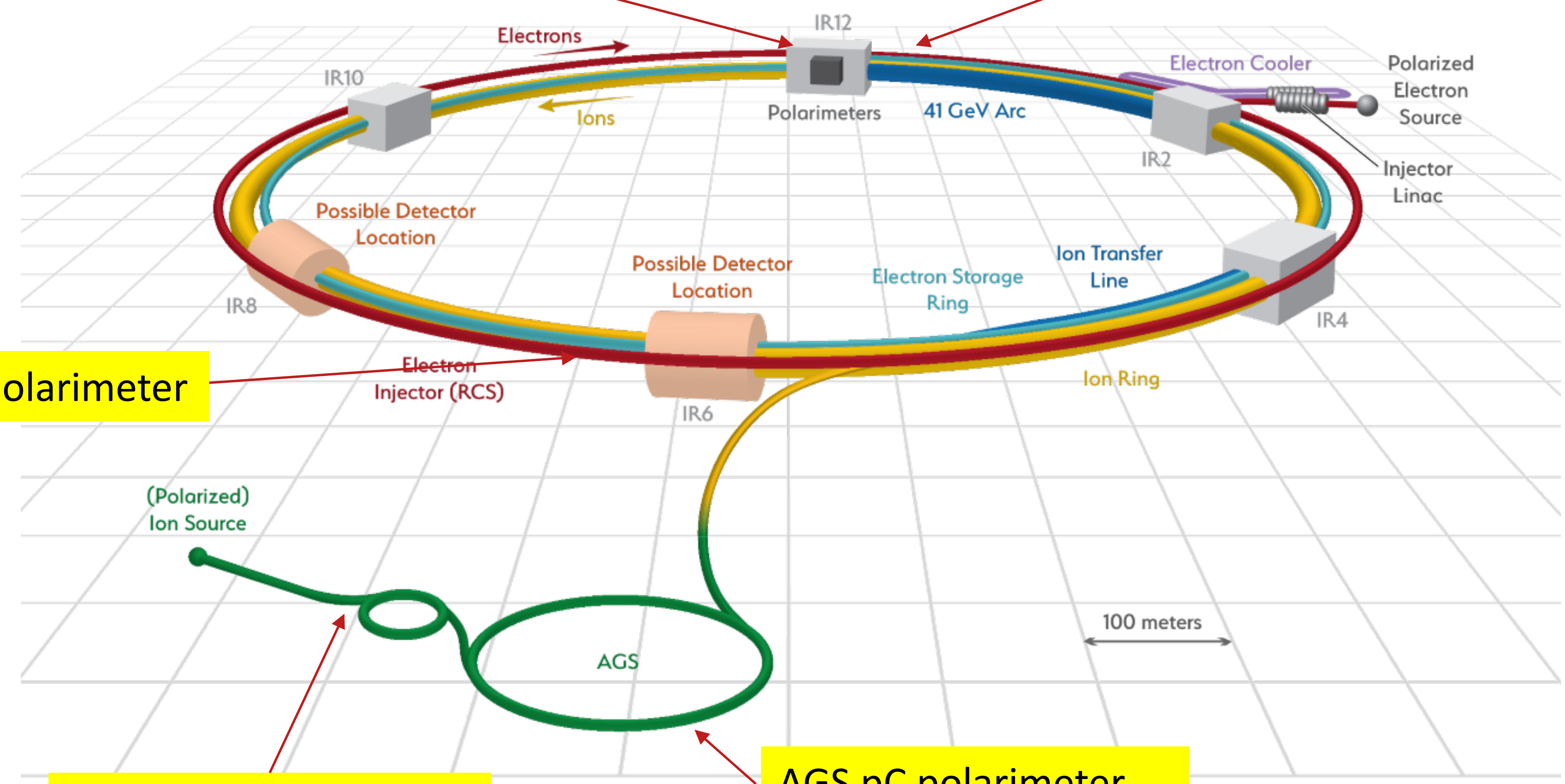
Hadron Polarimetry at EIC

Thanks to Bill Schmidke (BNL) for much of this material

Hadron Polarimetry for EIC

- New set of polarimeters needed for electrons at EIC
- EIC will make use of existing set of polarimeters that were used at RHIC for protons
  - 200 MeV polarimeter just after polarized source
  - p-Carbon polarimeter in AGS
  - Hydrogen Jet polarimeter for absolute measurement in ring (IP12)
  - p-Carbon polarimeter for fast, relative measurements in ring (IP12)
  - Additional p-Carbon polarimeter near experiment IP
  - Improvements for polarimeters in ring needed/planned
  - Extend existing polarimeters for use with light ions → ^{3}He (D)
- Requirements similar to electron beam
  - Bunch-by-bunch polarization
  - Rapid measurements
  - Ability to measure polarization profiles (longitudinal and transverse)

Hadron polarimeters at EIC



Hydrogen jet polarimeter

pC polarimeter

Local pC polarimeter

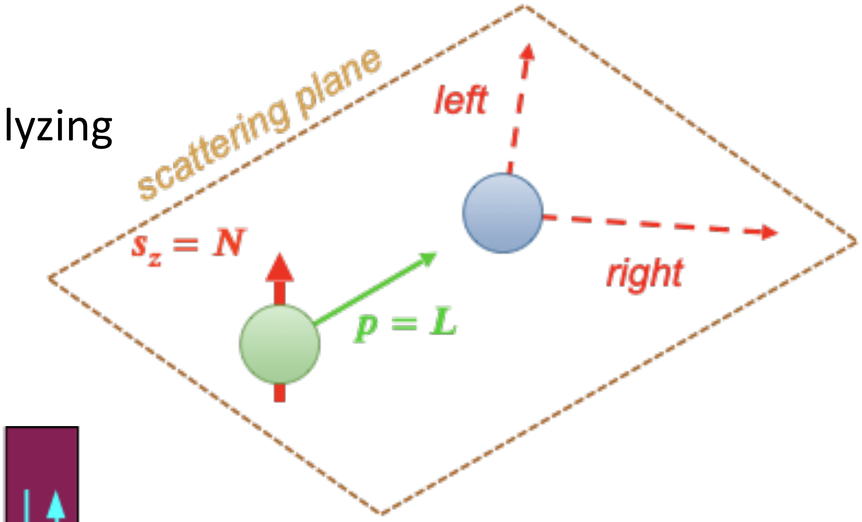
200 MeV polarimeter

AGS pC polarimeter

Measurement of Absolute Polarization

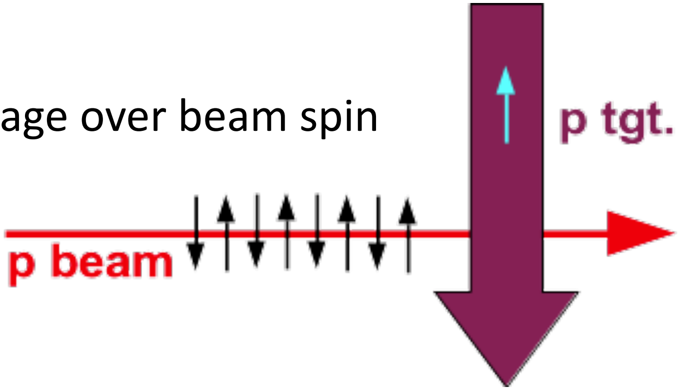
Electron polarimetry benefits from known QED processes (Compton, Møller scattering)
→ No equivalent processes for hadrons to measure absolute polarization → analyzing power a priori unknown

Use of polarized target with polarized beam bypasses need to determine analyzing power from first principles



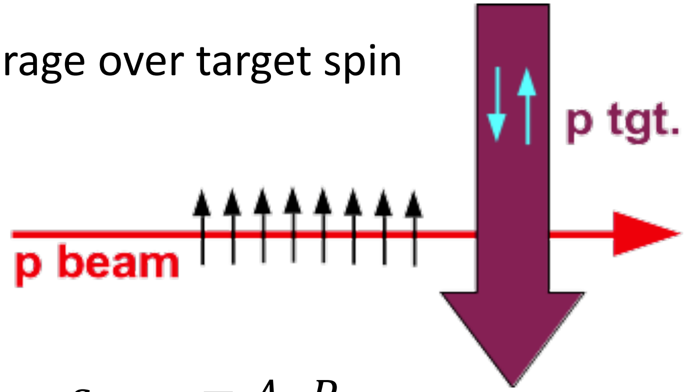
$$\epsilon = \frac{N_R - N_L}{N_R + N_L} = A_N P$$

Average over beam spin



$$\varepsilon_{target} = A_N P_{target}$$

Average over target spin



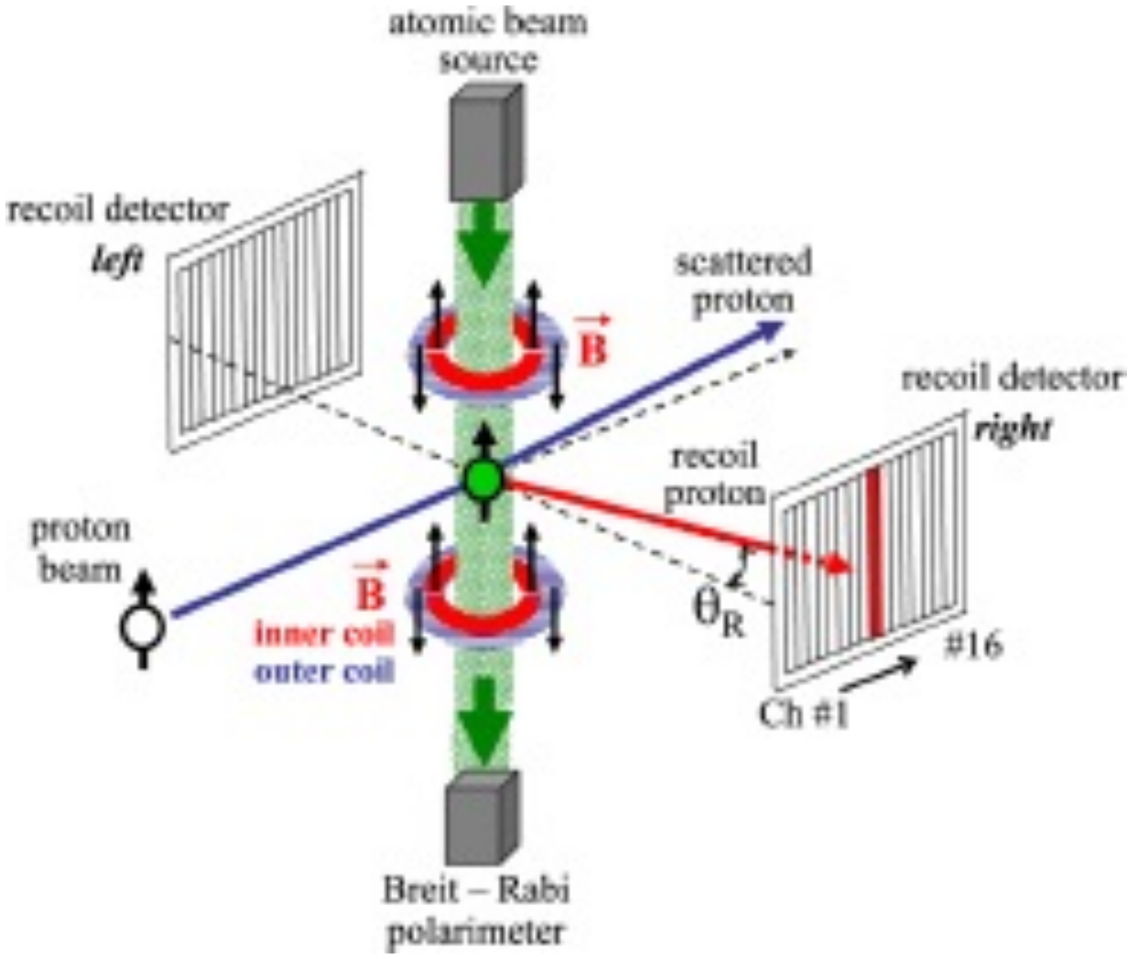
$$\varepsilon_{beam} = A_N P_{beam}$$

→ $$P_{beam} = \frac{\varepsilon_{beam}}{\varepsilon_{target}} P_{target}$$

Hydrogen-Jet Polarimeter

H-Jet Polarimeter installed at IP12

→ Uses of elastic p-p scattering in the Coulomb-nuclear interference (CNI) region
→ Polarized atomic H source, $1.2 \cdot 10^{12}$ atoms/cm2
→ Target polarization measured w/ Breit-Rabi polarimeter, $P_{target} \approx 96\%$
→ Silicon strip detectors, 12 strips 3.75 mm pitch
→ H-Jet has achieved high precision at RHIC: $(dP/P)_{syst}=0.6\%$
→ Measurements time consuming: $(dP/P)_{stat} \sim 2\%$ for 8 hour period



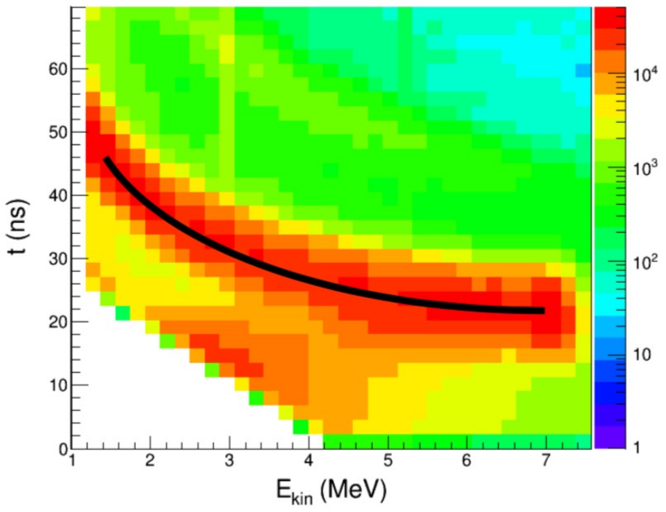
Hydrogen-Jet Polarimeter

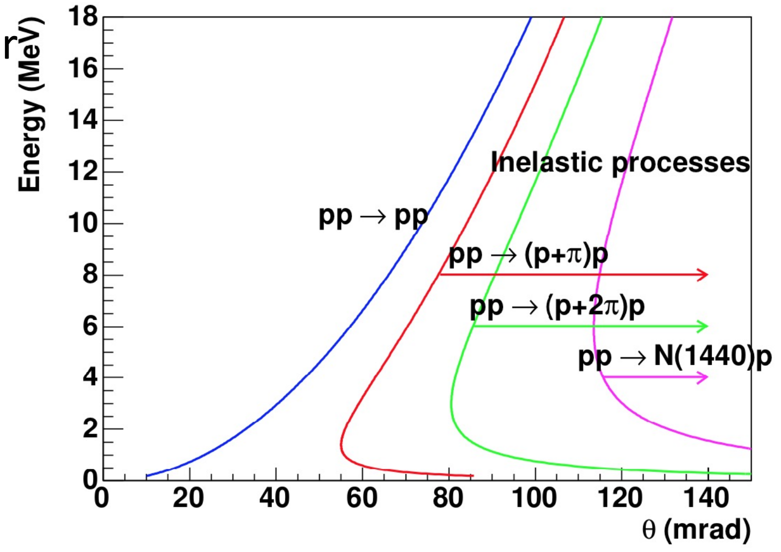
Elastic events identified via TOF-Kinetic energy correlation
→ “Banana” plot
Silicon strip detectors read out with wave-form digitizers that simultaneously provide energy and TOF information

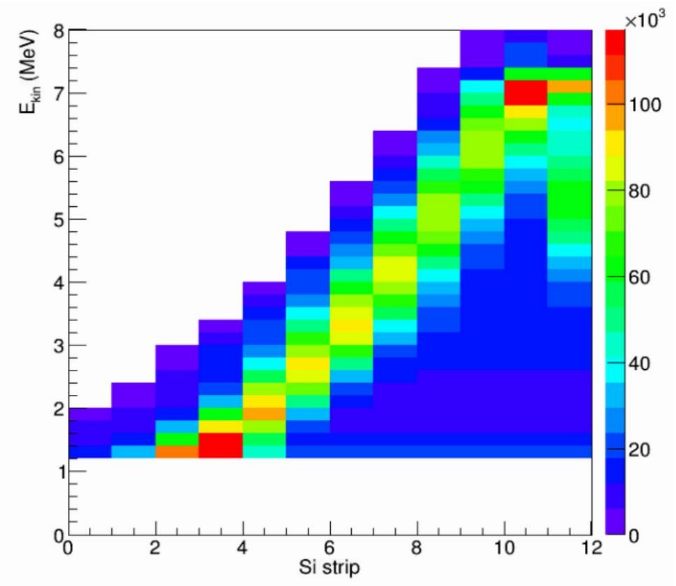
Asymmetry extracted from “cross-ration” → reduces sensitivity to left-right acceptance differences

$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$

E-θ correlation different for elastic and inelastic processes







Strip number → θ

p-Carbon Polarimeter

p-Carbon polarimeter also uses elastic scattering in CNI region

→ Located about 70 m from IP12

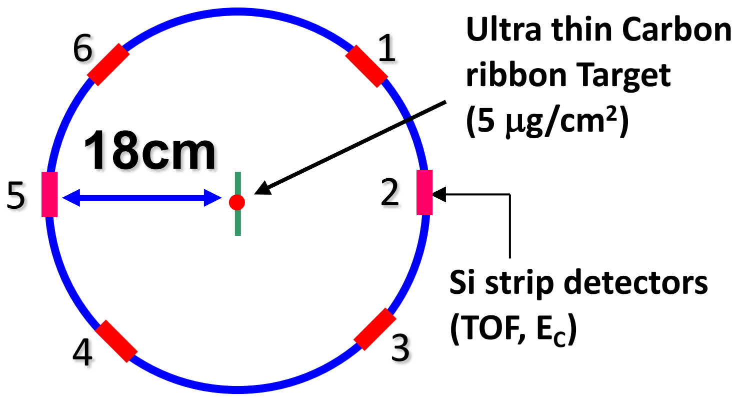
→ Uses thin carbon ribbon

→ Very low energy, recoiling carbon detected in silicon strip detectors

→ Polarization extracted via L-R asymmetry

→ Analyzing power requires cross-calibration with H-jet polarimeter

2 p-Carbon polarimeters → vertical and horizontal target to characterize beam profile



Ultra thin Carbon ribbon Target (5 μg/cm²)

Si strip detectors (TOF, E_C)

Nominal target size:
2.5 cm · 10 μ · 50 nm

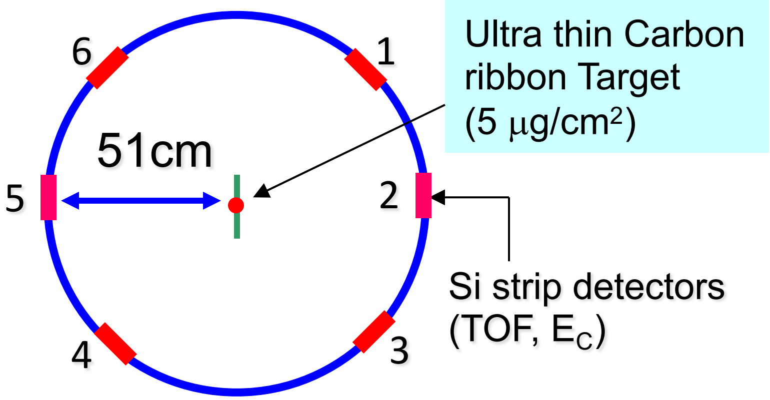
Passed across beam & back
~2-5 sec. in beam each pass
lifetime: few - few hundred passes

AGS and 200 MeV Polarimeters

AGS p-Carbon polarimeter similar to RHIC p-Carbon polarimeter with slightly different layout

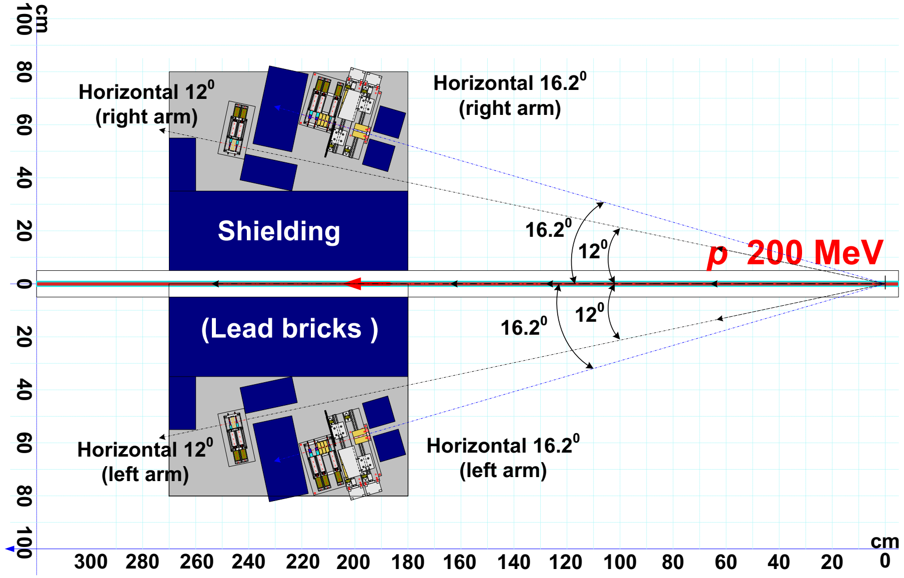
→ Fast, relative measurements

→ Verify beam polarization before injection into EIC ring at ~ 25 GeV



Ultra thin Carbon ribbon Target ($5\ \mu g/cm^2$)

Si strip detectors (TOF, E_C)



200 MeV Polarimeter located after linac following polarized source

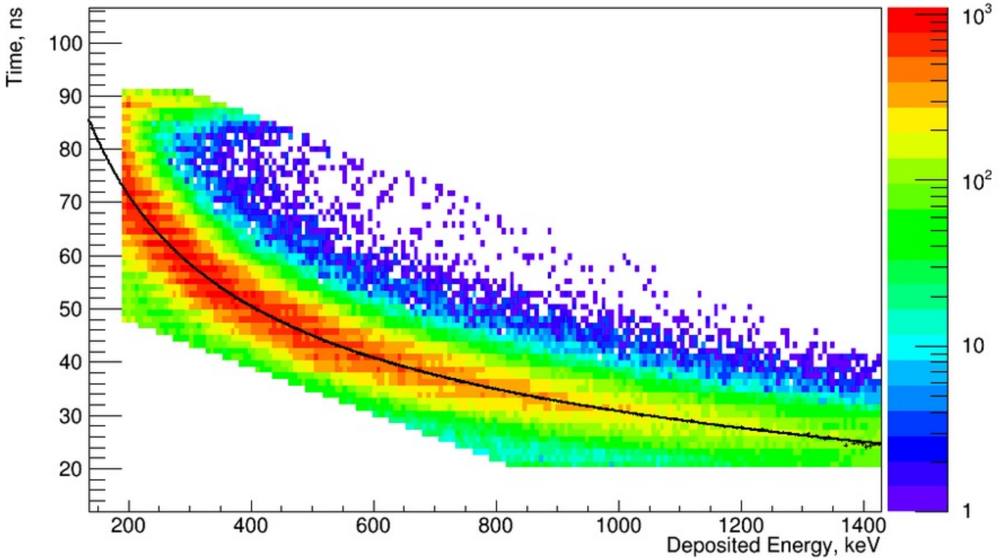
→ Analyzing power well known from measurements at IUCF

A_N= 0.993+/- 0.003

→ Total systematic error dP/P ~ 0.6%

p-Carbon Polarimeter

Similar to H-Jet polarimeter elastic events selected via TOF-energy correlation → banana plot



Asymmetry extracted for each detector

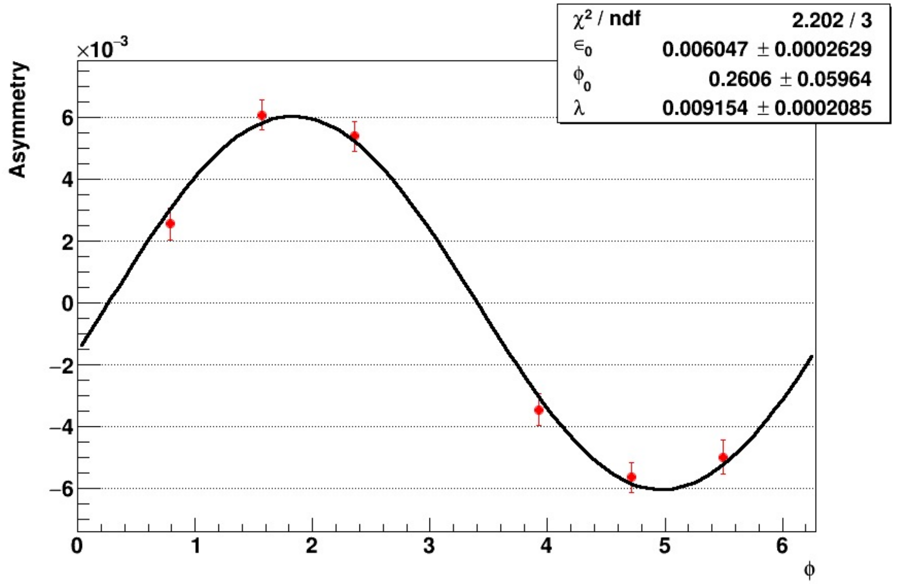
$$\epsilon = \frac{N_+ - N_-}{N_+ + N_-}$$

Fit to azimuthal dependence gives polarization:

$$\varepsilon(\phi) = \varepsilon_0 \sin(\phi - \phi_0)$$

Polarization magnitude

Spin tilt relative to vertical

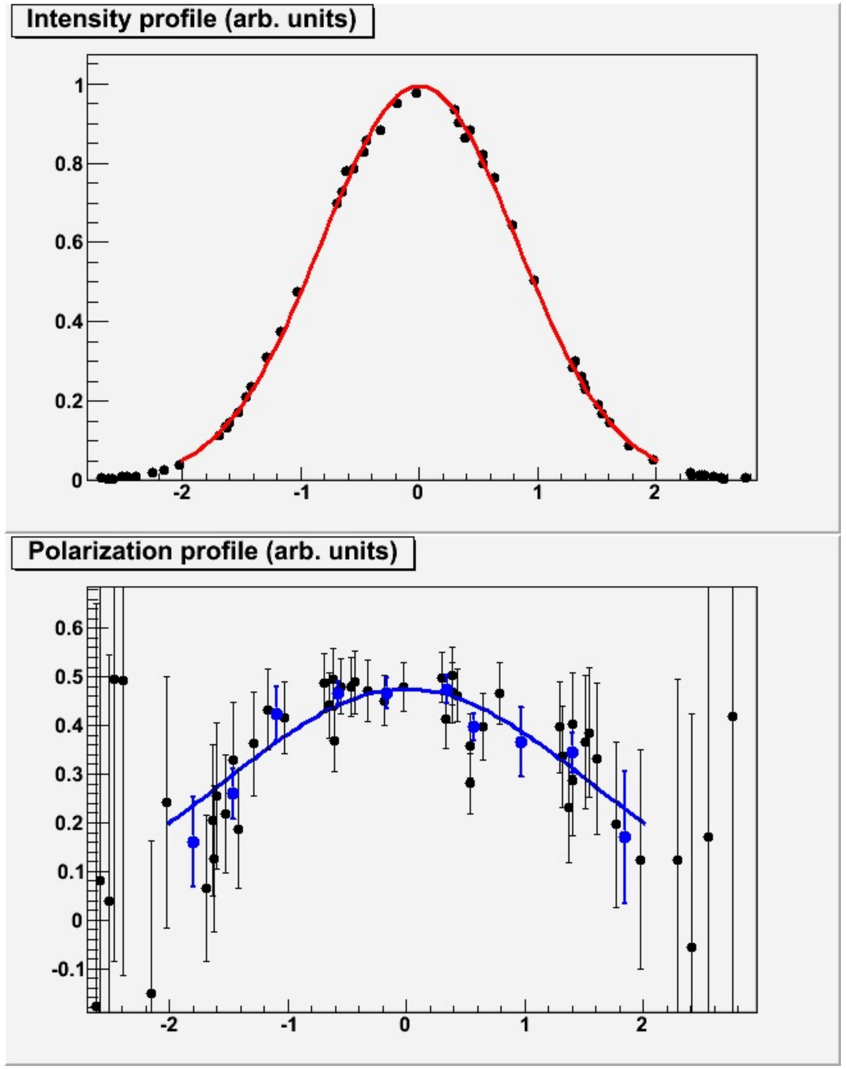


Polarization Profile

High rates + thin polarimeter target allows measurement of beam polarization profile

- → Target position relative to beam not known from stepper motors
- → Position inferred from measurement of rate in detector (beam profile): I(x) → $e(-x^2/\sigma^2_{\mathrm{beam}})$
- → Polarization profile plotted in units of σ_{beam}
- → Useful to define ratio of profile sizes:

$$R=(\sigma_{\mathrm{beam}}/\sigma_{\mathrm{polarization}})^2$$



Position $(x/\sigma_{\mathrm{beam}})$

Polarization vs. Time

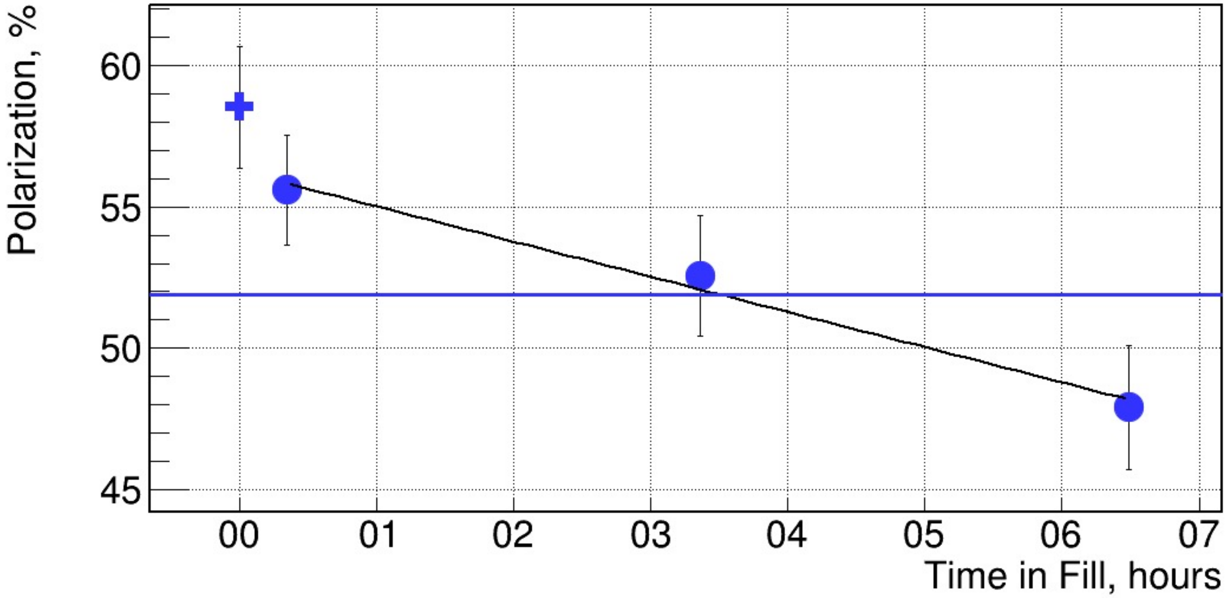
Multiple polarization measurements made during fill

→ Before ramping from 24-255 GeV (+)

→ Start of store

→ Middle (or every 3 hours)

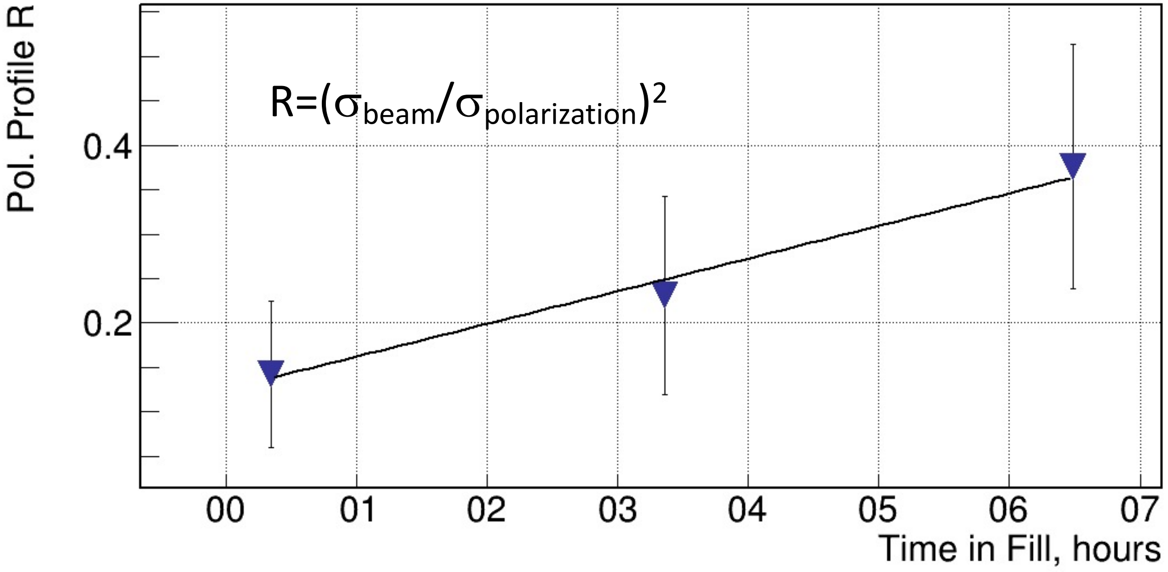
→ End of store



Polarization lifetime:

P~ $e^{-(t/\tau)}$

τ = 200-400 hours



$R=(\sigma_{beam}/\sigma_{polarization})^2$

Polarization drops with time,
Profile (R) grows

Longitudinal Polarization Profile

In addition to transverse polarization profile, there is an apparent longitudinal profile

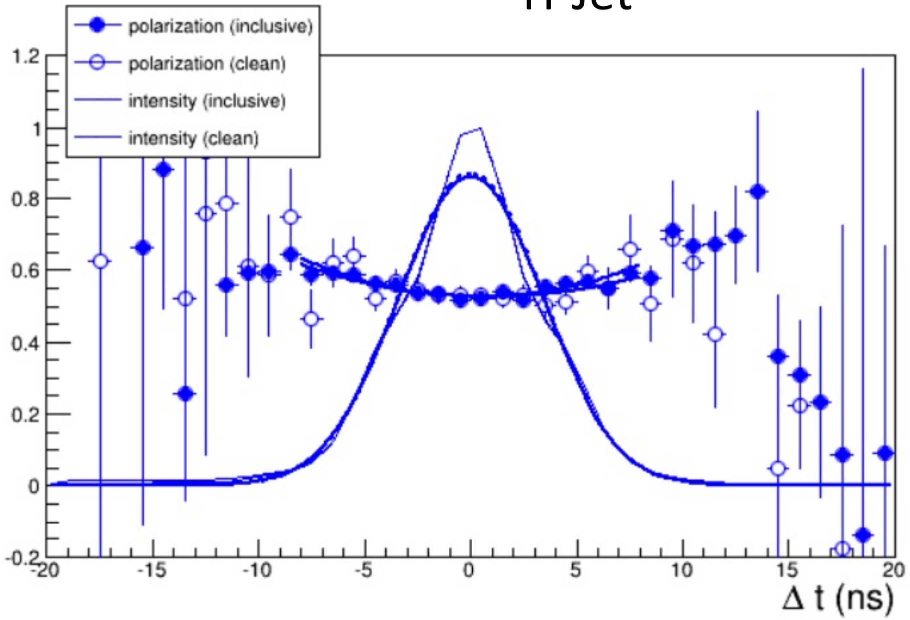
→ Asymmetry changes for different time bins along the bunch

→ Polarization lower at center of bunch

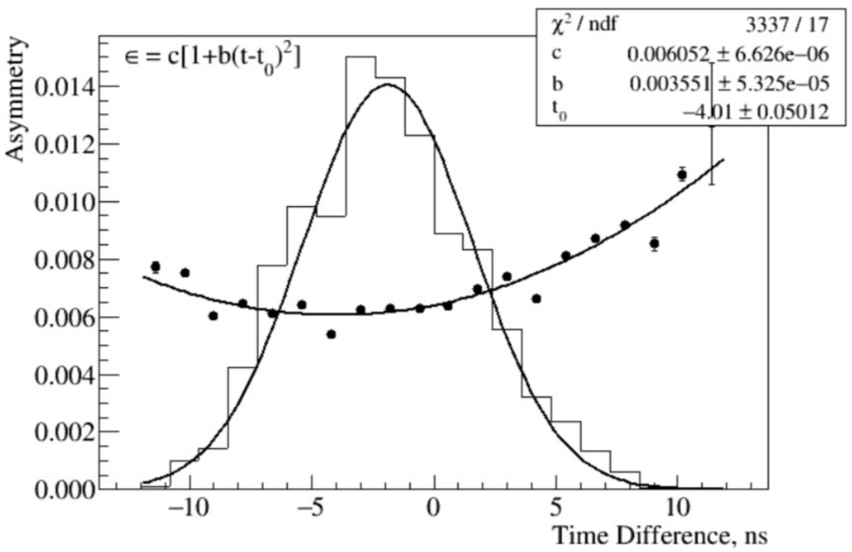
→ Depolarizing beam-beam effect? Largest at t=0 (highest bunch intensity)

→ Unexpected effect

H-Jet



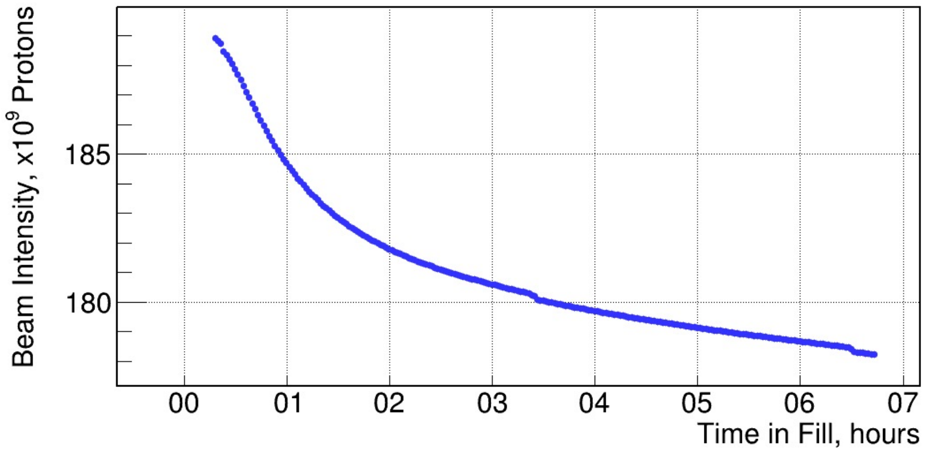
p-Carbon



p-Carbon/H-Jet Normalization

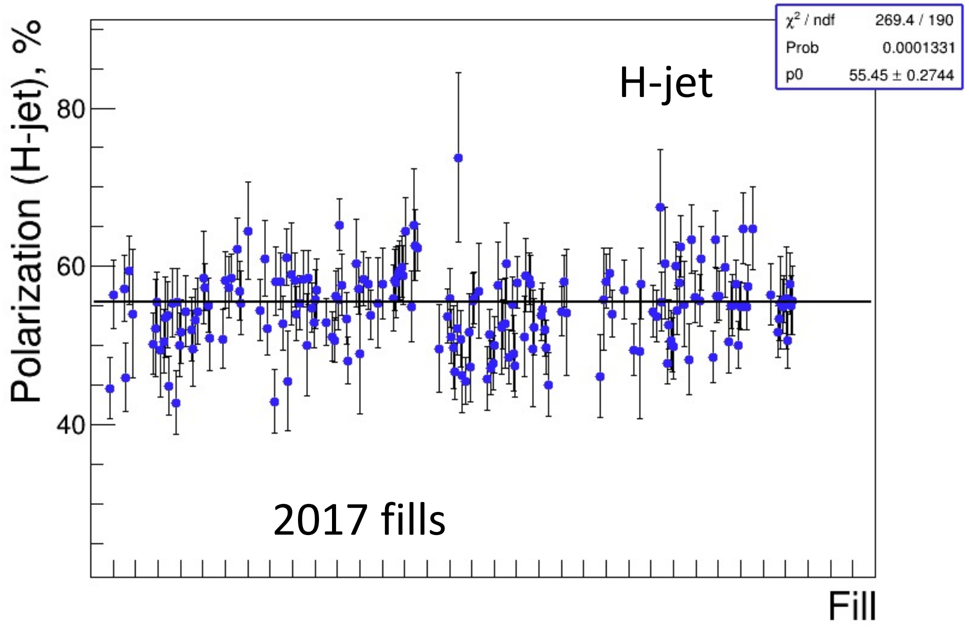
H-jet measures polarization over a whole fill → current weighted average polarization for that fill

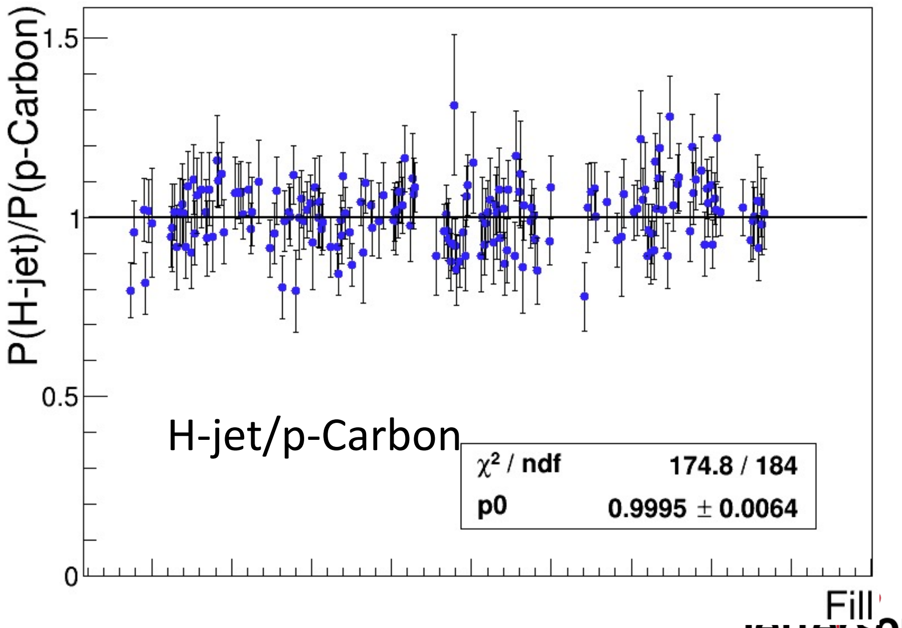
$$P_{Hjet} = \frac{\int P(t)I(t)dt}{\int I(t)dt}$$



Normalize intensity-weighted average for p-Carbon to H-Jet

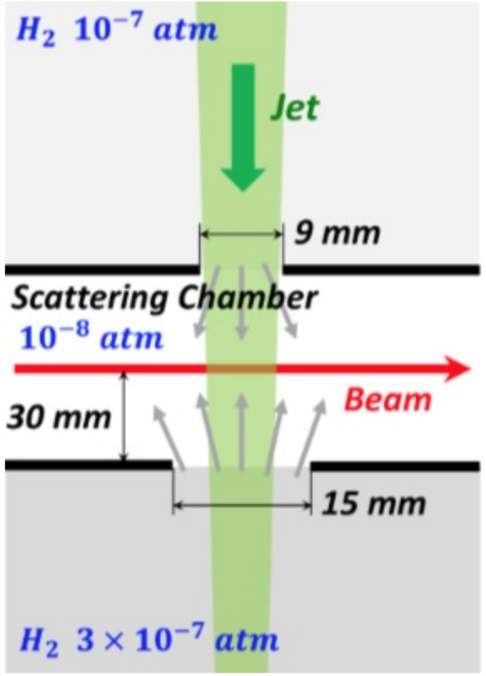
→ Scale uncertainty 1-1.5%

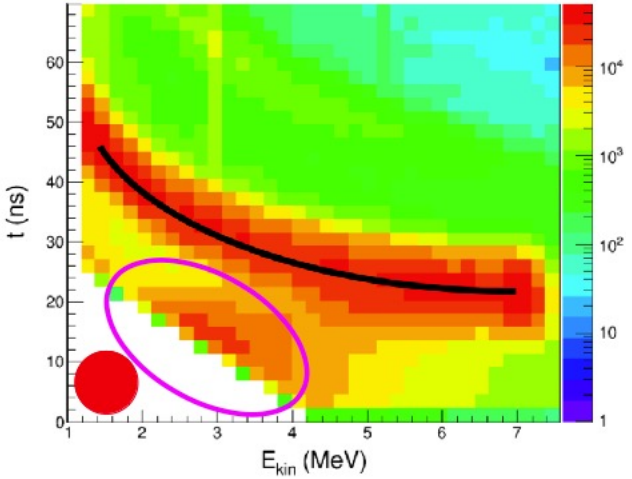




Polarimetry Challenges at RHIC

- H-Jet target H_2 contamination
  - Target polarized H_1
  - Molecular H_2 (unpolarized) leads to dilution
  - Largest systematic until 2017 → estimate based on bench measurement
  - 2017 in situ measurements reduced systematic, but improvements still possible
- Backgrounds
  - Background from non-elastic events leak under signal – estimated and subtracted
  - Origin under study – limits H-jet systematic uncertainty
- Detector energy calibration
  - Due to steep dependence of A vs. E, results very sensitive to this calibration
- Target lifetime
  - p-carbon ribbons survive a few 100 passes through beam
  - 6 targets on ladder, but eventually need to replace (interrupts RHIC operations)



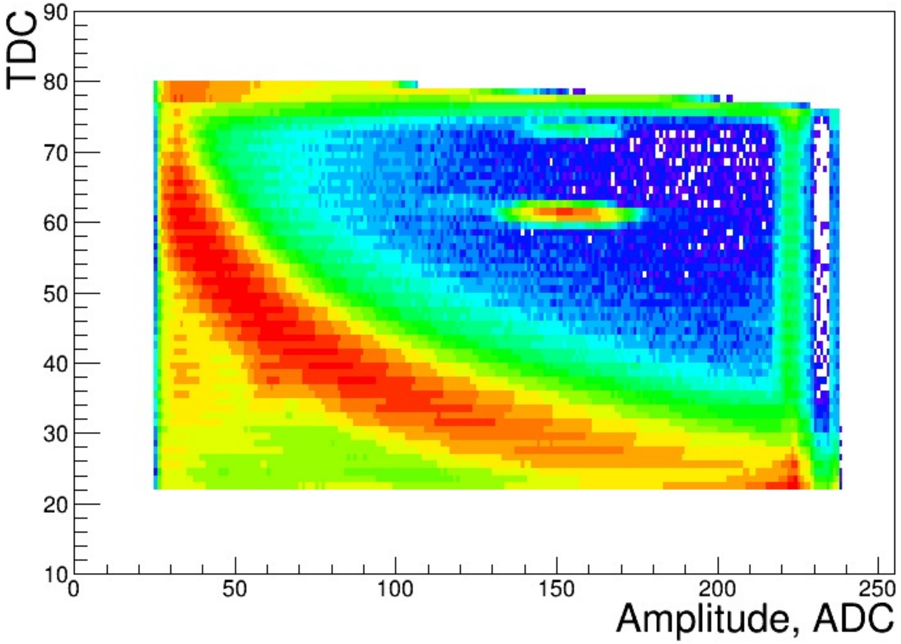


Hadron Polarimetry Challenges at EIC

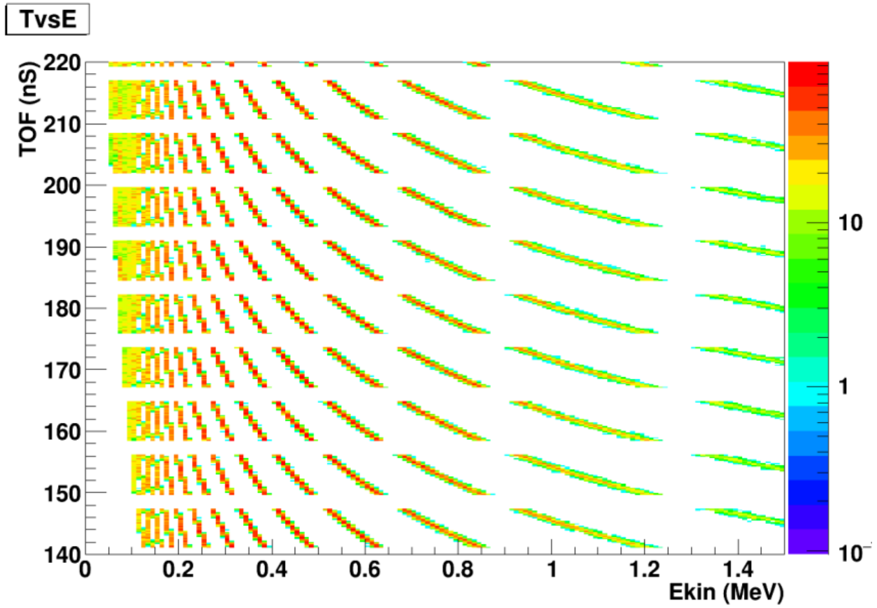
- EIC Hadron Polarimetry will make use of existing H-Jet and p-Carbon systems with additional p-Carbon polarimeter near IP6
- EIC will have shorter bunch spacing than RHIC → challenges for identifying good events
- EIC will have higher beam current → p-Carbon target will likely not survive in beam
- Light-ion polarimetry
  - RHIC polarimeters designed for protons
  - Similar processes can be used for light-ions (^{3}He), but may be additional backgrounds from breakup
  - Deuteron beams not part of baseline, but are also of interest → analyzing power for deuteron predicted to be much smaller than for p and ^{3}He

Bunch Spacing

RHIC – pC data (107 ns bunch spacing)



EIC – (~10 ns bunch spacing)

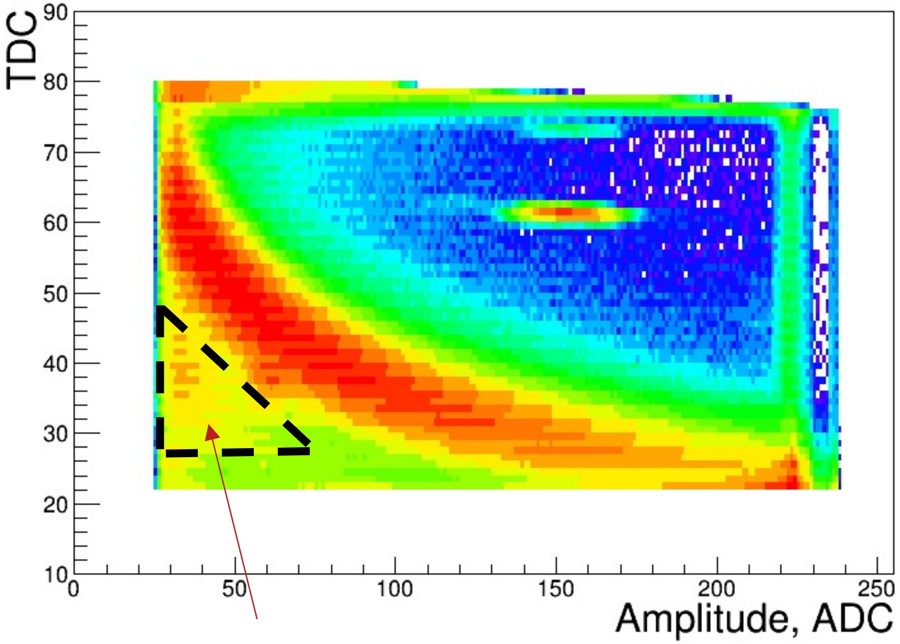


Smaller bunch spacing makes selection of good events via TOF-E correlation impossible

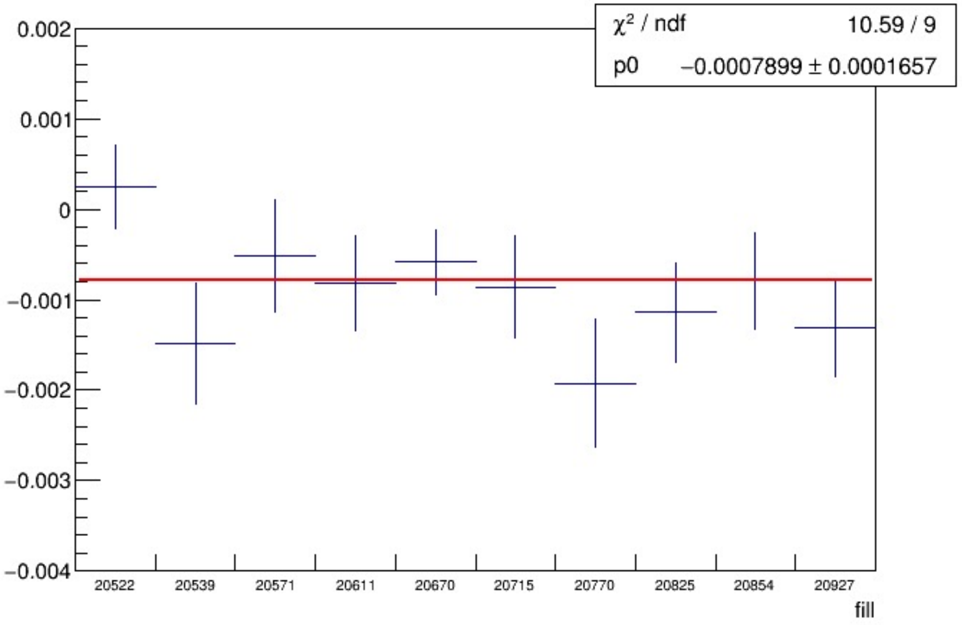
→ Several bunches will overlap

→ Impossible to cleanly identify elastic signal, remove background

Backgrounds



background



Background asymmetry

Bunch-spacing issues prevent clean removal of backgrounds

→ Fast particles – pions, photons up to a few GeV

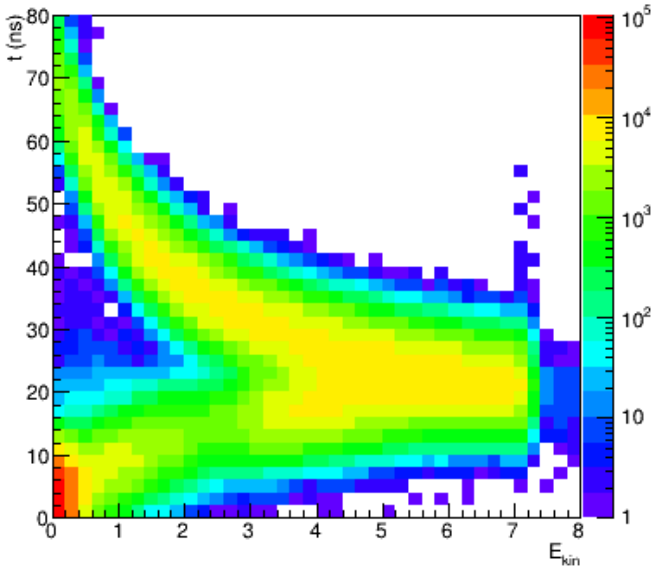
→ Background more than just a dilution – appears to carry non-zero asymmetry

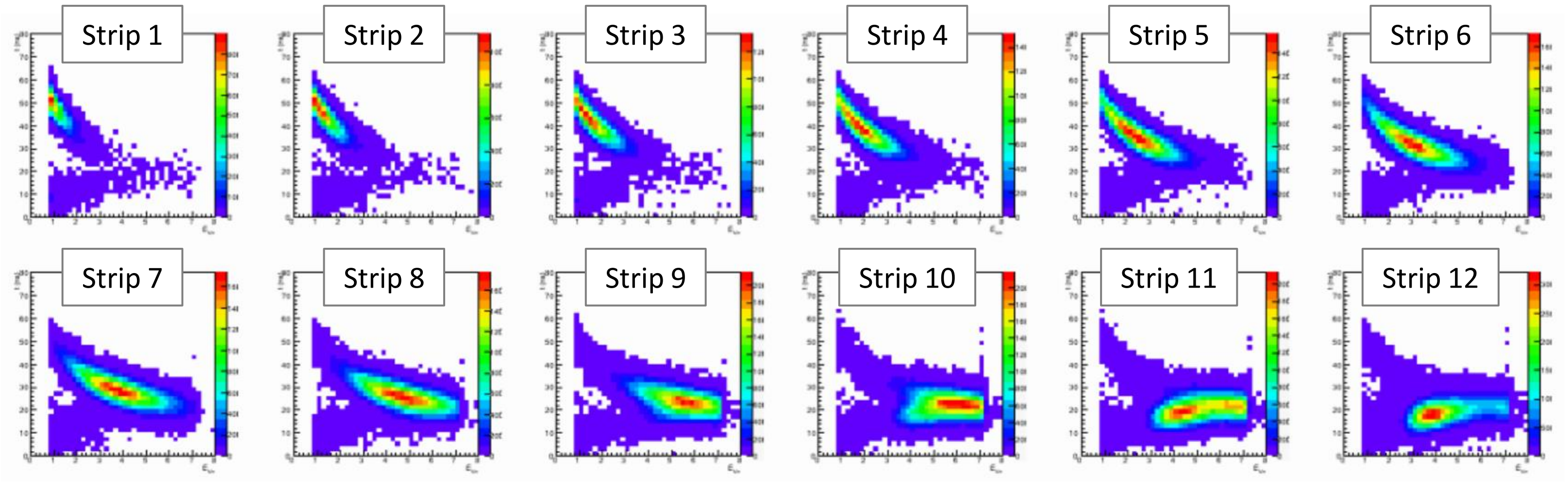
H-Jet will have similar issues

Background Simulations

Attempts have been made to better understand the backgrounds using PYTHIA + GEANT4 simulation of polarimeter

Simulation reproduces general features
→ Elastic correlation
→ Signal/background





Background Rejection

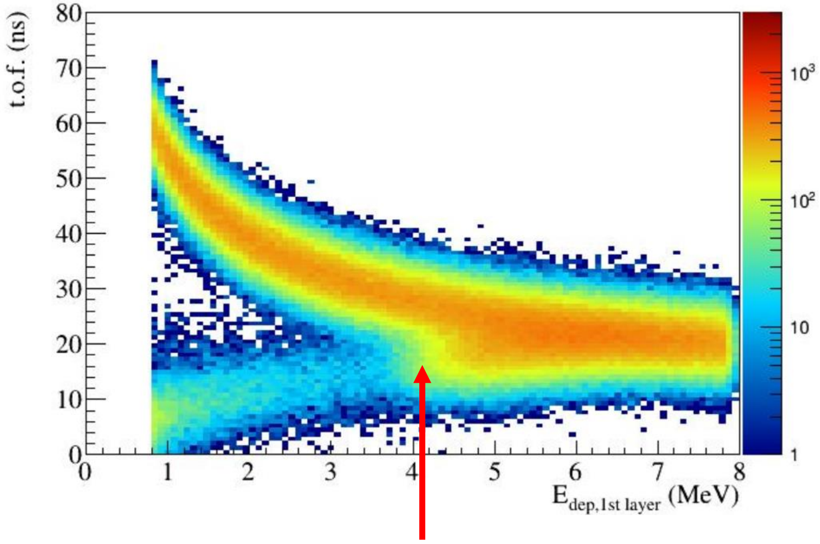
Protons in general are stopped in Si detector

→ Additional layer could be added to veto fast higher energy particles

→ Simulations suggest this would be effective

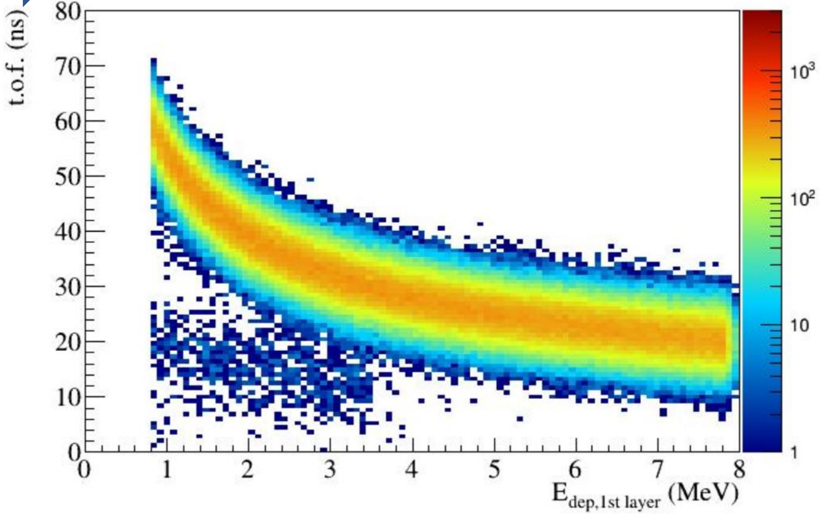
This can be tested in upcoming RHIC proton run

Layer 1



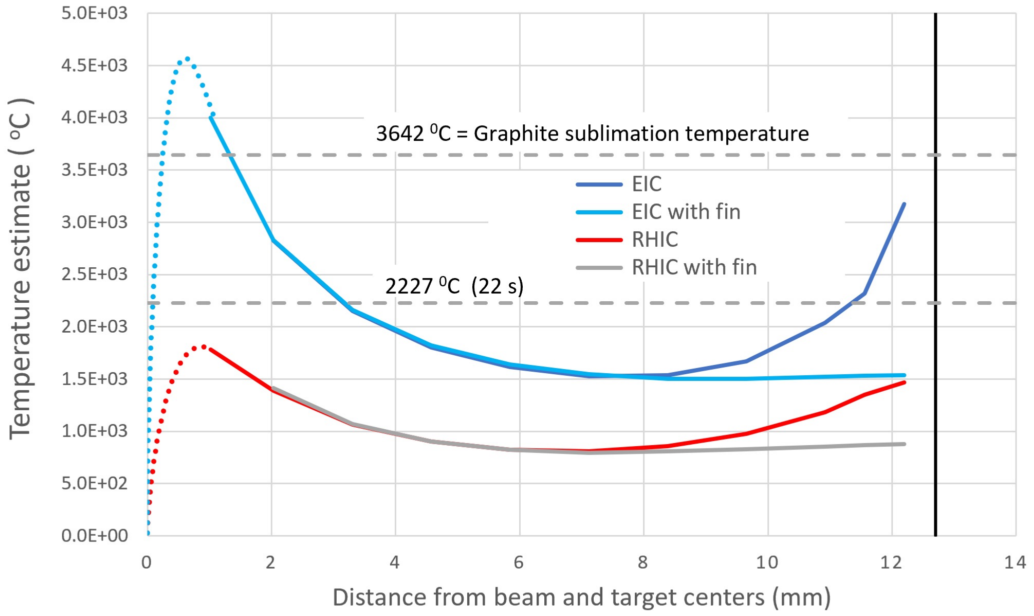
detector acceptance
for elastic protons

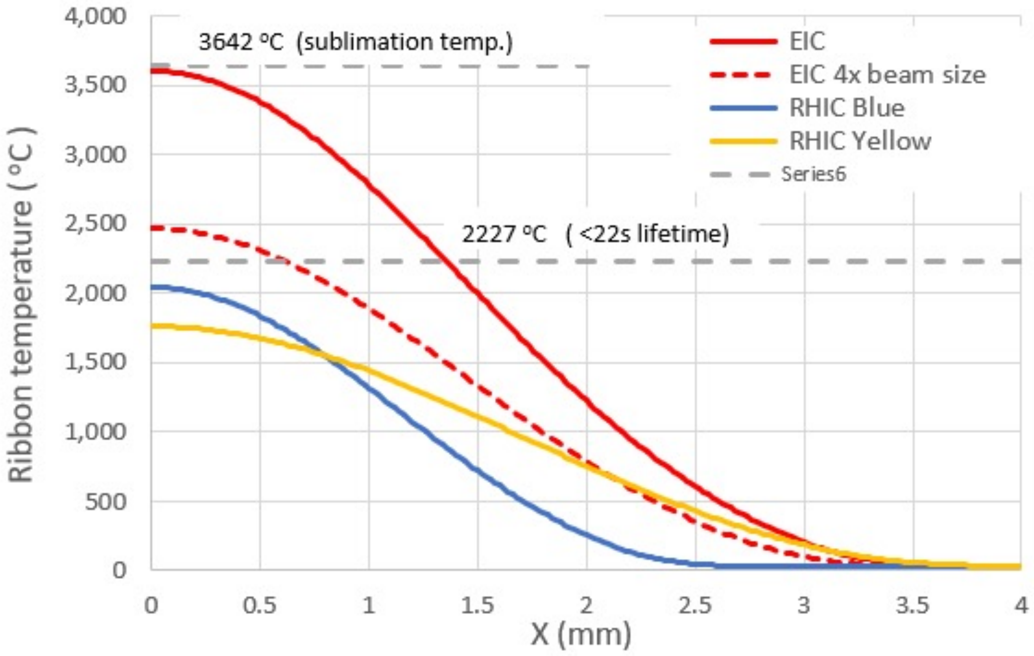
/w veto from layer 2



p-Carbon Target Viability

Simulated temperature along target center → edge





Carbon targets do not survive indefinitely at RHIC → close to rapid sublimation

→ Estimated lifetime ~440 s, can be used for a few 100 measurements

→ Consistent with observed lifetime

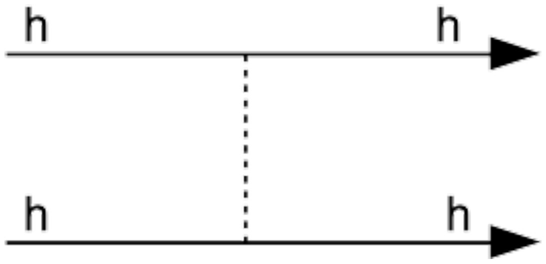
At EIC, targets are well into rapid sublimation (few seconds)

→ Alternate target materials likely required

^{3}He Breakup

Absolute polarimetry with polarized jet target requires elastic scattering

→ Helion can breakup into d+p or n+p+p



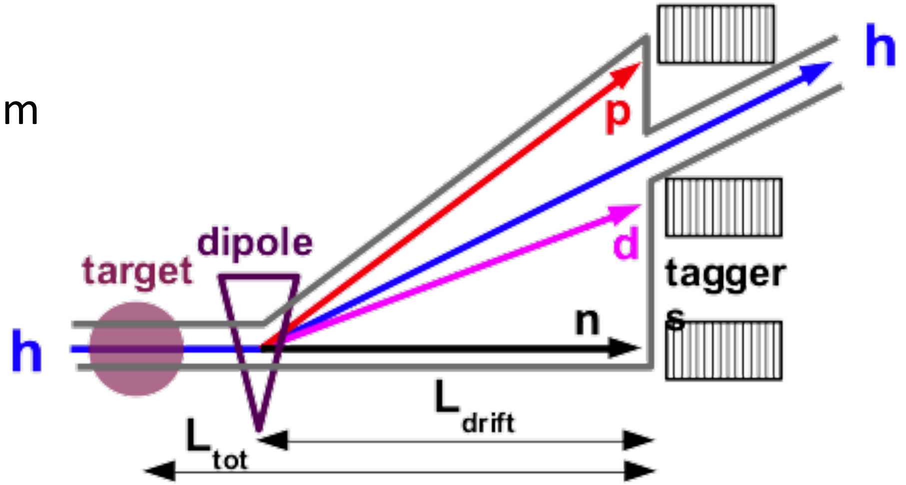
h = helion, ^{3}He
d = deuteron
p = proton
N = neutron

Mass difference between h and (d+p) only 5 MeV → too small to resolve with target recoil detectors
→ For elastic pp, nearest inelastic channel is single pion production, 140 MeV

Need to tag helion breakup fragments and reject from polarimetry analysis

Near threshold, breakup fragments travel colinearly with beam
→ Tagging requires dipole to separate n/p/d
→ Detectors placed at appropriate separation for each

Deuteron will face similar breakup issues; d→p+n



Plans for Tests at RHIC

Background veto layer tests

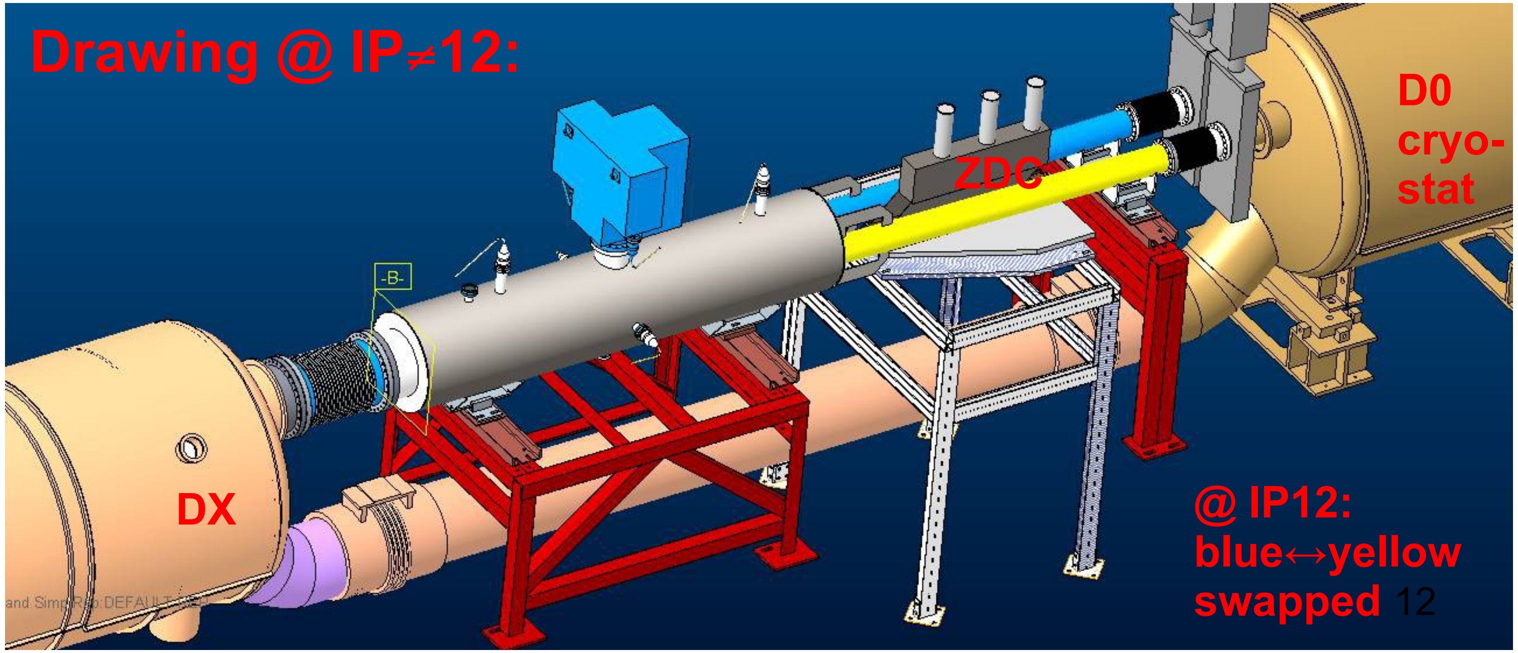
→ Some tests already done using H-Jet detector – results inconclusive

→ Pursuing adding 2nd layer to some of the p-Carbon detector planes

Helion breakup tagging

→ DX dipole downstream of H-Jet separates breakup protons/neutrons from beam

→ Tag with spare Zero Degree Calorimeter (ZDC)



Drawing @ IP≠12:

@ IP12: blue↔yellow swapped

p-Carbon Target

→ No good alternatives identified yet, but any TBD options can be tested in existing polarimeters

Summary (Part 3)

- RHIC has wealth of experience that will facilitate high precision hadron polarimetry
- EIC will use existing RHIC hadron polarimetry techniques, but some improvements required
- Polarized jet target polarimeter will provide absolute calibration
- p-Carbon polarimeters calibrated to jet polarimeter
- Improvements needed for transition from RHIC to EIC
  - Understand/suppress backgrounds → high bunch frequency makes it difficult to isolate elastic signal
  - Alternate p-Carbon target material
  - Light breakup tagging

Compton Design

- Many Compton polarimeter requirements and specifications can be determined with fairly simple calculations
- In the end, final, detailed design should be based on GEANT simulations, but a good starting point can come from these simple calculations
- Examples:
  - Laser power, entrance window size
  - Luminosity for CW, pulsed lasers
  - Measurement times
  - Detector properties, sizes
  - Systematics – helicity correlated beam motion

https://github.com/gaskelld/compton_jupyter

Laser entrance window

Assume σ_{Laser} = 100 μm at collision point

→ Determine laser size at entrance window

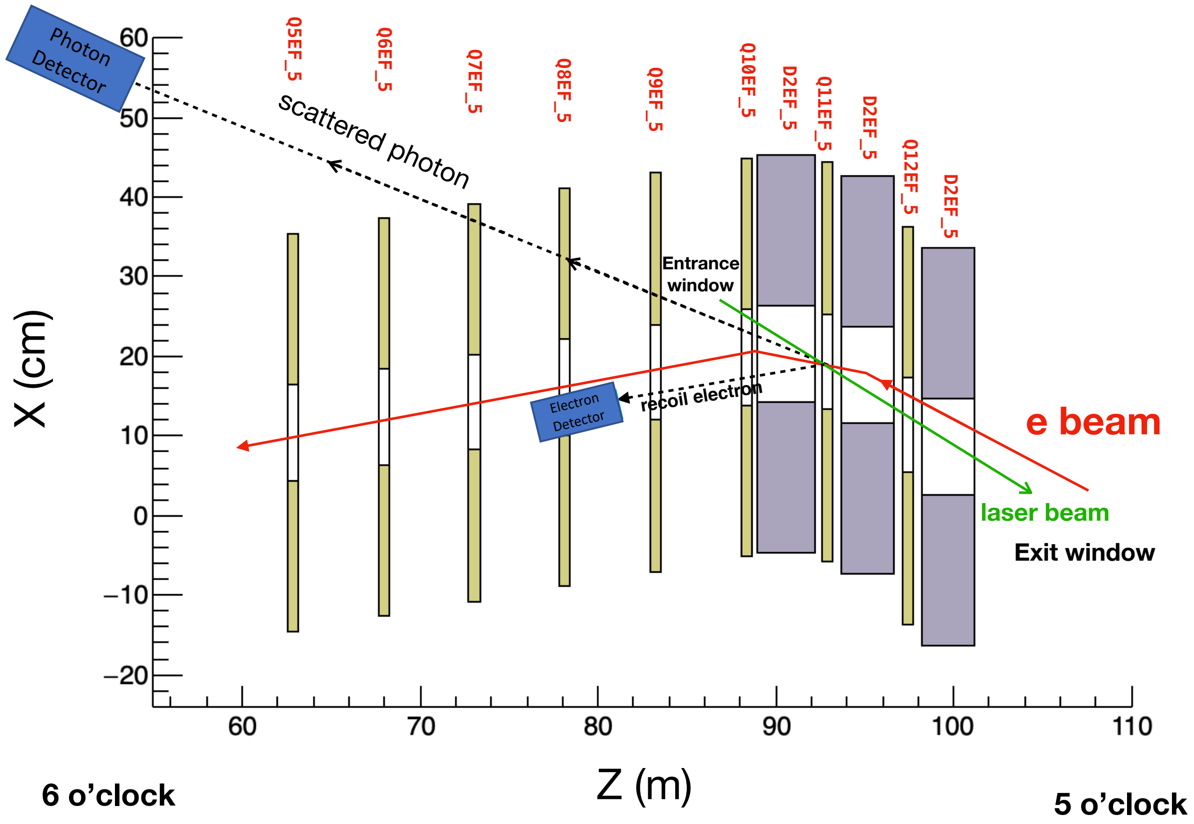
→ How big does the window need to be? Compatible with magnet apertures, vacuum pipe sizes?

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

$w = 2\sigma$

Diffraction limited beam:

$$z_R = \frac{\pi w_o^2}{\lambda}$$



Laser enters vacuum ~ 6 m from IP

Basic Kinematics

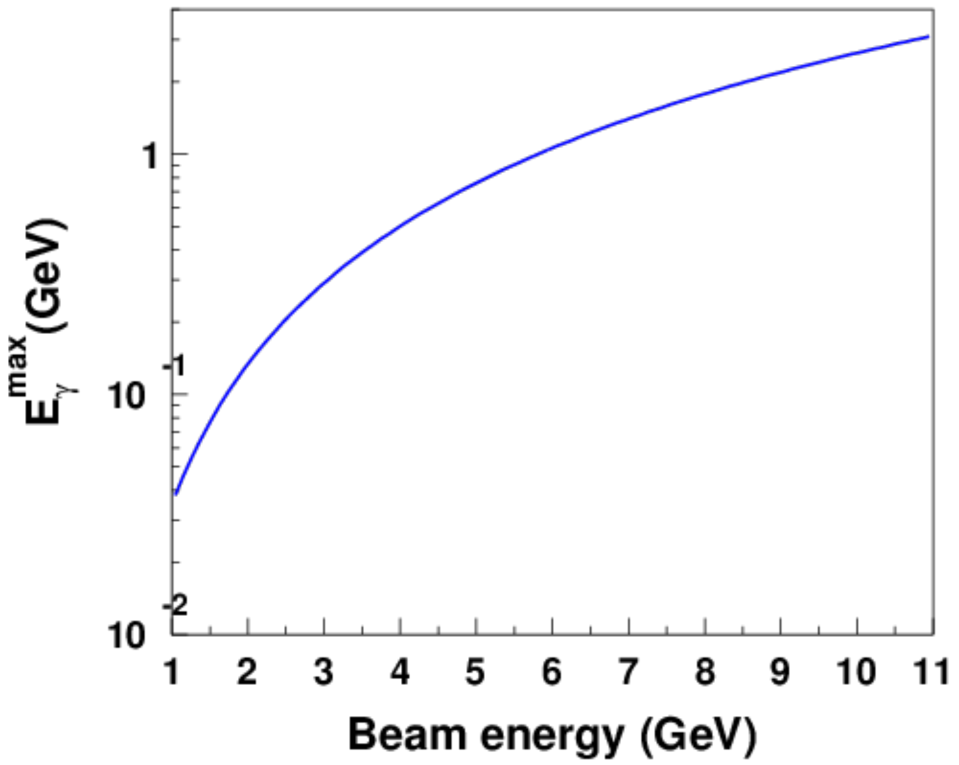
$$E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}$$

$$a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}$$

Maximum for $\theta = 0$ (photon along electron direction)

Angle at which $E_\gamma = E_\gamma^{max}/2$

$$\theta_{\gamma 1/2} = \frac{1}{\gamma\sqrt{a}}$$



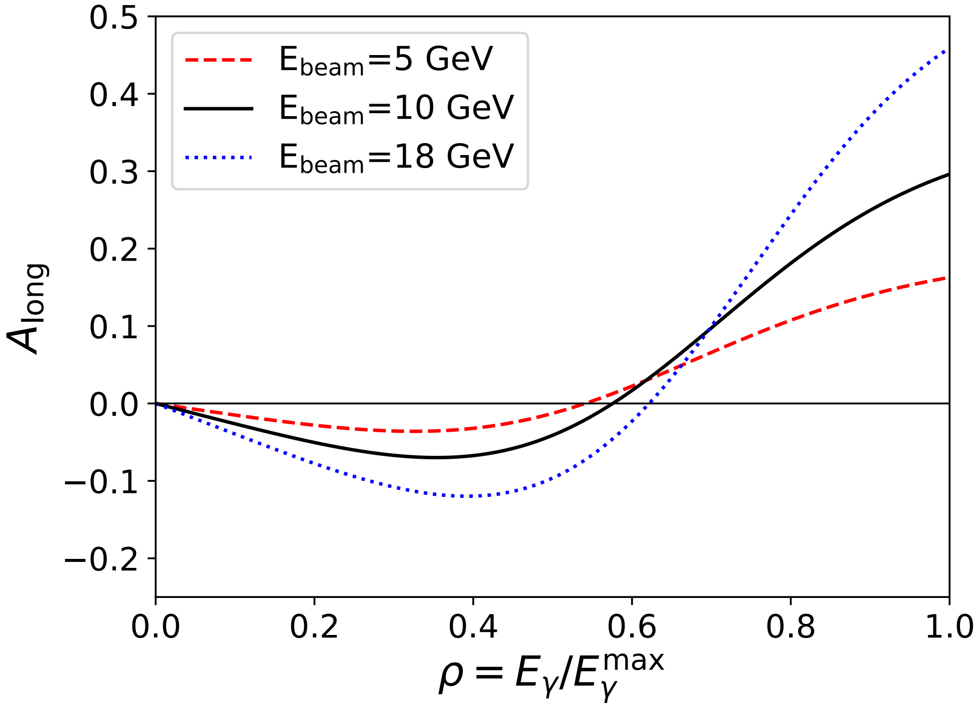
Cross Section and Analyzing Powers

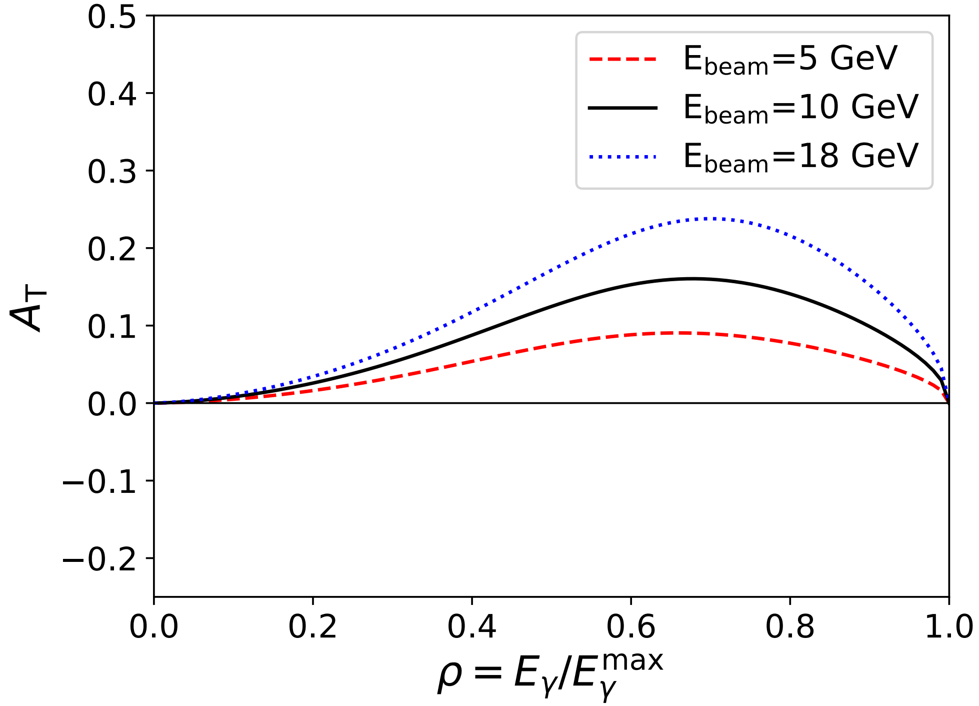
$$\frac{d\sigma}{d\rho} = 2\pi r_0^2 a \left[\frac{\rho^2(1-a^2)}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$

r_0 = classical electron radius

$$A_{\mathrm{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

$$A_{\mathrm{T}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))} \right]$$





Luminosity – CW laser vs. Pulsed

CW

$$\mathcal{L} = \frac{(1+\cos\alpha_c)}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{\sin\alpha_c}$$

Pulsed

$$\mathcal{L} = f_{coll} N_\gamma N_e \frac{\cos(\alpha_c/2)}{2\pi} \frac{1}{\sqrt{\sigma_{x,\gamma}^2 + \sigma_{x,e}^2}} \frac{1}{\sqrt{(\sigma_{y,\gamma}^2 + \sigma_{y,e}^2)\cos^2(\alpha_c/2) + (\sigma_{z,\gamma}^2 + \sigma_{z,e}^2)\sin^2(\alpha_c/2)}}$$

Beam current 1 A at 5, 10 GeV (~4 times less at 18 GeV)
Beam sizes at Compton IP: on the order of 300-400 μm
0.7 cm rms bunch length (~23 ps)

IP6 Compton → 10 mrad crossing angle

What laser power required for ~ 1 backscattered photon/collision?

Measurement Times

$$t^{-1} = \mathcal{L}\sigma \left(\frac{\Delta P}{P}\right)^2 A^2_{method}$$

Average analyzing power: $A^2_{method} = \langle A \rangle^2$ → Average value of asymmetry over acceptance

Energy-weighted: $A^2_{method} = \left(\frac{\langle EA \rangle}{\langle E \rangle}\right)^2$ → Energy deposited in detector for each helicity state

Differential: $A^2_{method} = \langle A^2 \rangle$ → Measurement of asymmetry bin-by-bin vs. energy, etc.

$$\langle A \rangle^2 < \left(\frac{\langle EA \rangle}{\langle E \rangle}\right)^2 < \langle A^2 \rangle$$

Time for 1% measurement of a single bunch at laser power that gives ~1 backscattered photon/crossing?

Photon Detector Size Using Transverse Asymmetry

Lab scattering angle

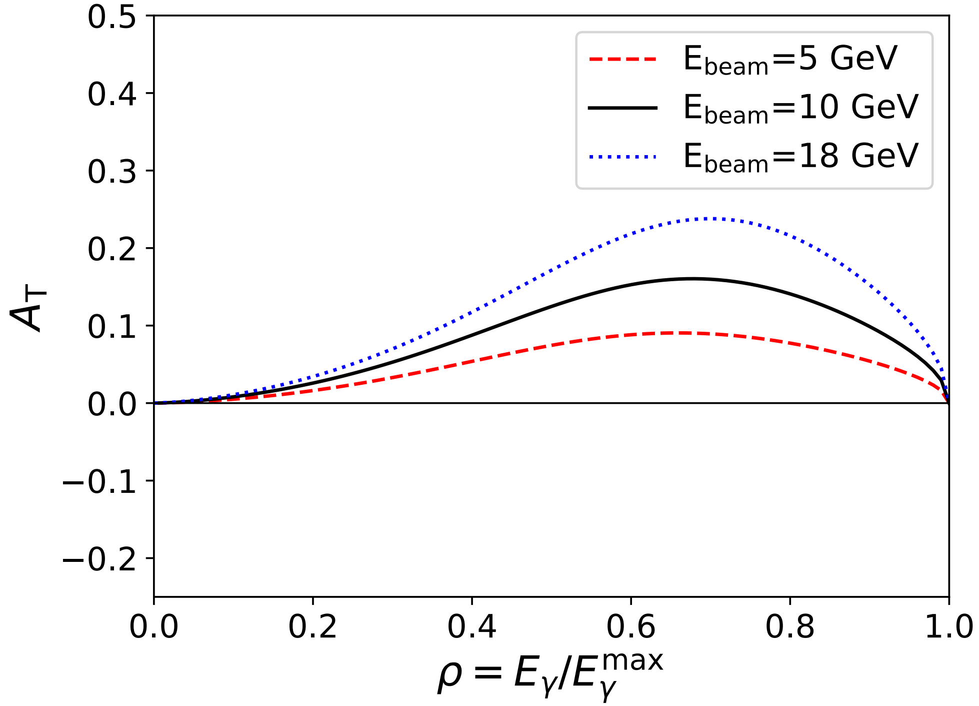
$$\cos\theta_\gamma = \frac{E_{beam} + E_{laser} - 2E_{laser}E_{beam}/E_\gamma}{E_{beam} - E_{laser}}$$

Simplified approximate expression

$$\theta_\gamma = \frac{1}{\gamma}\sqrt{\frac{(1-\rho)}{a\rho}}$$

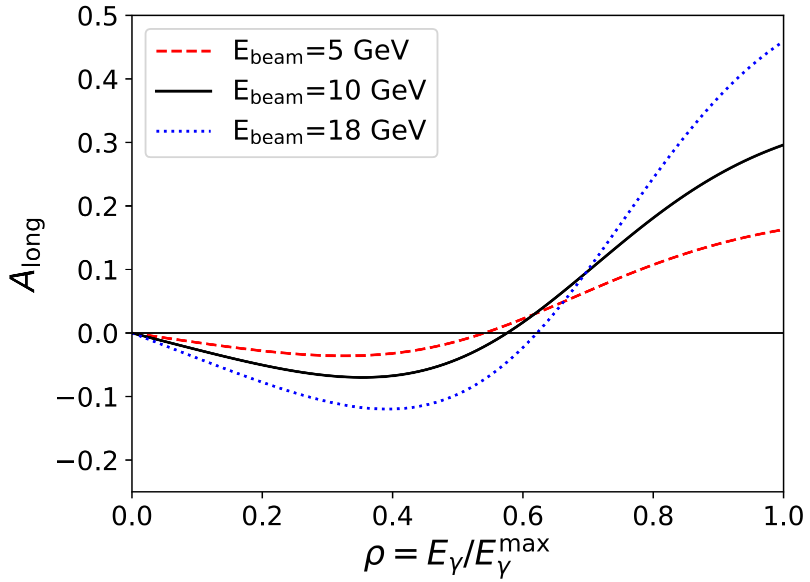
Detector position vs. backscattered photon energy

Calculate transverse asymmetry at projected detector position



Electron Detector Size and Segmentation

Design electron detector to be able to capture asymmetry endpoint and zero-crossing



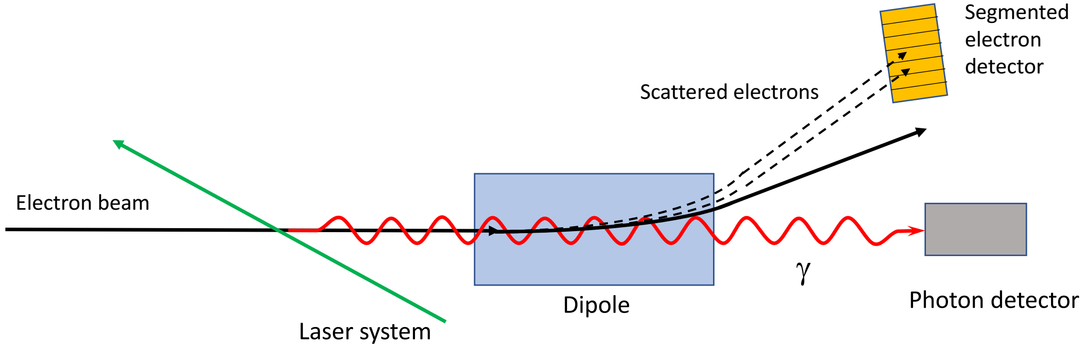
From nominal dipole length, bend angle, calculate dipole field

$R = L_{dipole}/\theta_{bend}$

$B_{dipole} = (10/3)\ E_{beam}/R$

Ignoring electron scattering angle, position at electron detector from deflection through magnet + drift to detector

$$Xdet = 10/3*(E_e/B_{dipole})*[1-\cos(\theta_e)] + z_{det}*\tan(\theta_e)$$



Calculate for nominal beam energy, asymmetry end point, etc.

Helicity Correlated Position Differences

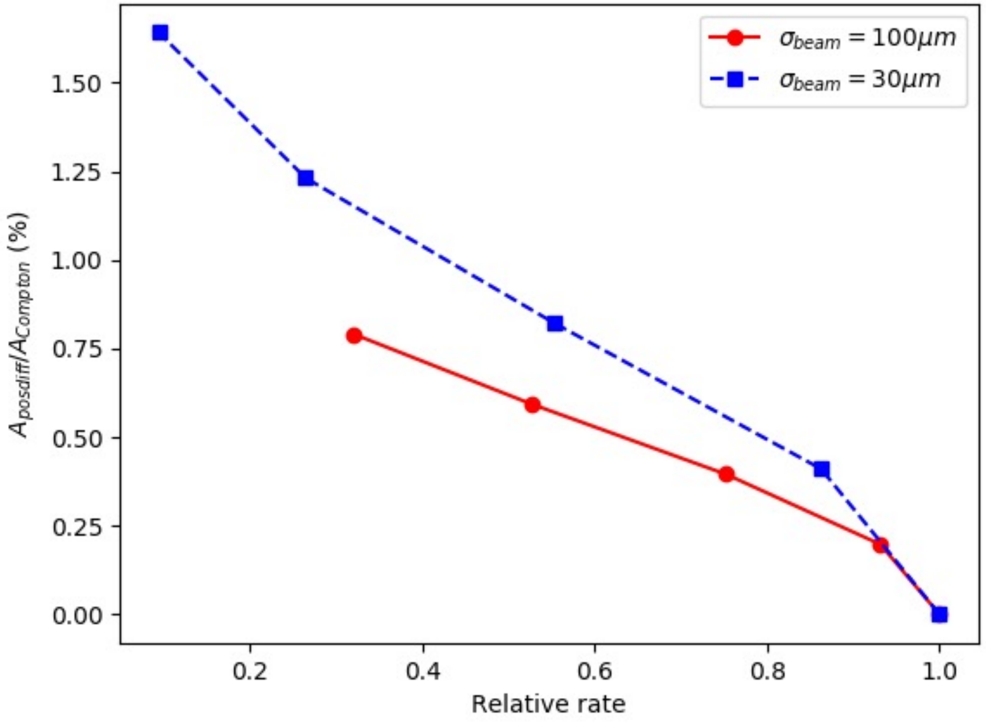
Laser/beam helicity correlated motion can result in false asymmetries if beam and laser alignment not optimized

Example: JLab @ 2 GeV, beam/laser misalignment that results in 20% reduction in Compton rate can lead to ~0.5% error in polarization

Rate of Compton events can be monitored to check beam-laser alignment
→ Assumes constant beam size

For measurement of a single bunch, beam trajectory/position must be the same at each pass through IP

Laser position shifts must be minimized when flipping helicity



Relative change in measured beam polarization for +/- 25 nm beam motion vs. relative Compton rate (rate is lower due to misalignment)