Hadron Polarimetry

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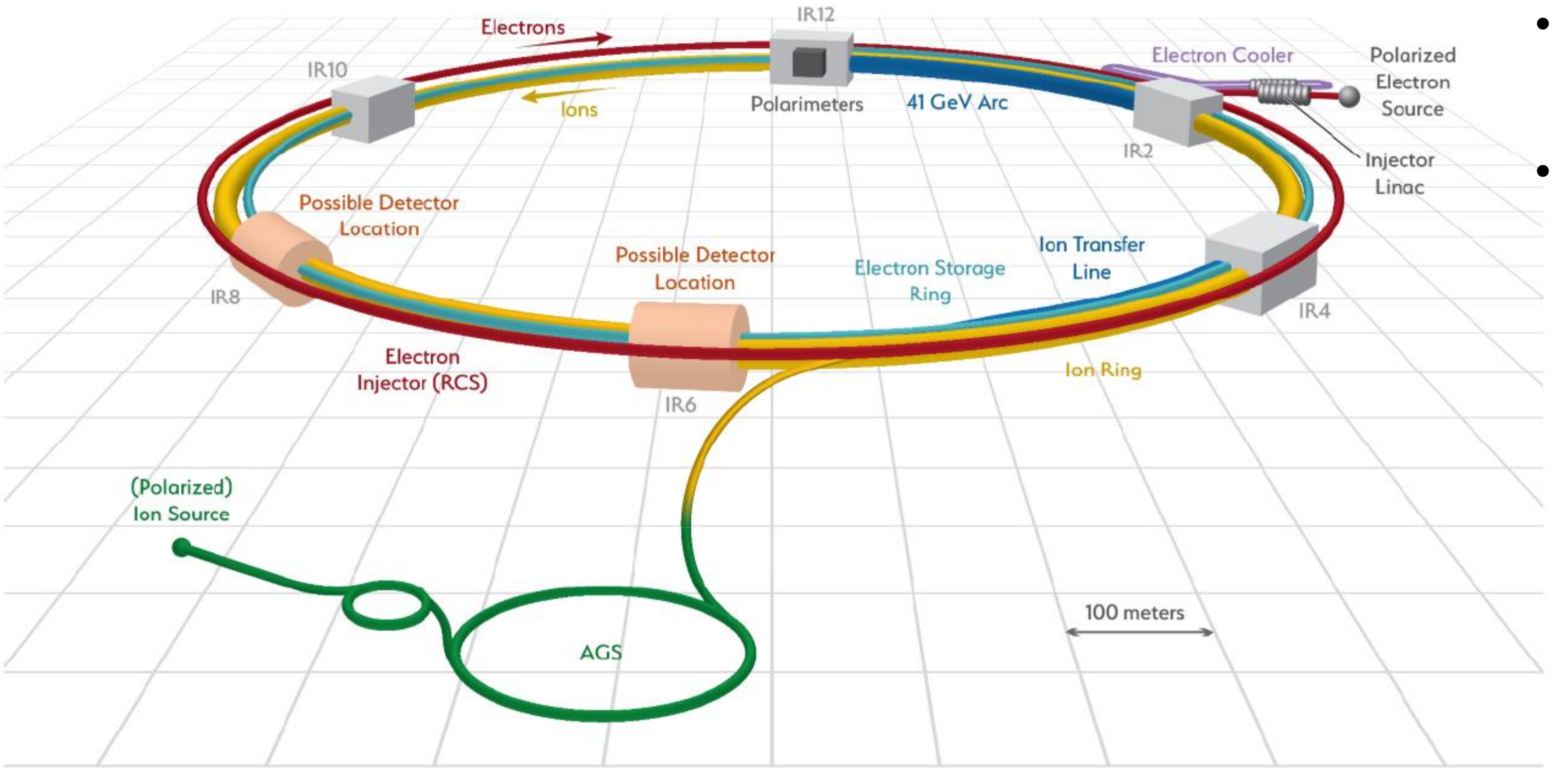
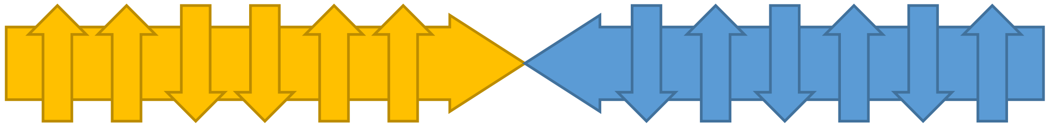
Outline

- Introduction: A Polarized Electron-Ion Collider
- I. Polarized Particle beams
- II. Hadron Polarimetry
- Outlook / Summary

Recap: Requirements for Polarimetry





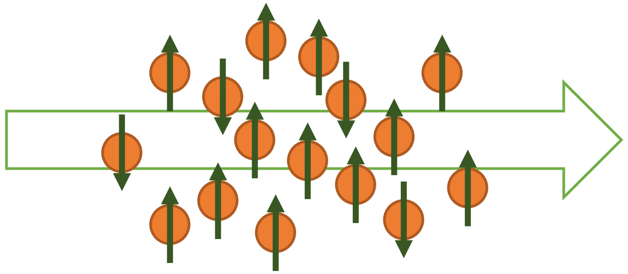
- Required:
  - Absolute beam polarization $\Delta P/P \approx 1\%$
- Consider:
  - Time-dependence (polarization decay)
  - Bunch-by-bunch polarization
  - Polarization profile of bunches
  - Polarization during ramp (acceleration)
  - Polarization vector at experiment

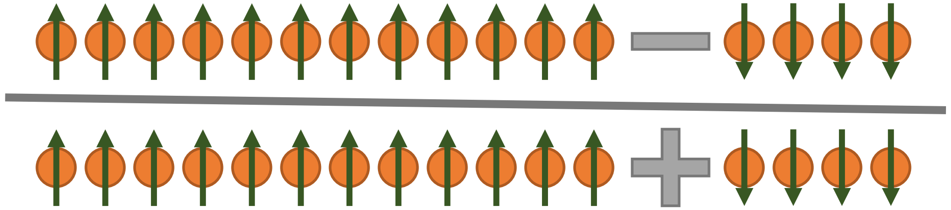
II.
Polarimetry of High Energy Hadron Beams

Polarization of Particle Bunches

A bunch of particles in vacuum travelling at almost the speed of light

Goes in circles, will be back in about 13 μs (78 kHz).





- For the determination of the polarization we will have to devise an experiment which is spin-dependent.
- We need a representative sample of scattered particles to make conclusive statements about the polarization.
- Only a fraction of the scattering probability will depend on the spin: $\sigma^{\uparrow\downarrow} = \sigma_0 \pm \sigma_s = \sigma_0(1 \pm a_s)$
- It is convenient to introduce an asymmetry: $\epsilon = (\sigma^{\uparrow} - \sigma^{\downarrow})/(\sigma^{\uparrow} + \sigma^{\downarrow}) = a_s$

The Right Frame

- The momentum and spin direction define a coordinate system.

  Longitudinal $\boldsymbol{L}$

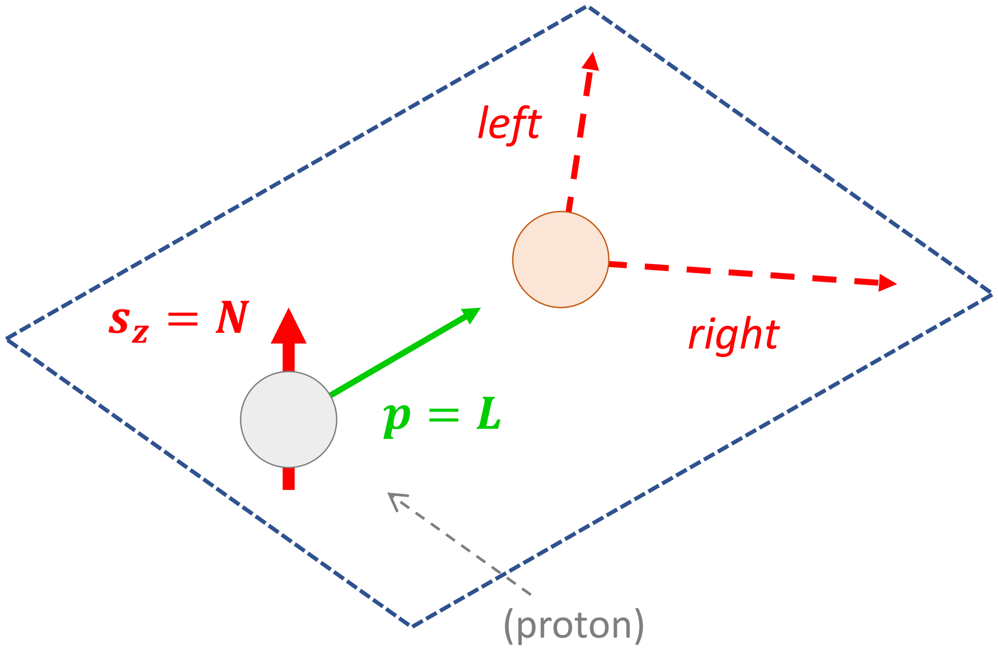
  Normal $\boldsymbol{N}$

  Sideways $\boldsymbol{S}$

$$\boldsymbol{S} = \boldsymbol{N} \times \boldsymbol{L}$$

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

refers to the projectile



Analyzing power A_N

Polarization $P = \frac{n^{\uparrow} - n^{\downarrow}}{n^{\uparrow} + n^{\downarrow}}$

The Full Picture

- Elastic scattering obeys parity conservation and time invariance.
- The collision is symmetric (in the center-of-mass frame), recoil and ejectile are indistinguishable.

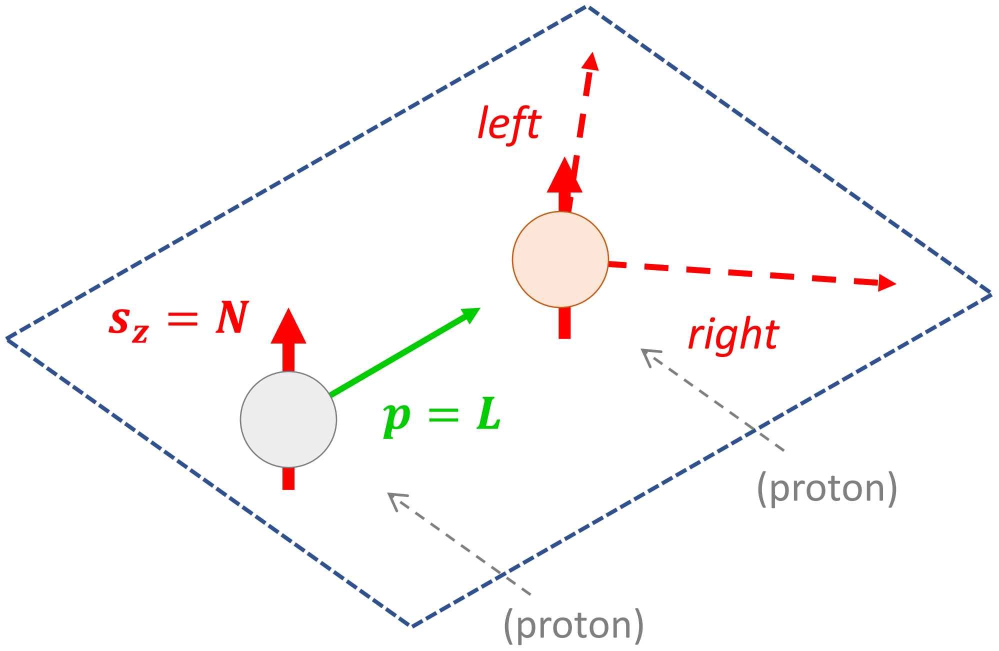
$$\rho_f = \boldsymbol{M}\rho_i\boldsymbol{M}^* \qquad \rho = \sum_n p_n\,|n\rangle\langle n| \qquad \boldsymbol{M} = \sum_{i,f} a_{f,i}\sigma_i \otimes \sigma_f$$

$$\rho_i = \rho_{beam} \otimes \rho_{target}$$

$$\frac{d\sigma}{d\Omega} = Tr(\rho_f) = \sum_n p_n\,|\langle n|\boldsymbol{M}|n\rangle|^2$$

$$\frac{d\sigma}{d\Omega} = a_{0000} + \sum_n P_n a_{00n0} + \sum_m Q_m a_{000m} + \sum_{m,n} P_n Q_m a_{00nm} + \cdots$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left(1 + \sum_n P_n A_{00n0} + \sum_m Q_m A_{000m} + \sum_{m,n} P_n Q_m A_{00nm} + \cdots\right)$$



→ 4^4=256 possible Observables (25 independent parameters)

Transverse Single-Spin Asymmetries

- Elastic scattering obeys parity conservation and time invariance.
- The collision is symmetric (in the center-of-mass frame), recoil and ejectile are indistinguishable.

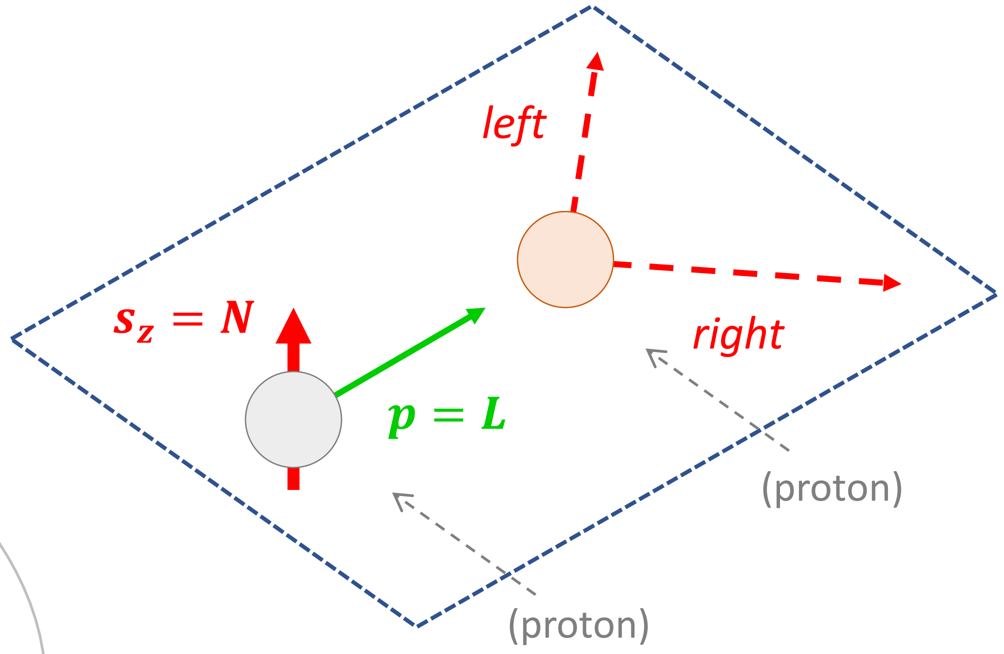
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left(1 + P_{beam}A_{00N0} + P_{target}A_{000N}\right)$$

ejectile, recoil, projectile, target

- For elastic scattering:

$$A_{00N0} = A_{000N}$$

$$P_{Beam} = \frac{\varepsilon_{Beam}}{\varepsilon_{Target}} P_{Target}$$

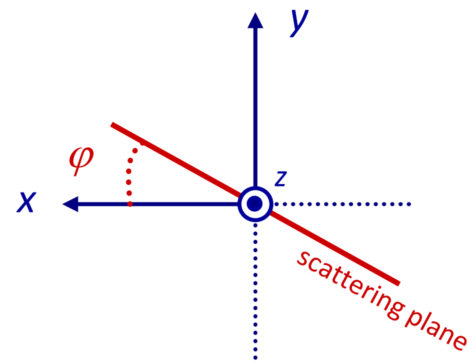


Remember, we just call this A_N

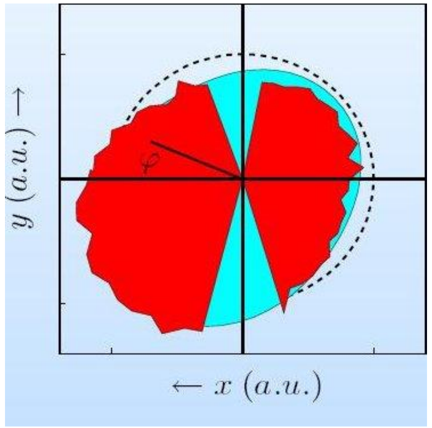
Transverse Single-Spin Asymmetries

- Transformation of $\boldsymbol{S} = \boldsymbol{N} \times \boldsymbol{L}$ into the laboratory frame

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left(1 + P \cdot A_N \cdot \cos\varphi\right)$$



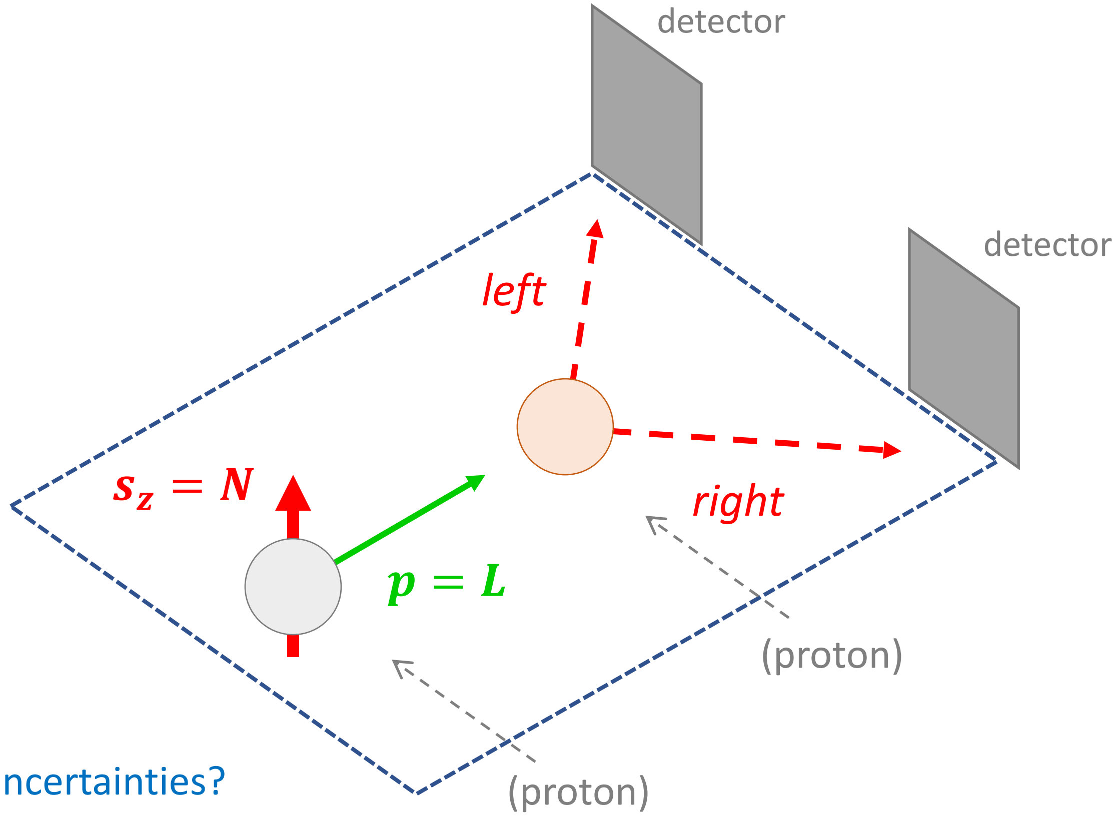
$$P_N = -P_x \sin\varphi + P_y \cos\varphi$$
$$P_S = P_x \cos\varphi + P_y \sin\varphi$$
$$P_L = P_z$$



$$N = \int \frac{d\sigma}{d\Omega} \mathcal{L}_P(t) e(d\Omega, t) d\Omega dt$$

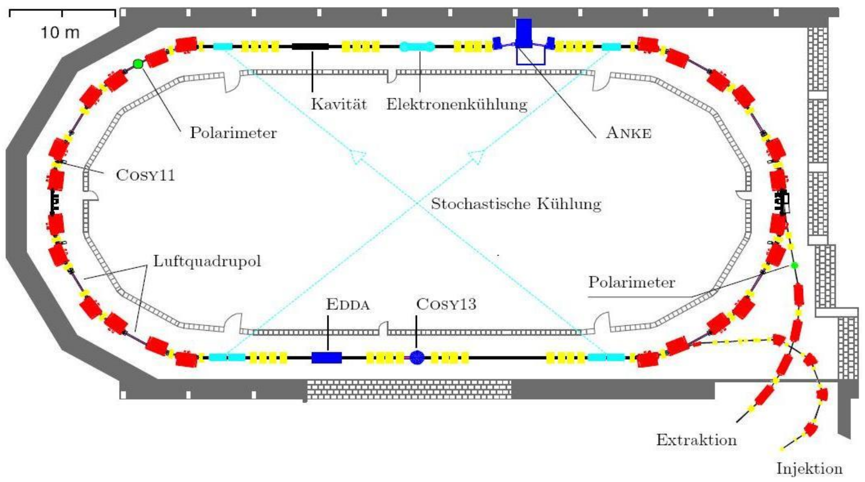
What are possible sources of systematic uncertainties?

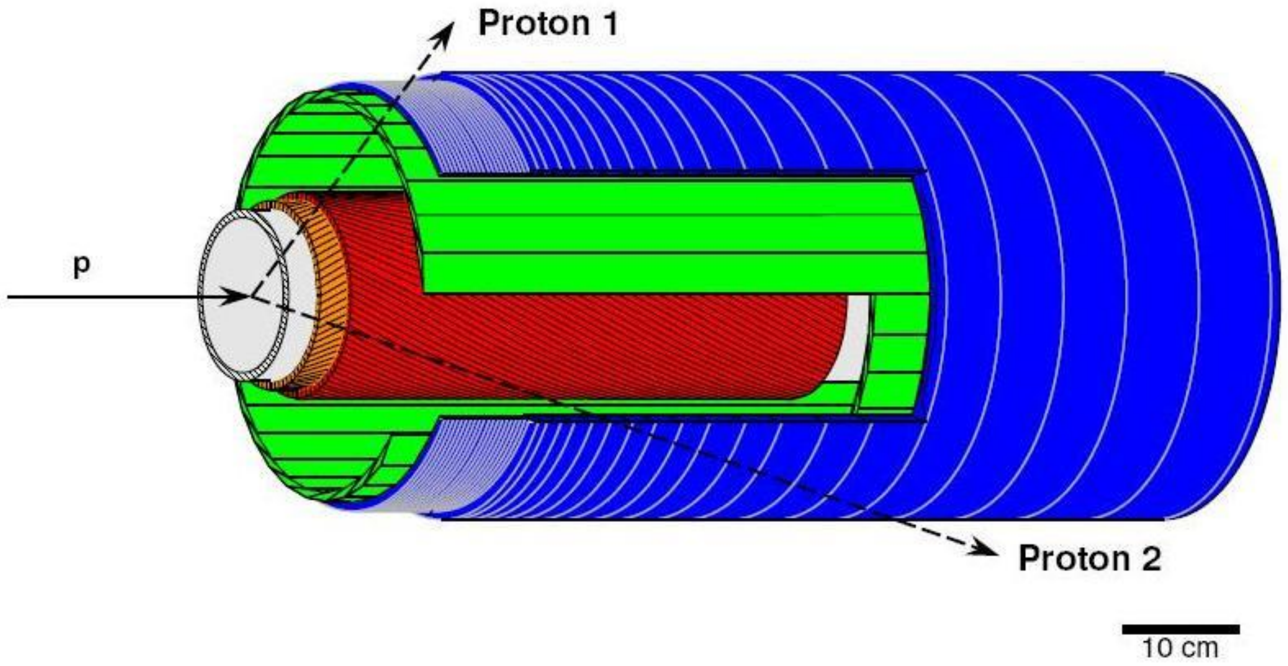
And how can you avoid them?



Elastic $p + p$ Scattering

- Example: EDDA @ COSY





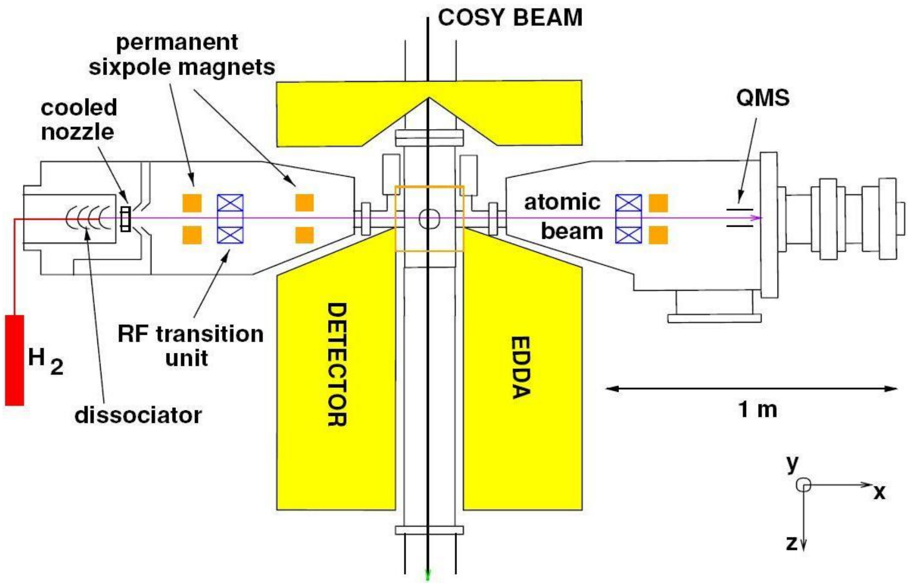
- Kinematic correlation in elastic scattering

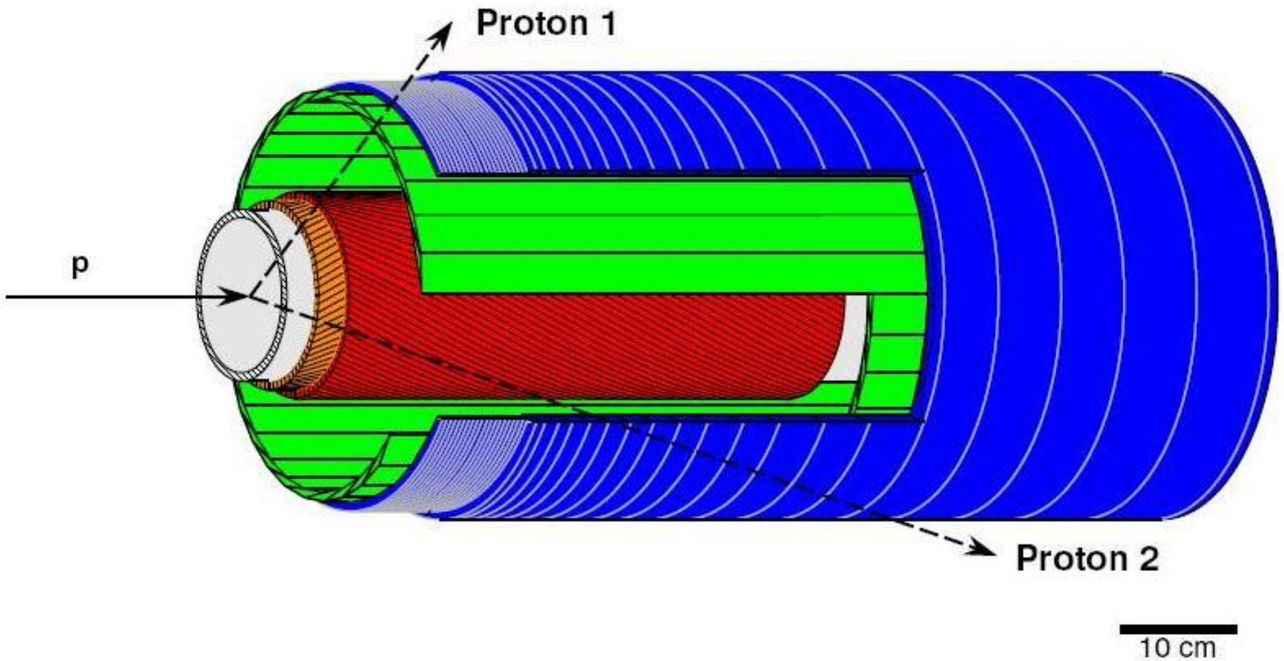
$$\varphi_1 - \varphi_2 = \pi$$
$$\tan\vartheta_1 \cdot \tan\vartheta_2 = 1/\gamma_{cm}^2$$

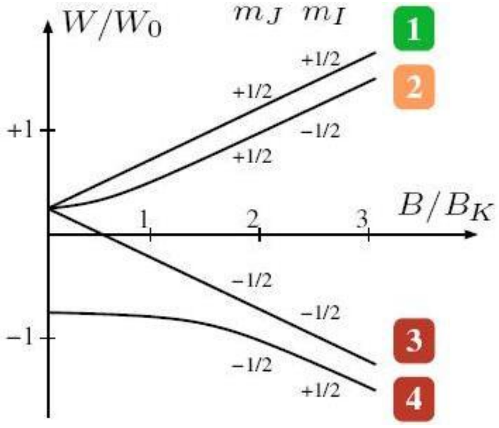
- EDDA detector
  - Scintillator hodoscope specifically designed for elastic $p + p$ scattering

Elastic $p + p$ Scattering

- Example: EDDA @ COSY







- Atomic hydrogen target
  - Selection of hyperfine state 1 (of 4)
  - Magnetic holding field $\mathrm{B_{x,y,z}} \approx 10\ \mathrm{G}$
  - Rabi unit for polarization measurement
  - Target polarization $Q \approx 70\%$

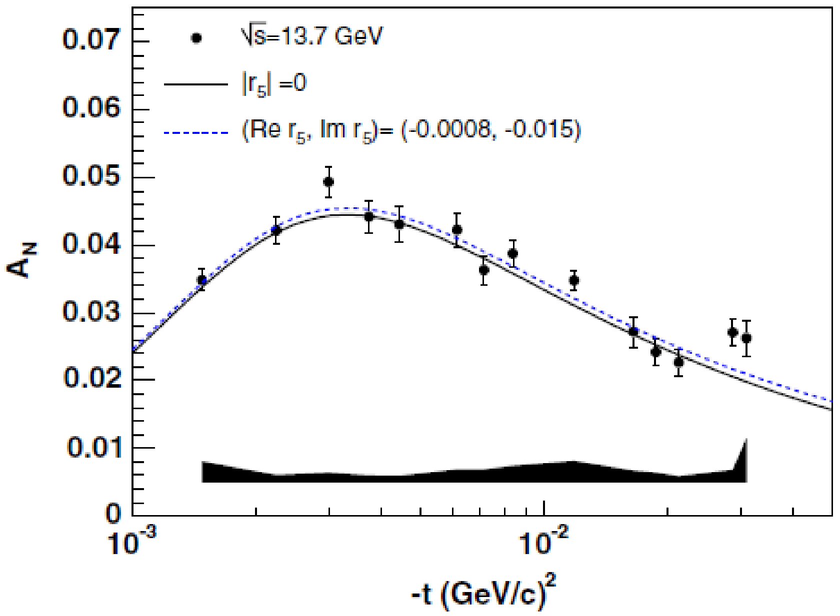
Elastic Scattering at RHIC energies

- The beam momentum is $100 - 250\ \mathrm{GeV}$.
- A significant analyzing power exists in the Coulomb-Nuclear Interference region.

$$\varphi(s,t) = \langle \lambda_C \lambda_D | \varphi | \lambda_A \lambda_B \rangle$$

$$\varphi_1(s,t) = \left\langle +\frac{1}{2} + \frac{1}{2} \middle| \varphi \middle| +\frac{1}{2} + \frac{1}{2} \right\rangle$$
$$\varphi_2(s,t) = \left\langle +\frac{1}{2} + \frac{1}{2} \middle| \varphi \middle| -\frac{1}{2} - \frac{1}{2} \right\rangle$$
$$\varphi_3(s,t) = \left\langle +\frac{1}{2} - \frac{1}{2} \middle| \varphi \middle| +\frac{1}{2} - \frac{1}{2} \right\rangle$$
$$\varphi_4(s,t) = \left\langle +\frac{1}{2} - \frac{1}{2} \middle| \varphi \middle| -\frac{1}{2} + \frac{1}{2} \right\rangle$$
$$\varphi_5(s,t) = \left\langle +\frac{1}{2} + \frac{1}{2} \middle| \varphi \middle| +\frac{1}{2} - \frac{1}{2} \right\rangle$$

A. Poblaguev et al., Phys. Rev. D 79, 094014 (2009)



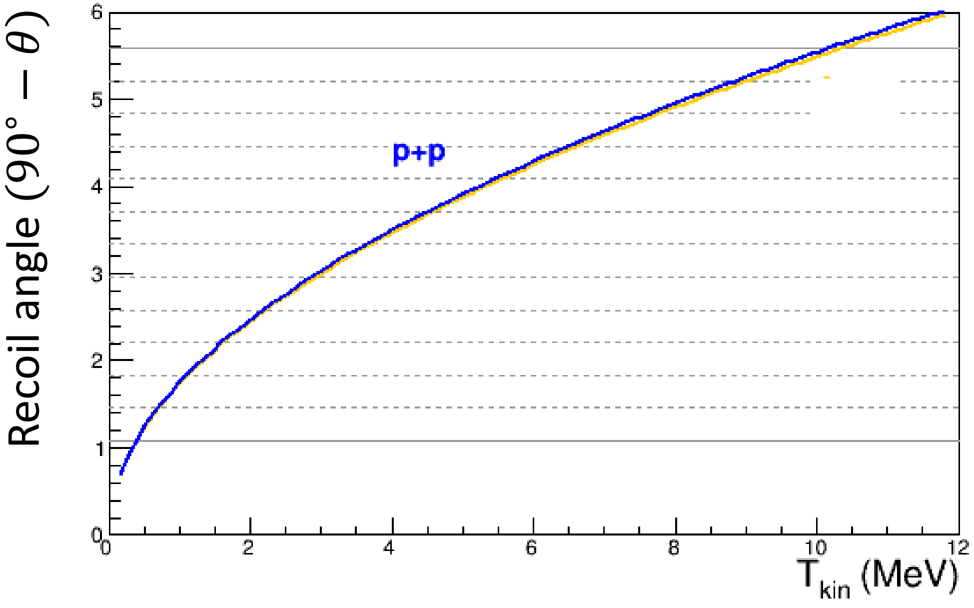
$$A_N \frac{ds}{dt} = -\frac{4\pi}{s^2} \mathrm{Im}\left[\varphi_5^{em*}(s,t)\varphi_+^{had}(s,t) + \varphi_5^{had*}(s,t)\varphi_+^{em}(s,t)\right]$$

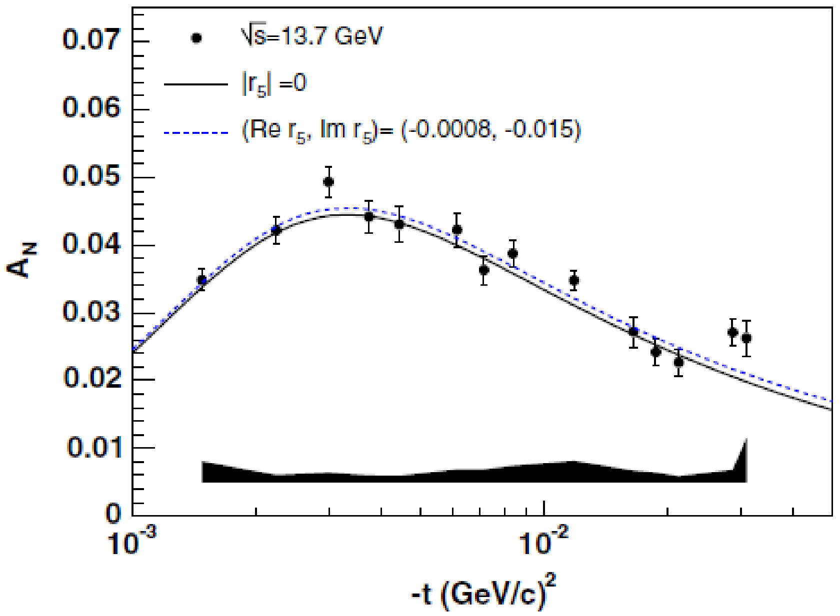
no-flip amplitude: $\varphi_+(s,t) = \frac{1}{2}[\varphi_1(s,t) + \varphi_3(s,t)]$

Elastic Scattering at RHIC energies

- The beam momentum is $100 - 250$ GeV.
- A significant analyzing power exists in the Coulomb-Nuclear Interference region.
- Recoil comes out almost perpendicular to the beam direction.

A. Poblaguev et al., Phys. Rev. D 79, 094014 (2009)

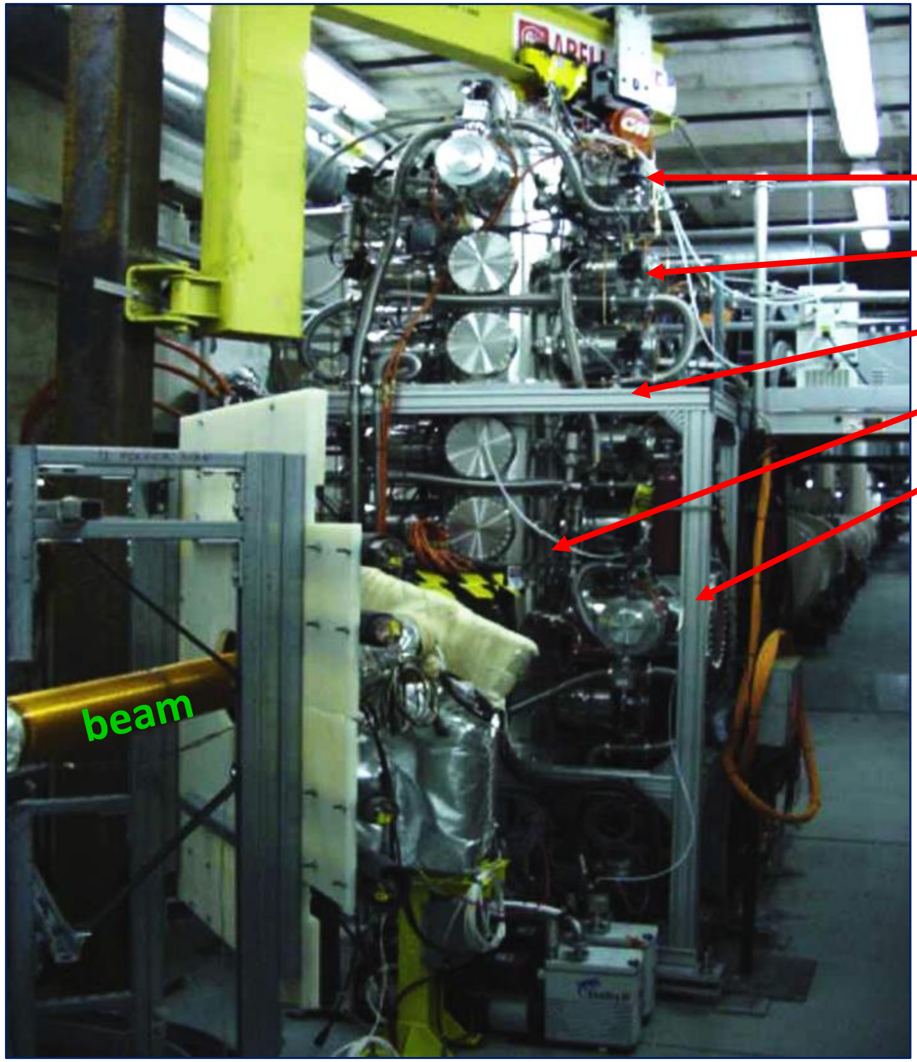




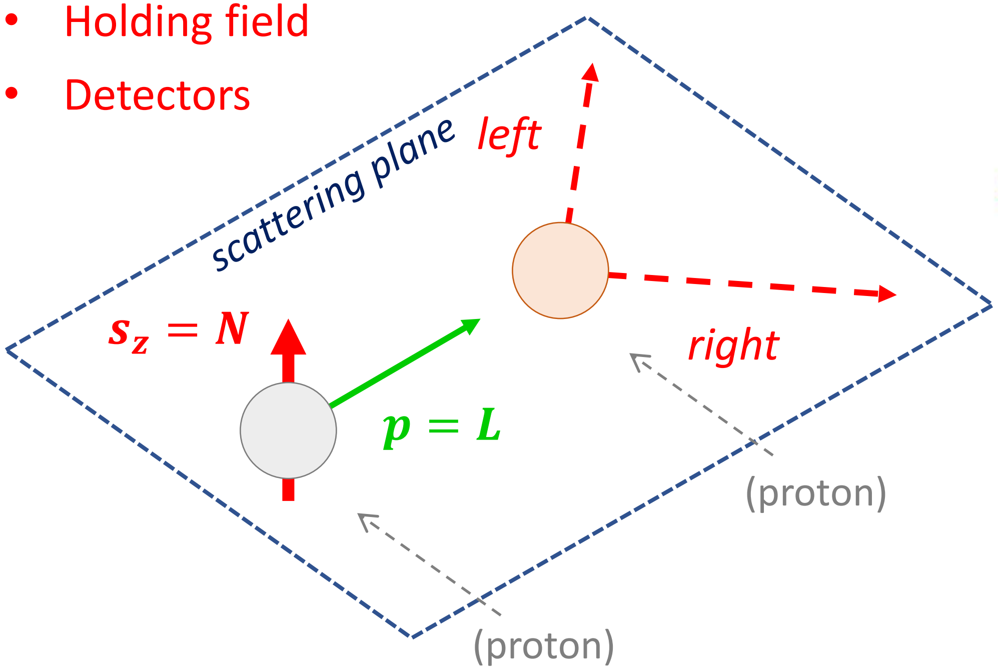
Kinetic energy of the recoil proton

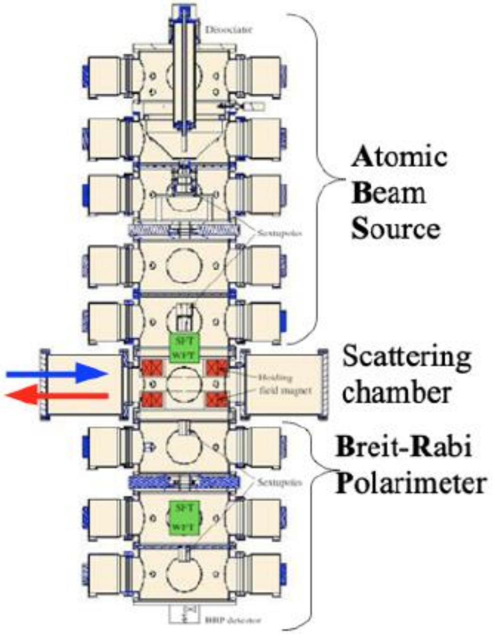
An Absolute Polarimeter at RHIC / EIC

- Polarized atomic hydrogen jet target (HJET)

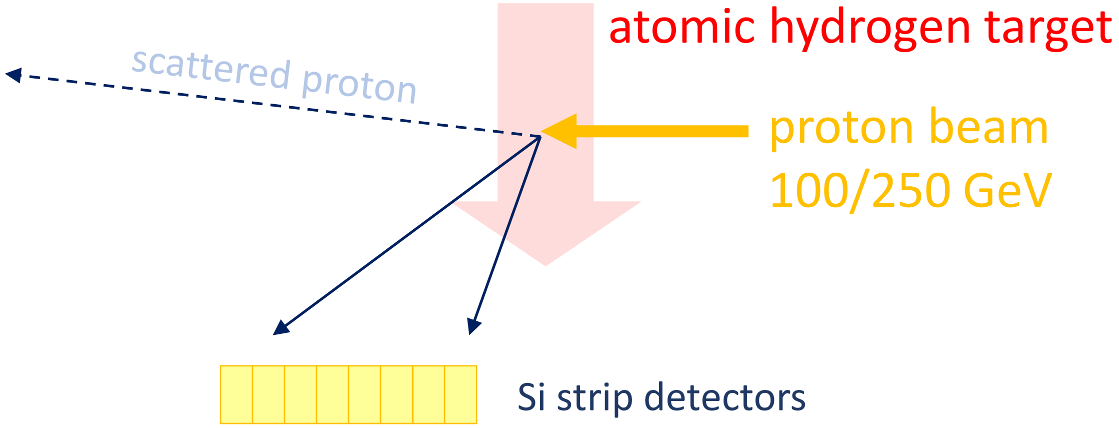


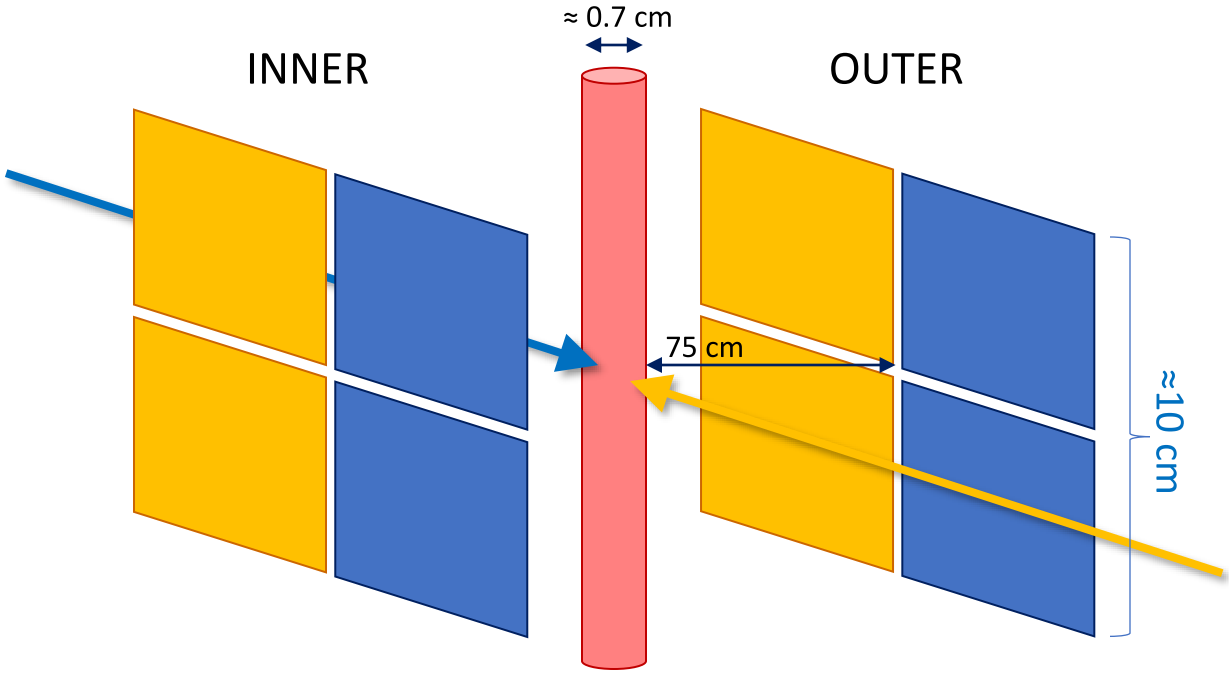
- H_2 source
- Dissociator
- RF unit
- Holding field
- Detectors



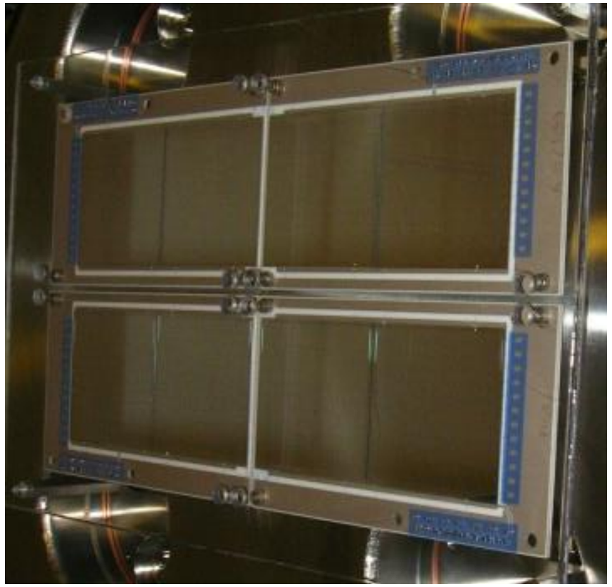


HJET Setup for RHIC / EIC

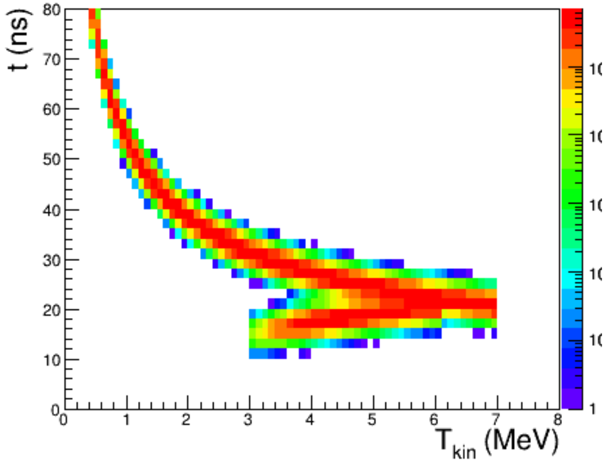




- Polarized atomic hydrogen jet target
- Set of eight Hamamatsu Si strip detectors
- 12 vertical strips
  - 3.75 mm pitch
  - 500 μm thick
- Uniform dead layer ≈ 1.5 μm



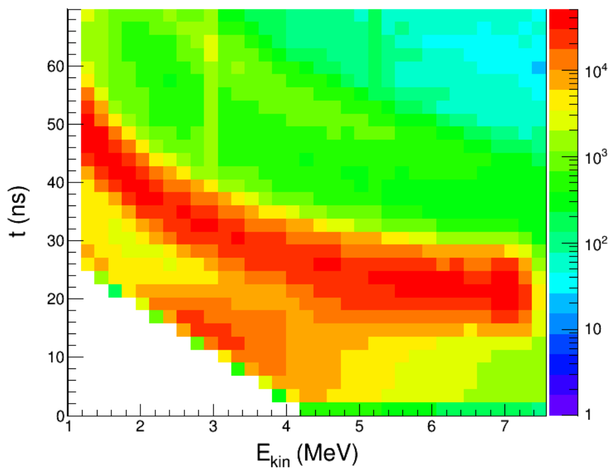
Proton Recoil Measurement



Expected elastic signal

Simple toy simulation with bunch length 3 ns

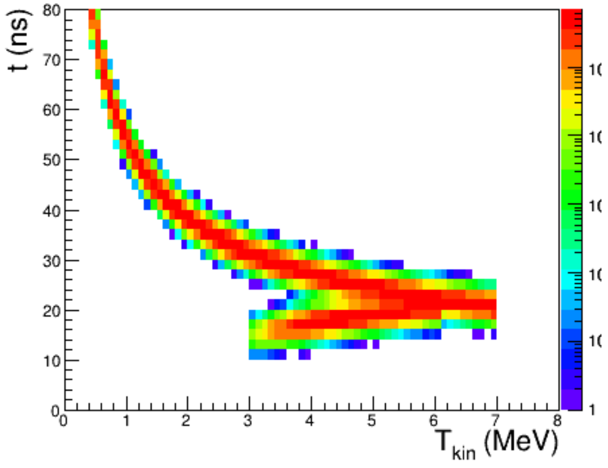
Non-relativistic: $T_{kin} = \frac{1}{2}mv^2$ → Time of flight is used for particle identification

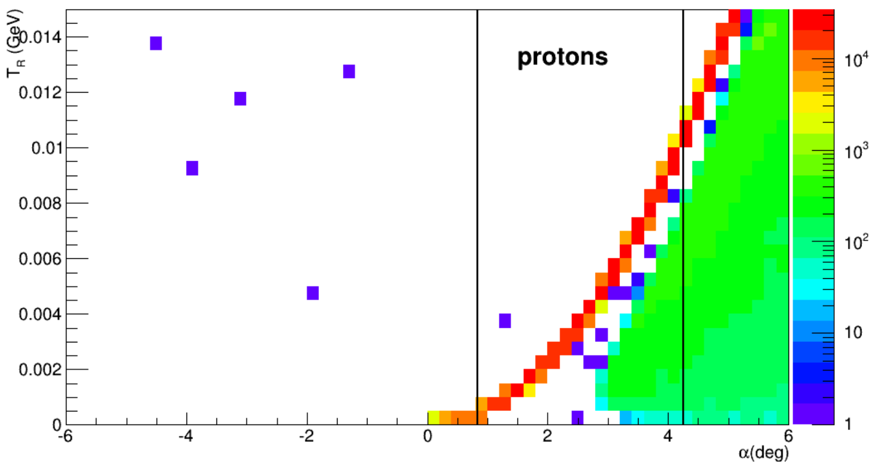


Real measurement

Already includes some basic cuts (low E, low t)

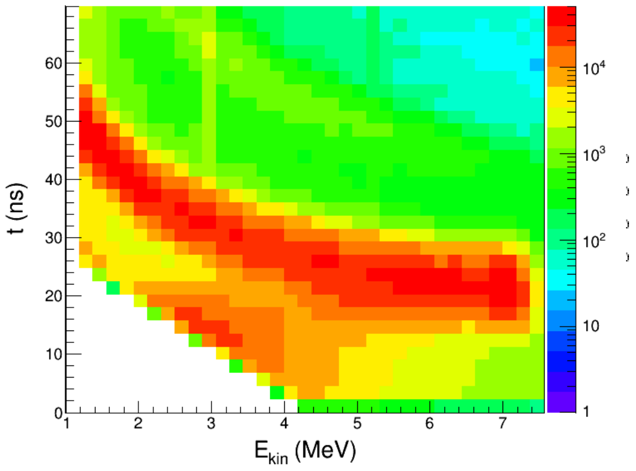
Proton Recoil Measurement

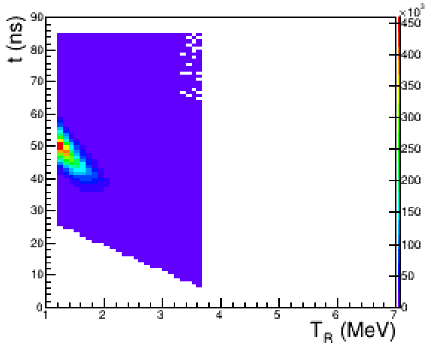


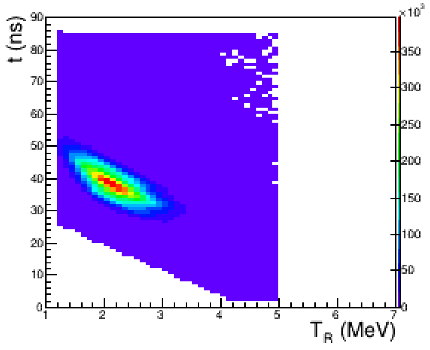


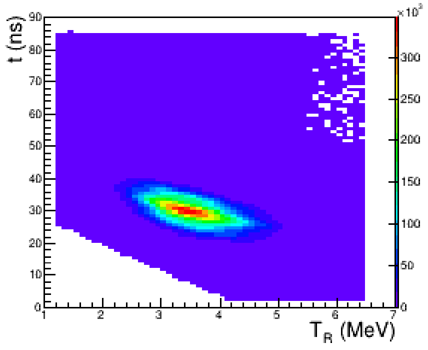
Time of flight is used for particle identification

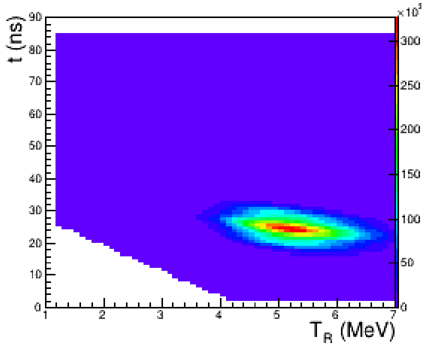
Recoil angle is used for kinematic correlation in elastic scattering











Absolute Beam Polarization

$$\varepsilon = A_N \cdot P$$

$$P_{Beam} = \frac{\varepsilon_{Beam}}{\varepsilon_{Target}} P_{Target}$$

1

Polarization independent background

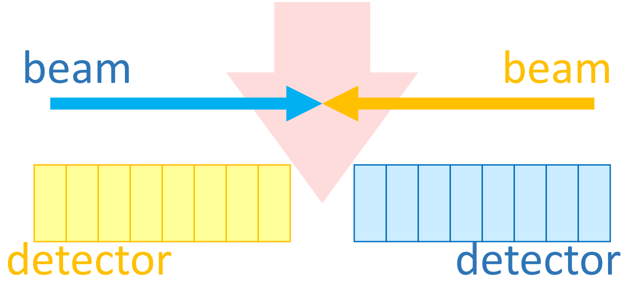
$$\varepsilon = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow} + 2 \cdot N_{bg}} \Rightarrow \frac{\varepsilon_B}{\varepsilon_T} = \frac{N_B^{\uparrow} - N_B^{\downarrow}}{N_T^{\uparrow} - N_T^{\downarrow}}$$

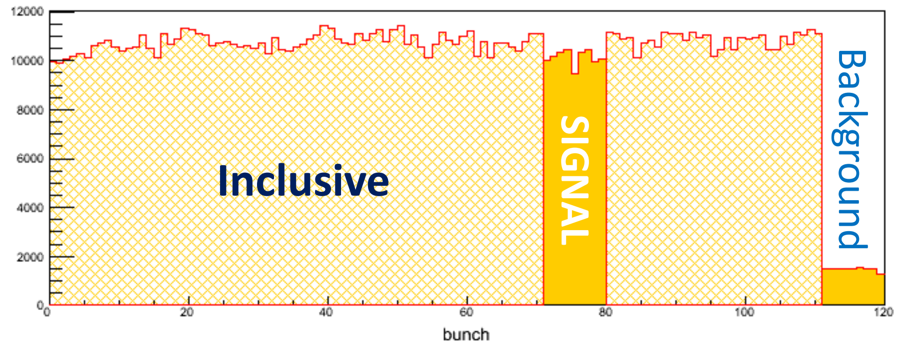
2

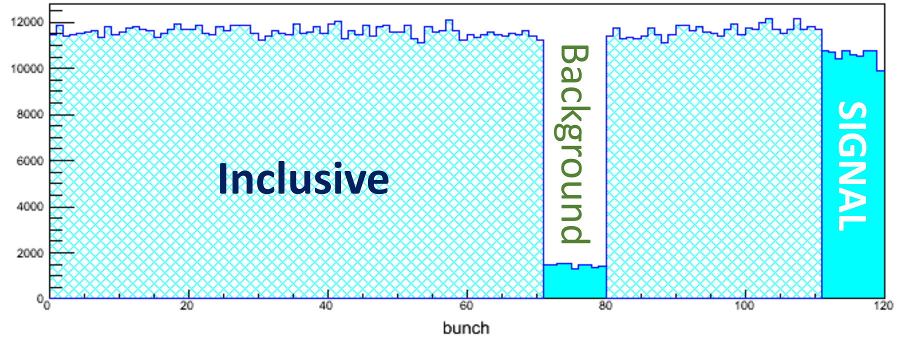
Polarization dependent background

$$\varepsilon = \frac{\varepsilon_{inc} - r \cdot \varepsilon_{bg}}{1 - r}$$

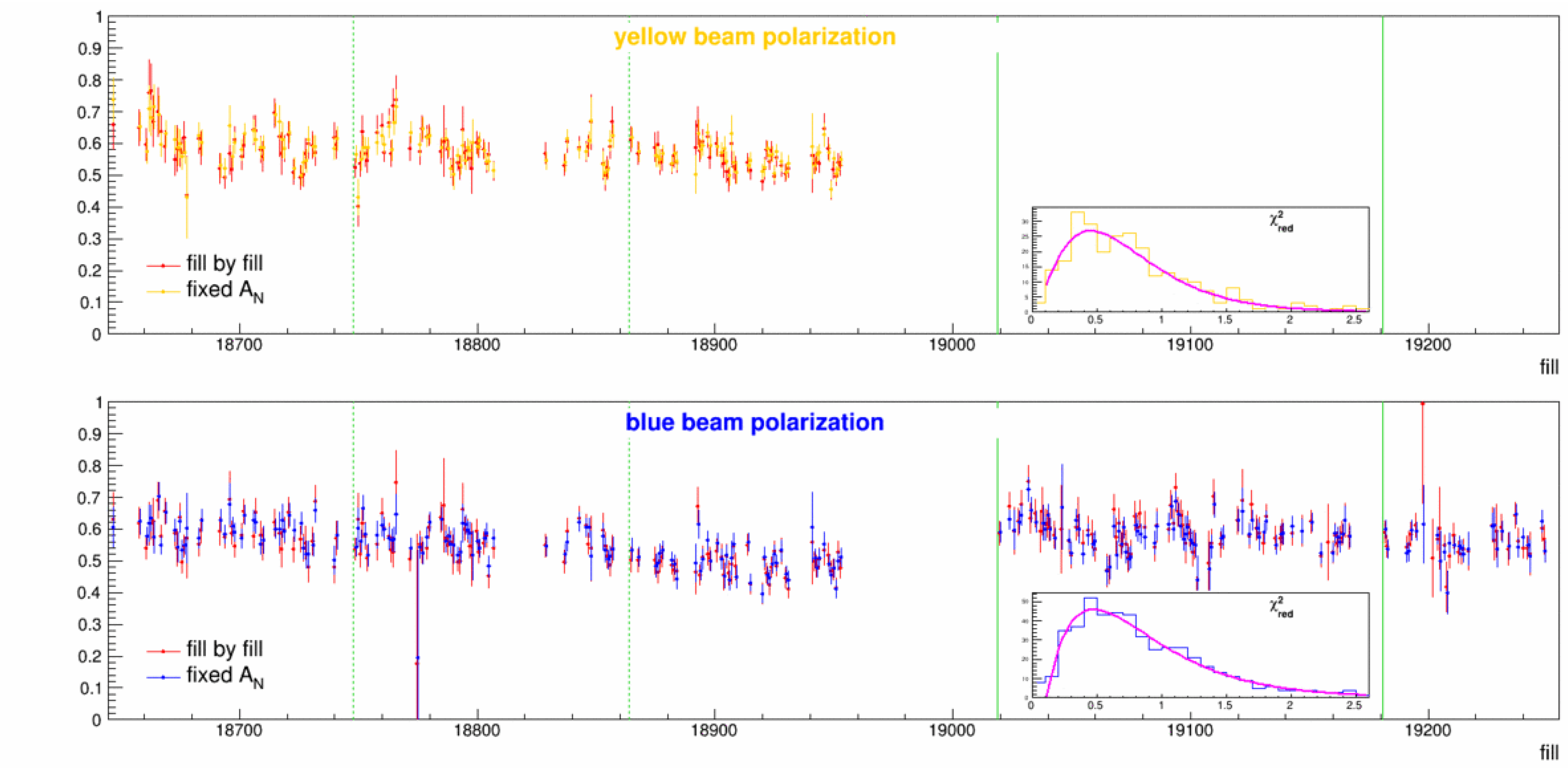
background fraction $r = N_{bg}/N$



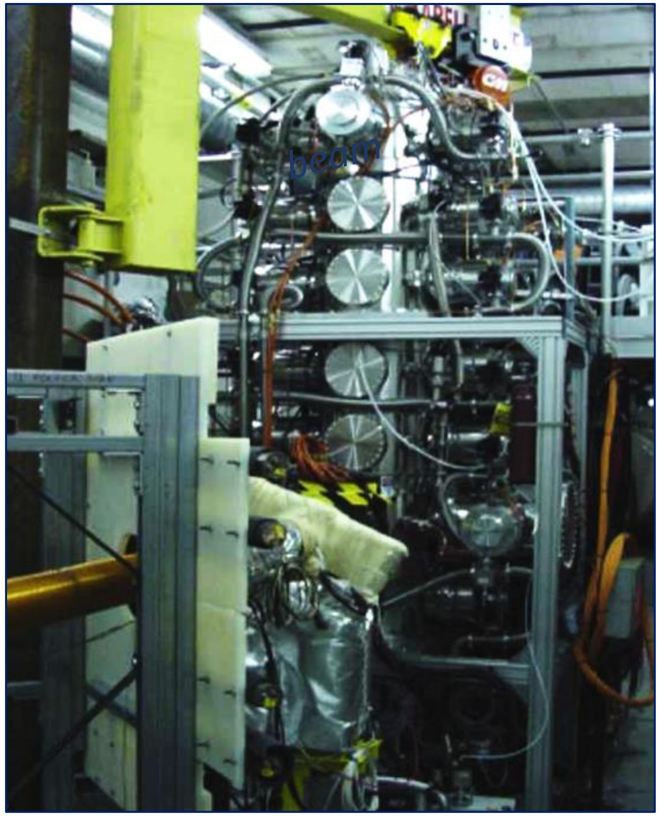




Measured Beam Polarizations



Additional Fast Polarimeters



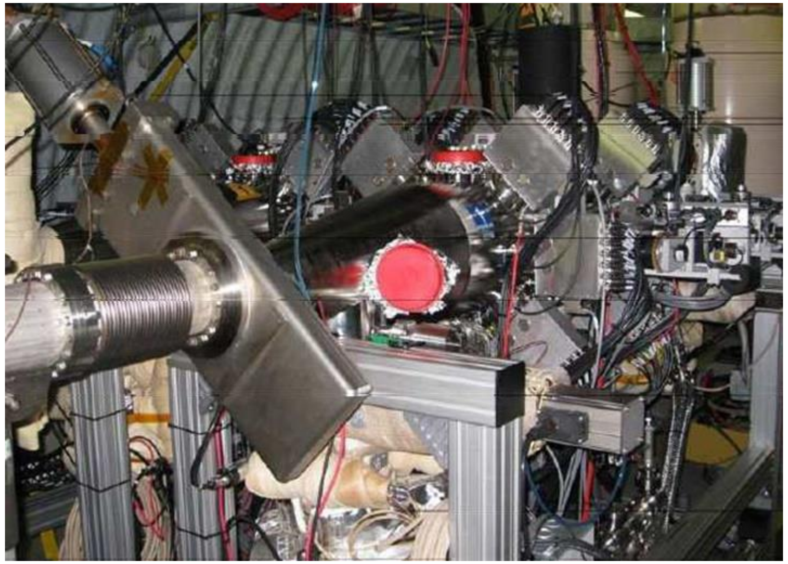
From our list of requirements:

Time-dependence (polarization decay)

Bunch-by-bunch polarization

Transverse polarization profile of bunches

Also has to be non-destructive!



Carbon polarimeters

Fast measurement

$\delta P/P \approx 4\%$

Beam polarization profile

Bunch-by-bunch

Polarization decay (time dependence)

Hydrogen jet polarimeter

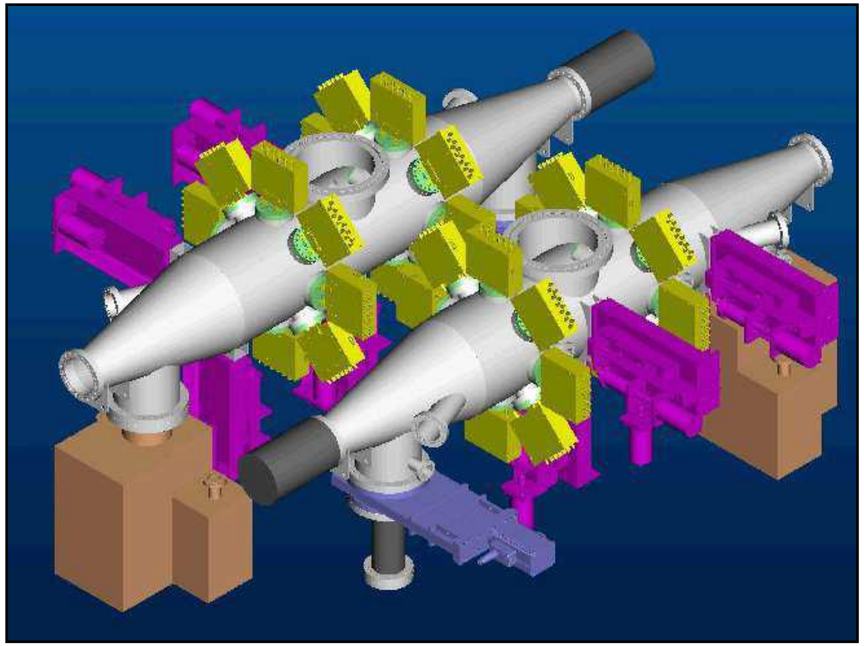
Polarized target

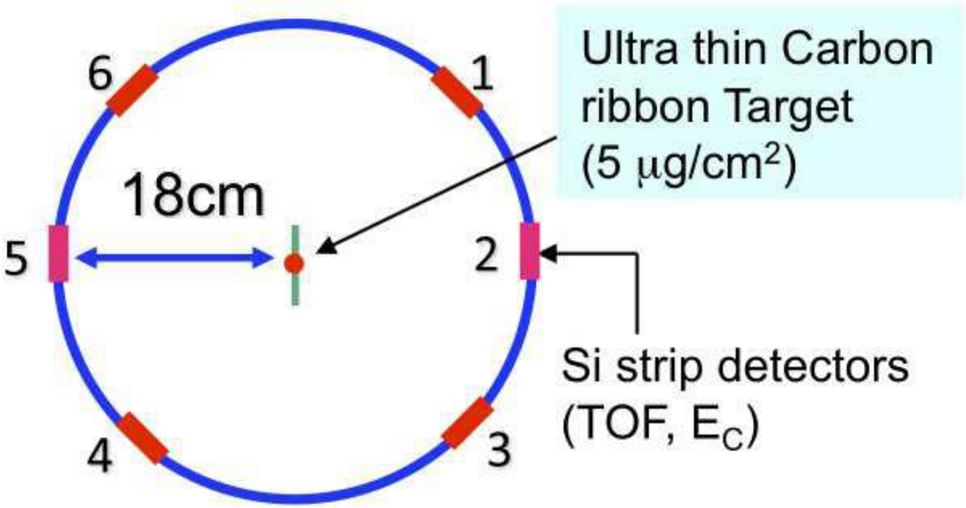
Continuous operation

$\delta P/P \approx 5-6\%$ per 8 hours of operation

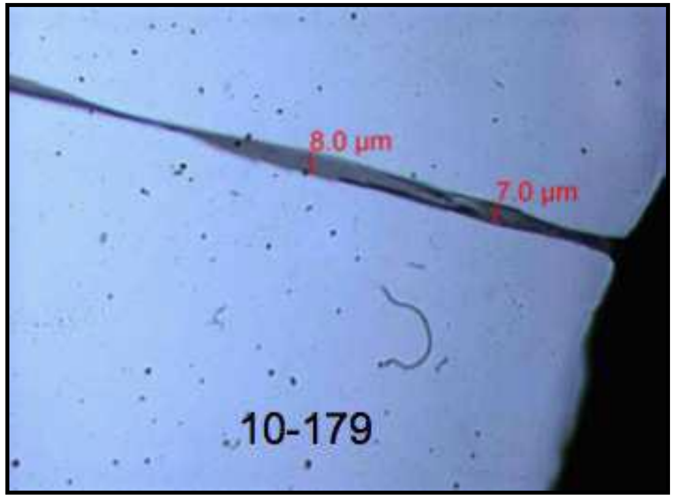
normalization →

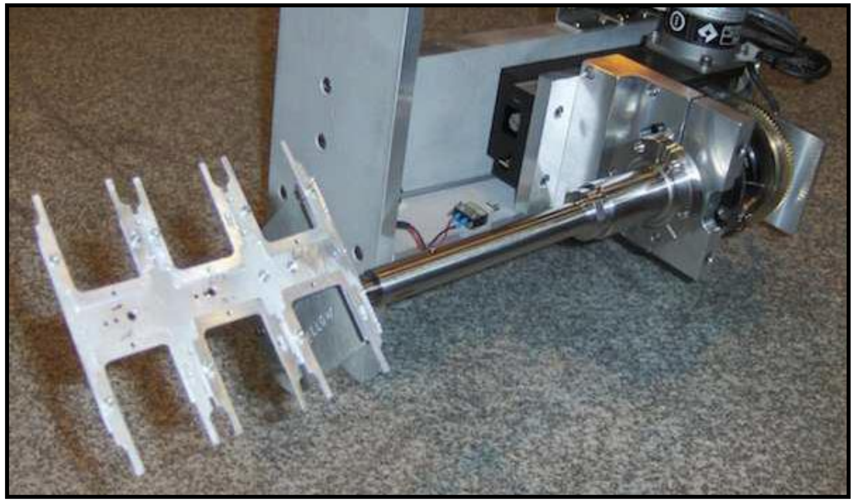
Fiber Target Polarimeters





- Ultra-thin ribbon targets:
  $\approx 10\ \mu\text{m}\ x\ 100\ \text{nm}$
- Target holder inside the beam pipe





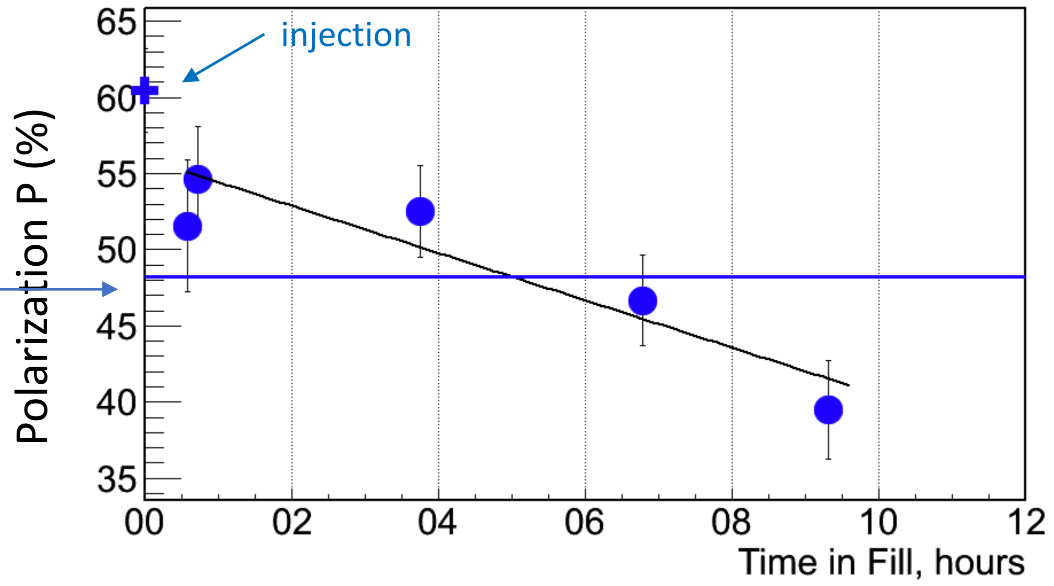
Polarization Decay

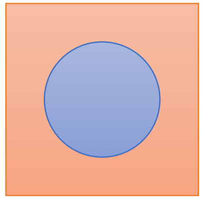
Polarization losses during the store are correlated to

- acceleration
- emittance
- profile

$$P = P_0 + \frac{dP}{dt}t$$

normalization with HJET





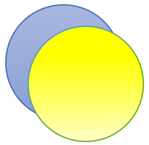
$$P_{jet} = \frac{\int dxdyP(t)I_B(t)}{\int dxdyI_B(t)}$$

Polarization Decay

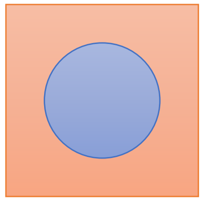
Polarization losses during the store are correlated to

- acceleration
- emittance
- profile

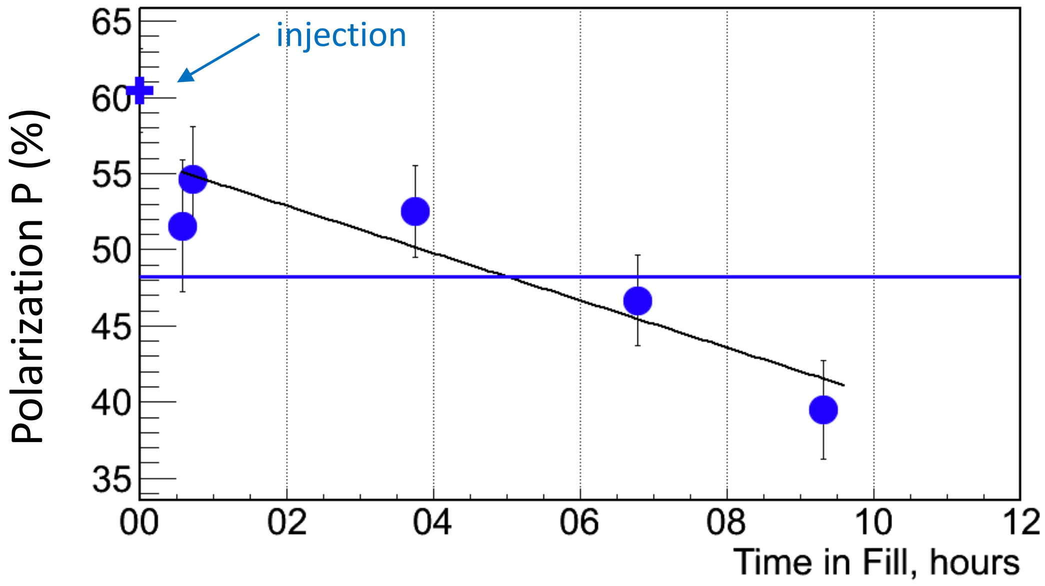
$$P = P_0 + \frac{dP}{dt} t$$



$$P_{coll} = \frac{\int dxdy P(t) I_B(t) I_Y(t)}{\int dxdy I_B(t) I_Y(t)}$$



$$P_{jet} = \frac{\int dxdy P(t) I_B(t)}{\int dxdy I_B(t)}$$



Important for experiments:

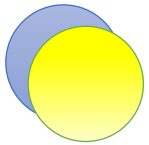
Luminosity changes throughout each store

Polarization Profile

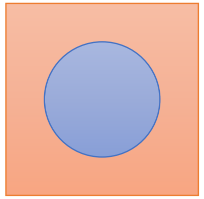
Polarization losses during the store are correlated to

- acceleration
- emittance
- profile

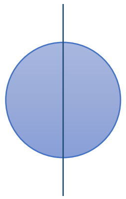
$$P = P_0 + \frac{dP}{dt}t \qquad \mathrm{R} = R_0 + \frac{dR}{dt}t$$



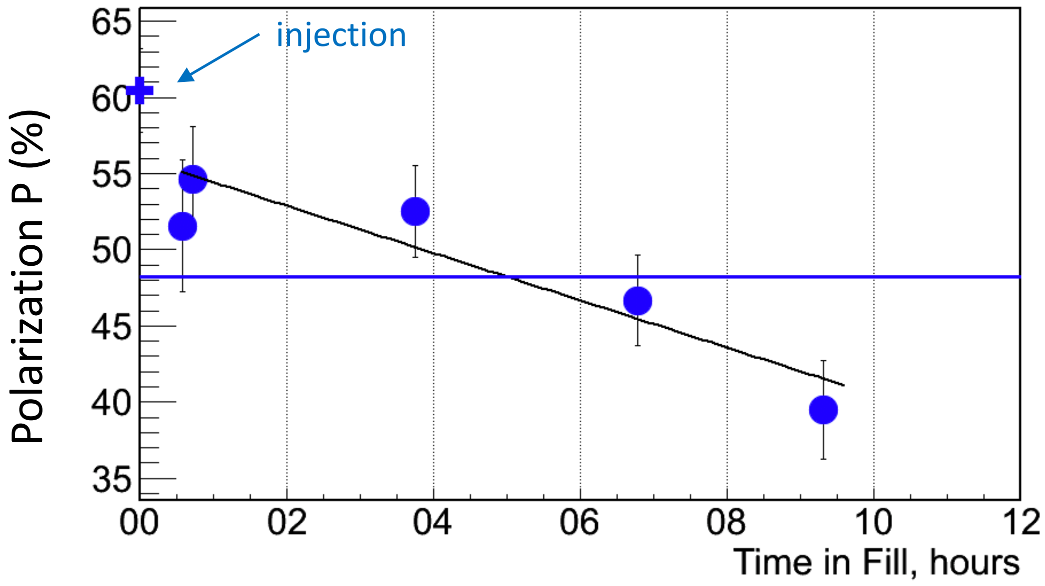
$$P_{coll} = \frac{\int dxdyP(x,y)I_B(x,y)I_Y(x,y)}{\int dxdyI_B(x,y)I_Y(x,y)}$$

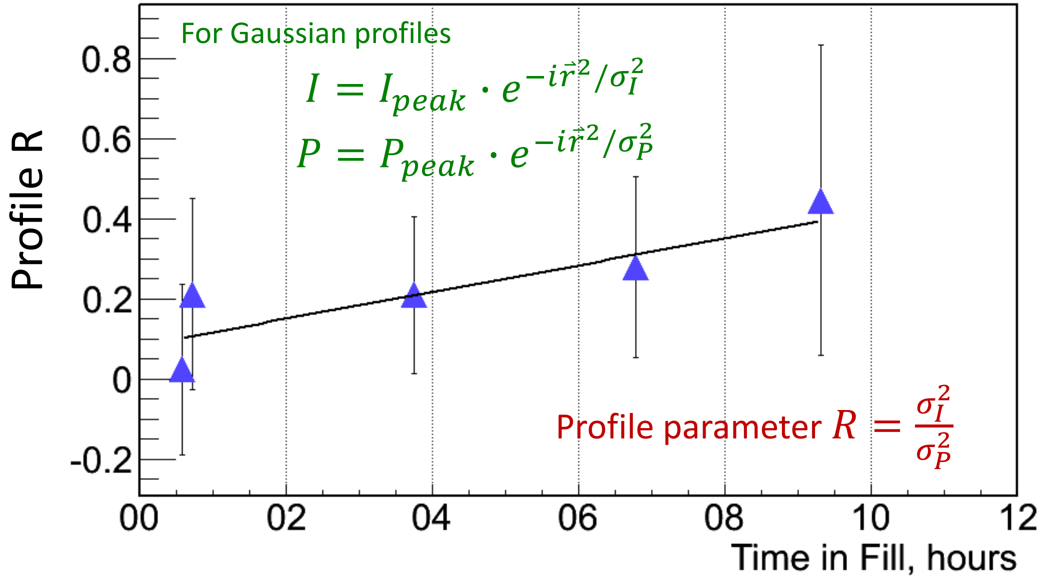


$$P_{jet} = \frac{\int dxdyP(x,y)I_B(x,y)}{\int dxdyI_B(x,y)}$$



$$P_{sweep} = \frac{\int dyP(y)I_B(y)}{\int dyI_B(y)}$$





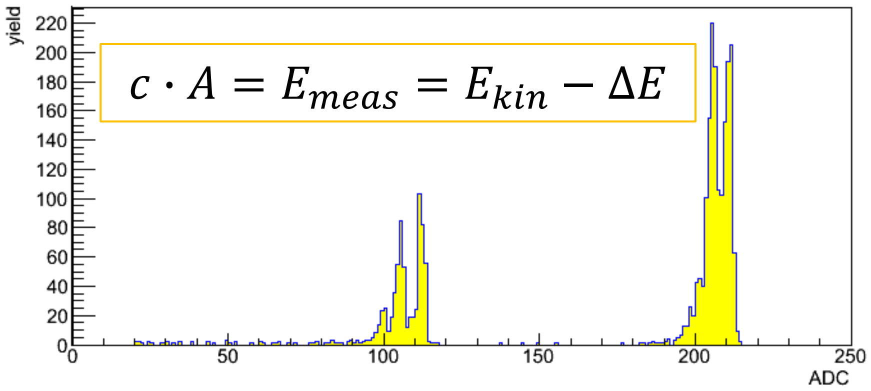
Limitations of the Measurement

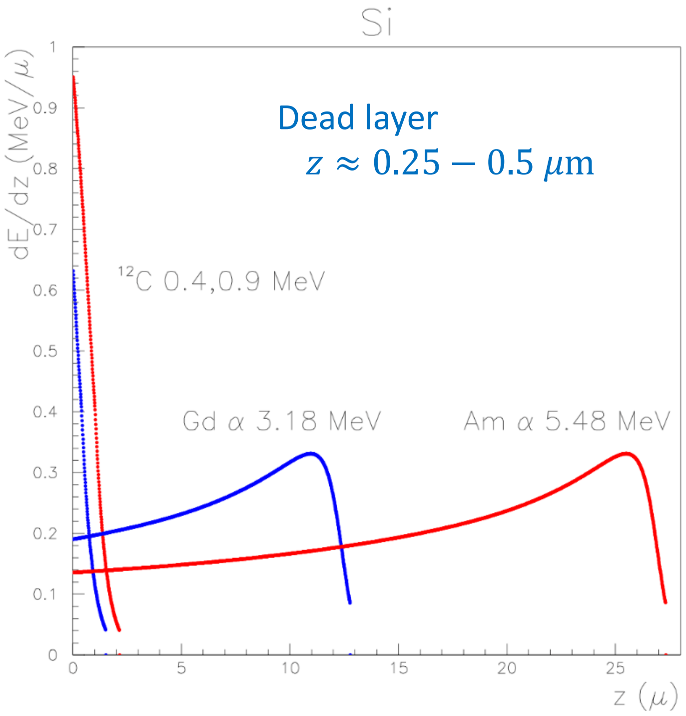
- Recoil particles have very low energy.
  - significant impact of the inactive detector parts (dead layer ΔE), especially for the Carbon measurement
  - Calibration with α-sources

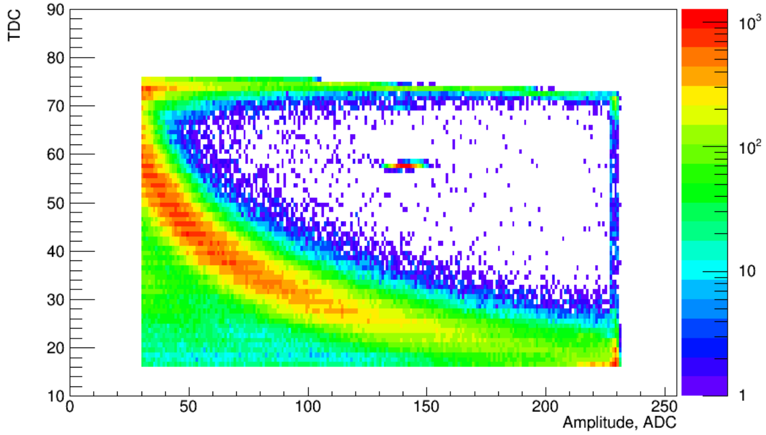
$$^{148}Gd(E_\alpha = 3.183\ \text{MeV})$$

$$^{243}Am(E_\alpha = 5.486\ \text{MeV})$$

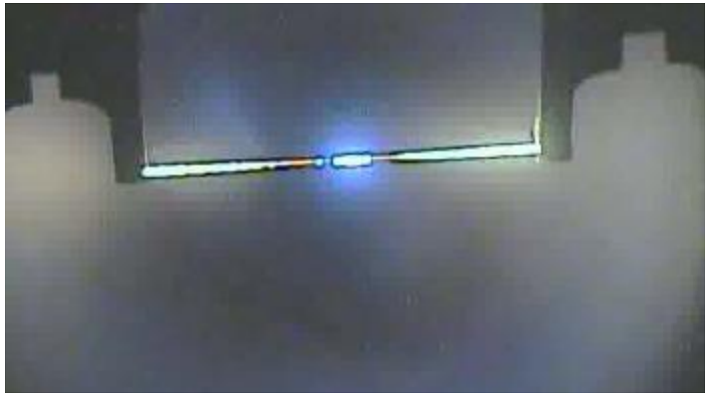
- Small angle scattering of recoil inside the target dilutes the kinematic correlation for elastic scattering.
  - Background dilutes the measured asymmetry (increases statistical uncertainty), but normalized with HJET
  - A_N drops above 1 MeV

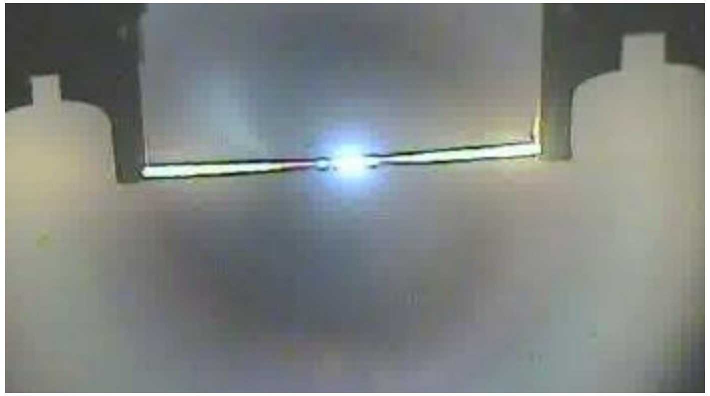


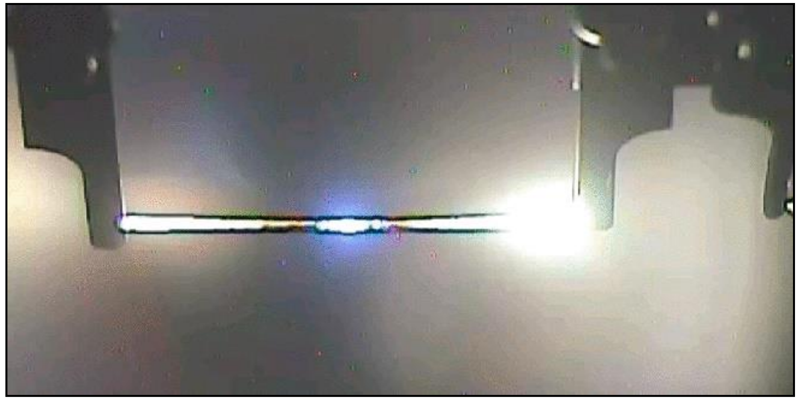




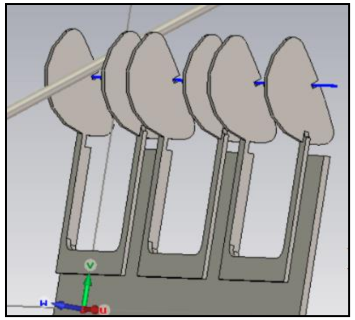
Target Lifetime

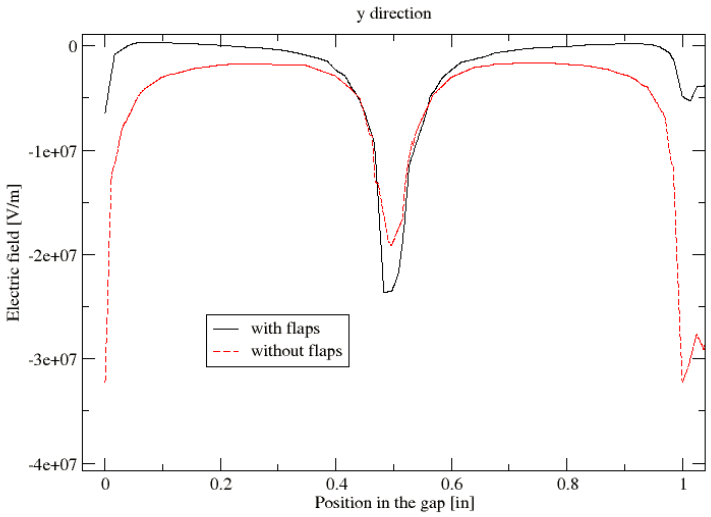






- High energy, high intensity proton beams provide an extreme environment
  - Energy loss of beam in the target
- Target is electrostatically attracted to the beam
  - Mechanical stress on target
  - Material in beam is hard to control
- Induced charge from wake field on target ends
  - Change to insulated ladder construction
- Targets have a limited lifetime

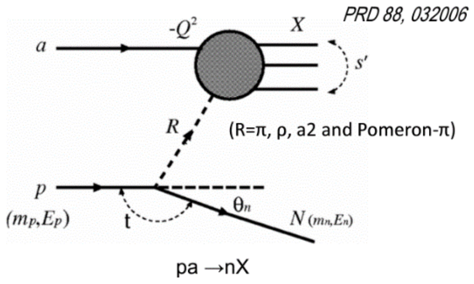


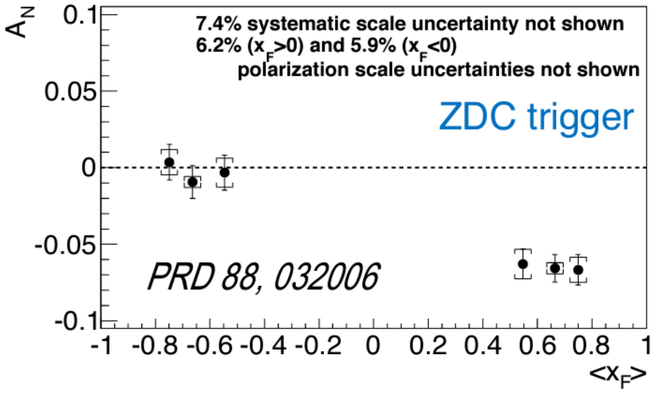


Simulation by J. Kewisch, BNL

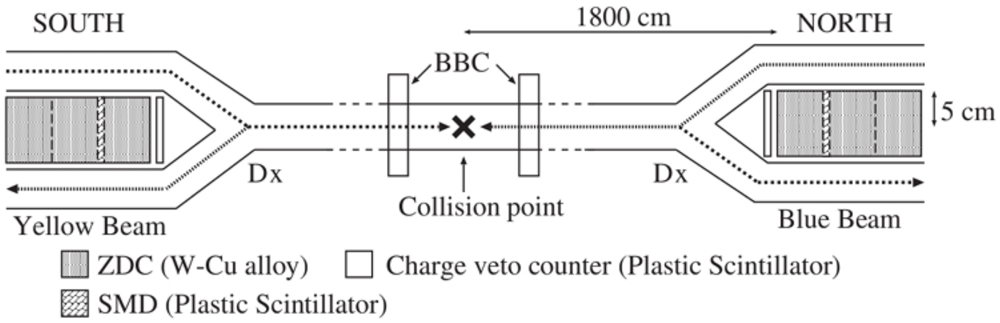
Local Polarimetry at RHIC

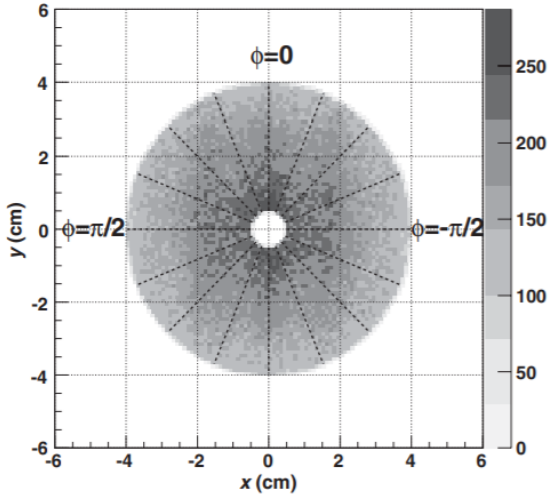
- Local polarimetry is primarily for confirming the direction of the polarization vector at the experiment.
    - Observe suppression of asymmetry or change of direction
    - Very forward going production of neutrons in $p + p$ collisions
    - First established at RHIC-IP12, standard method for RHIC experiments

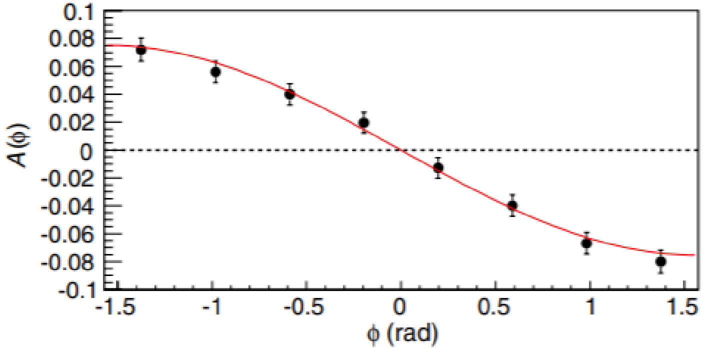




$x_F = 2p_z/\sqrt{s}$







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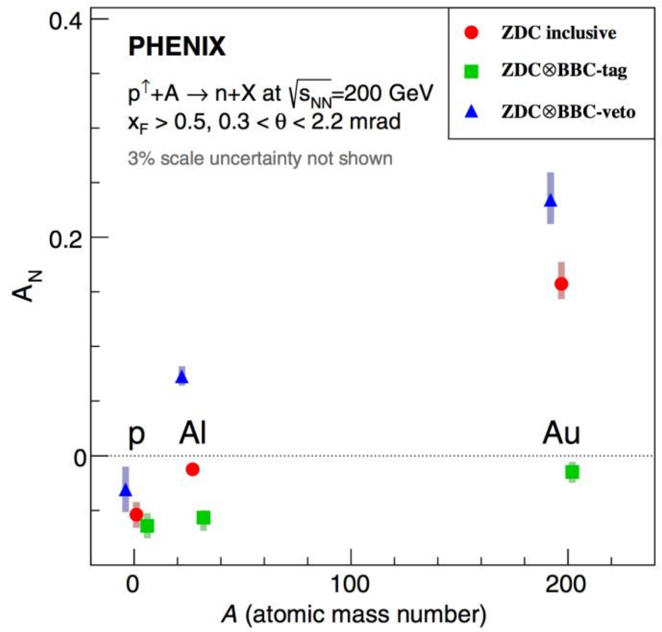
Potential for Future Applications

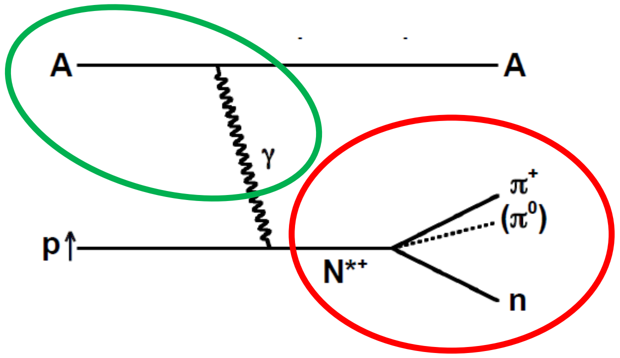
- Nuclear dependence of very forward going neutrons
  - Very large asymmetry (with opposite sign)
  - Select low multiplicity with beam-beam counters
  - Ultra-peripheral collision extension to π/a_1 model
  - Photon flux from STARlight
    Klein et al., Comput. Phys. Comm. 212 (2017) 258
  - $\gamma + p^{\uparrow} \rightarrow n + \pi^{+}$ from MAID
    Drechsel et al., Eur. Phys. J. A 34 (2007) 69

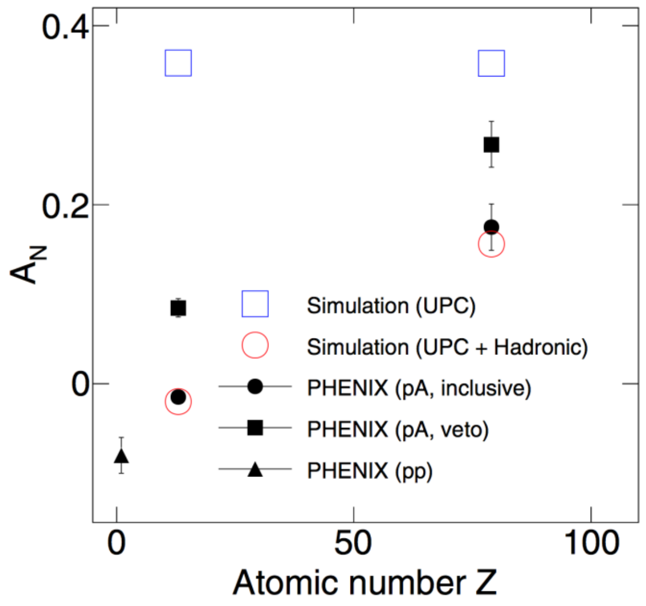
$p^{\uparrow} + p$

$p^{\uparrow} + Al$

$p^{\uparrow} + Au$



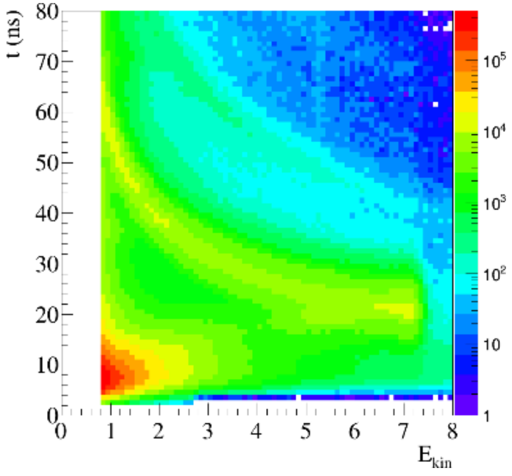




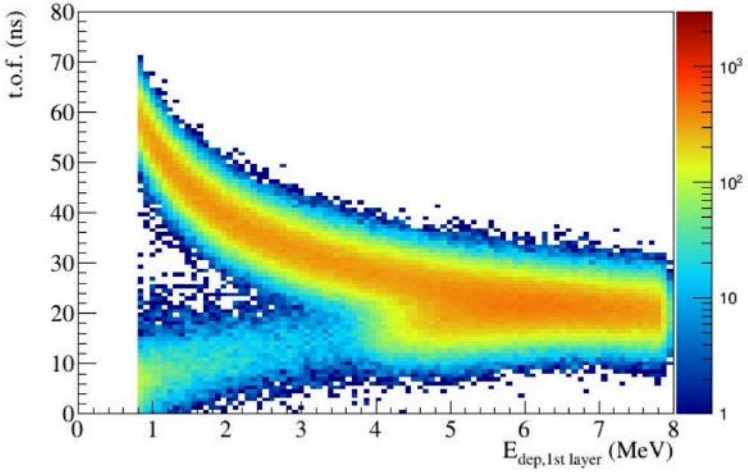
Phys. Rev. Lett 120 (2018) 022001
Phys. Rev. C 95 (2017) 044908

From RHIC…

RHIC Data



Simulation (PYTHIA+GEANT4)



- Reasonable description in simulation
- More background in real data
- Punch-through particles only leave fraction of their energy in detector

↕ Bunch length

↔ Detector resolution

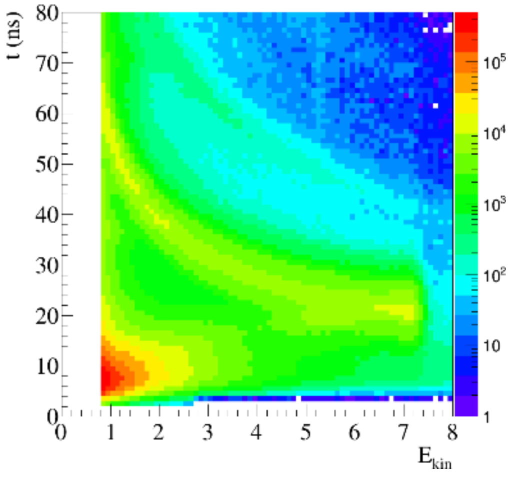
120 bunches

Bunch spacing 106 ns

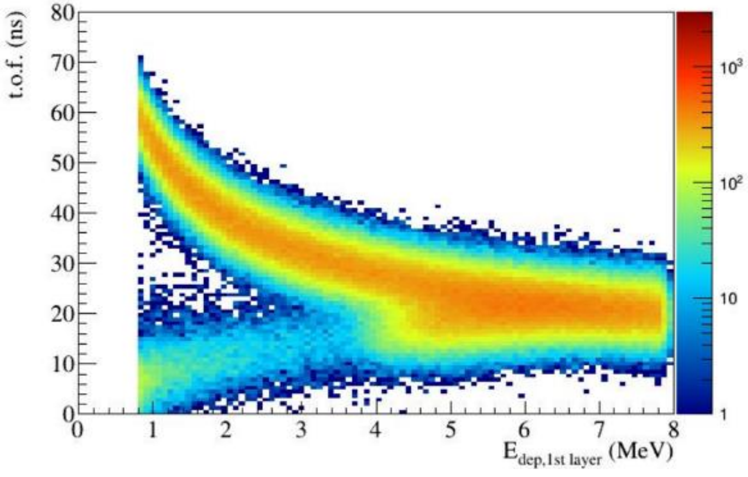
Bunch length 3.5 ns

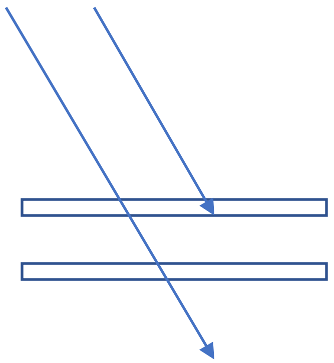
From RHIC to EIC

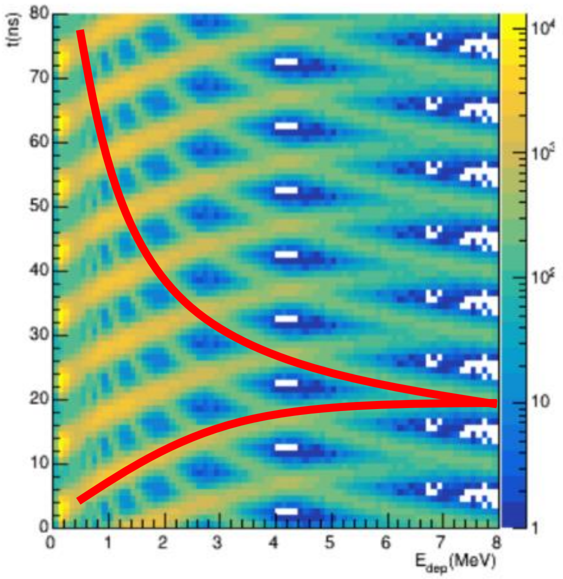
RHIC Data

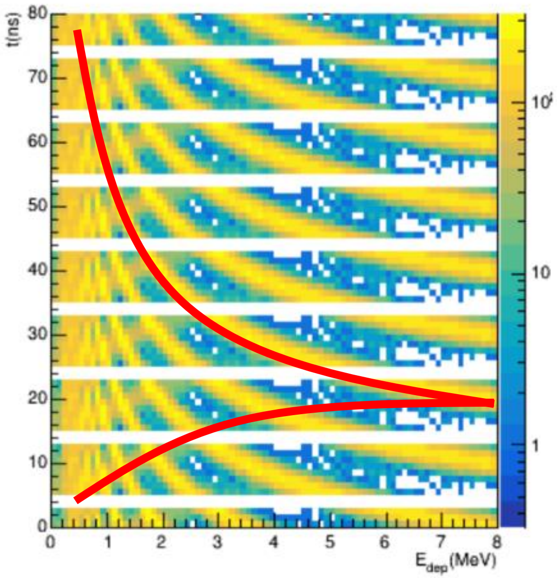


Simulation (PYTHIA+GEANT4)









↕ Bunch length

↔ Detector resolution

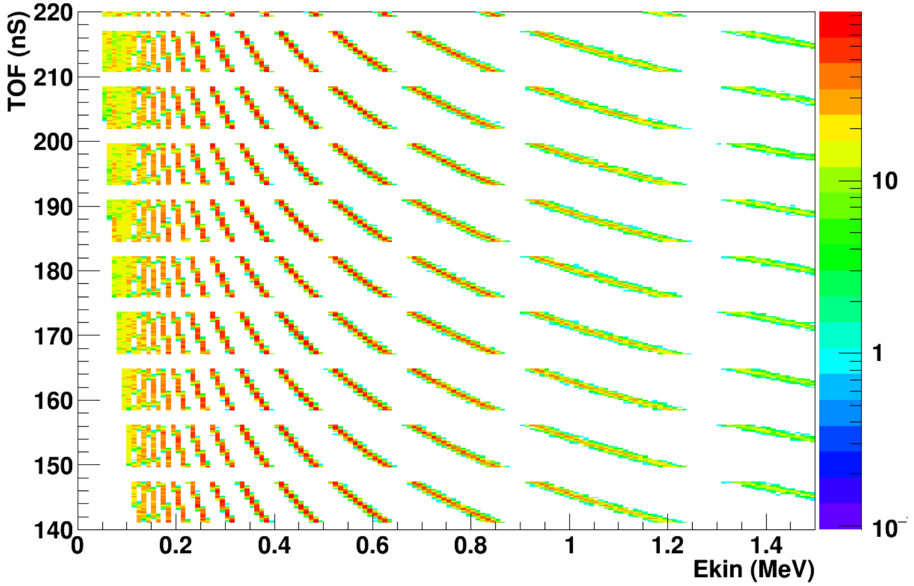
120 bunches → 1320 bunches

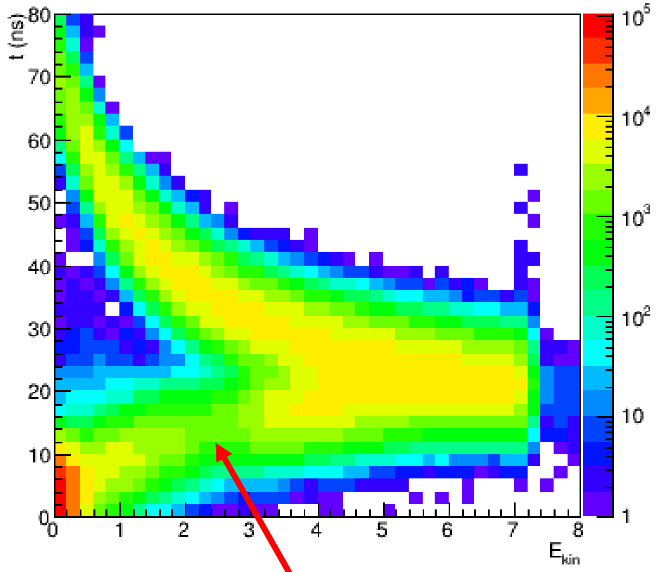
Bunch spacing 106 ns → 9.6 ns

Bunch length 3.5 ns → 0.2 ns

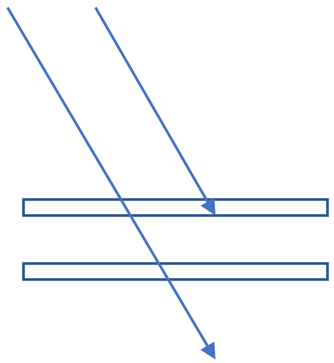
From RHIC to EIC

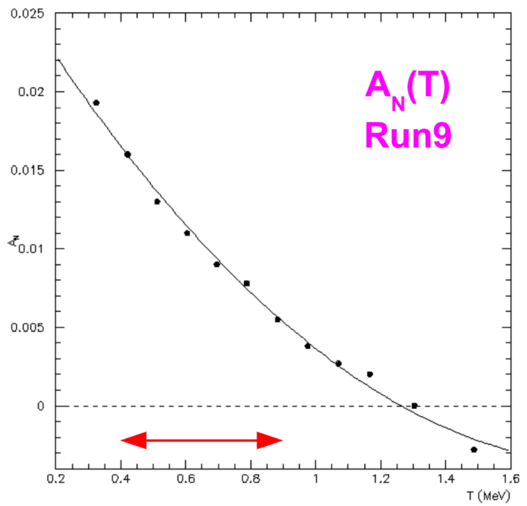
- Loss of increased asymmetry at lower energies, $A_N(-t)$
- Reduced bunch spacing requires much better understanding of background
  - Polarized or unpolarized
  - Better: reject/suppress background
  - Second detector layer to veto high energy particles





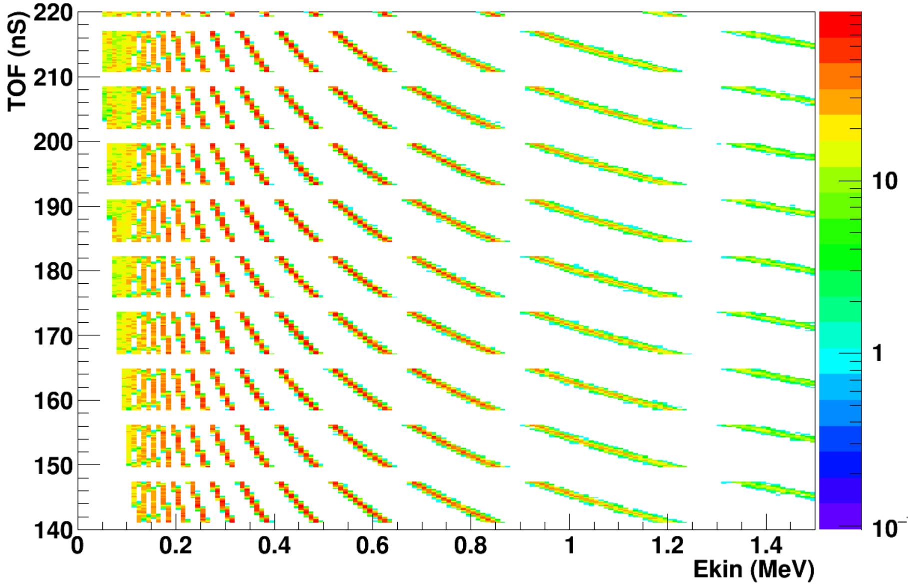
Punch through region

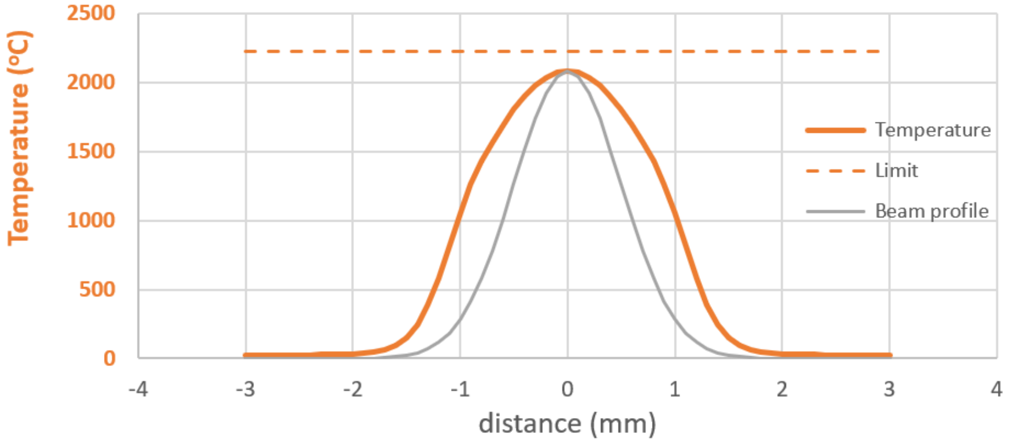




From RHIC to EIC

- Loss of increased asymmetry at lower energies, $A_N(-t)$
- Reduced bunch spacing requires much better understanding of background
  - Polarized or unpolarized
  - Better: reject/suppress background
- Increased beam current is problematic for the fiber target
  - Very limited cooling (radiation, thermal conductivity)
  - Sublimation temperature $T_{Carbon} \approx 2200° \, C$
  - Temperature saturates in a few ms





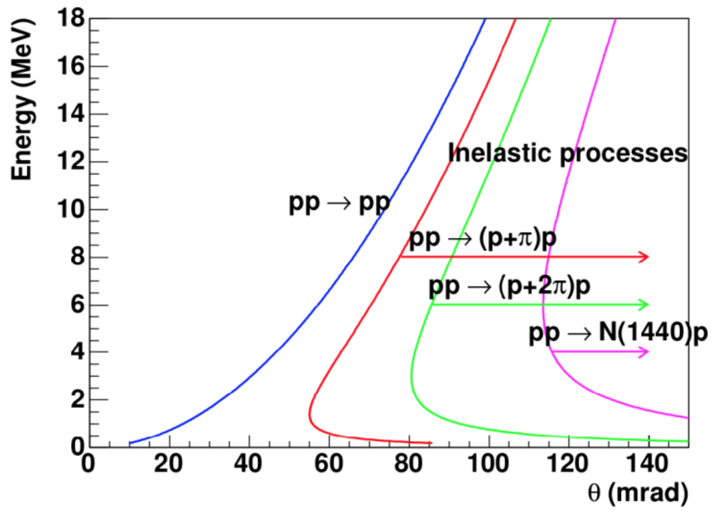
Can we find a target material that withstands higher temperatures?

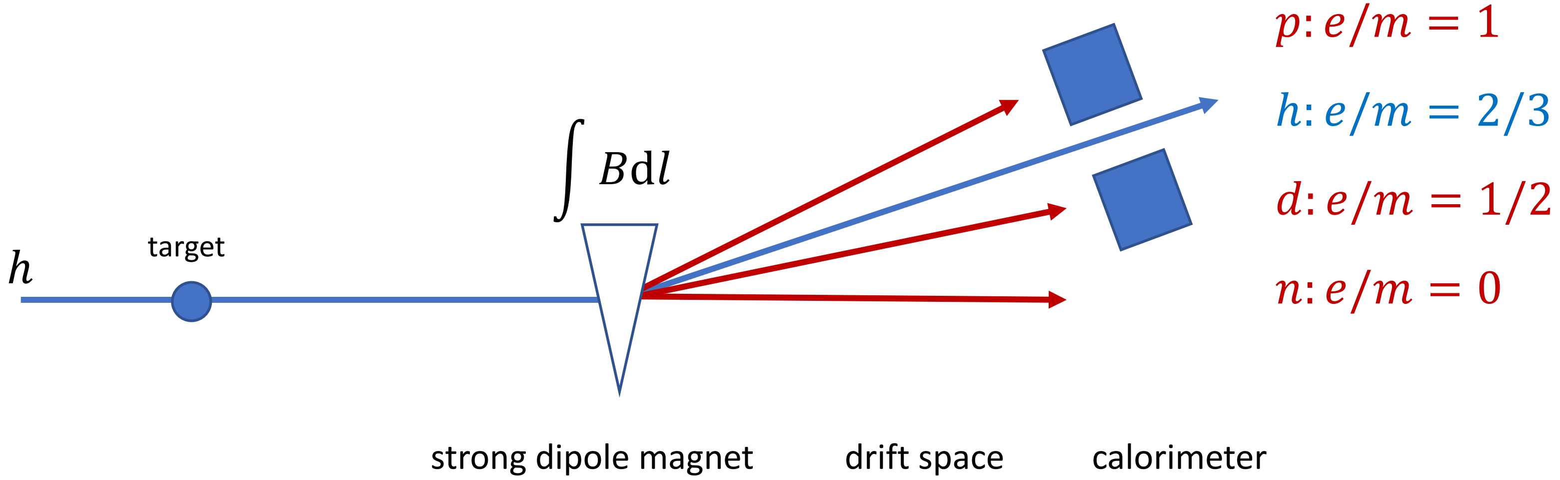
Calculation by P. Thieberger, BNL

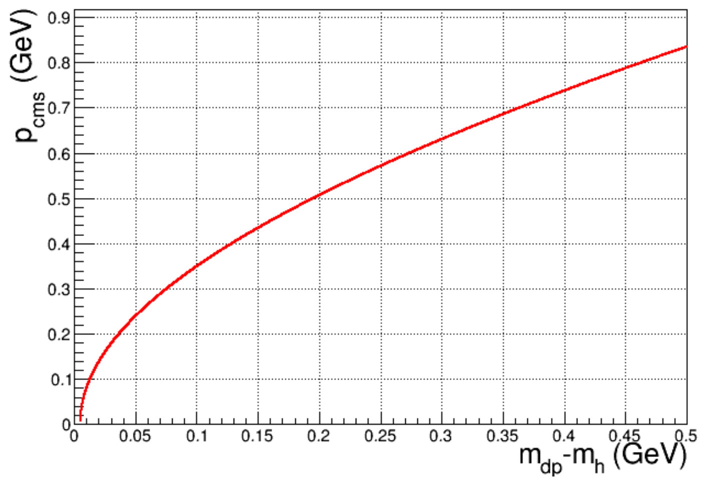
Polarized Light Ion Beams

- Polarized d and ^3He beams are not part of the EIC baseline design.
- Absolute polarization will (likely) require a polarized ^3He target.
  - Elastic scattering is necessary for the sign-flip of the analyzing power
    $$A_{00N0} = -A_{000N}$$
  - Breakup energy is only 5.5 MeV: problematic if beam breaks up $h \to pd$
  - Tag/veto breakup products downstream of the polarimeter

threshold for $pp \to pp\pi$







Outlook / Summary

Requirements and Delivery

	Polarized HJET	Unpolarized HJET	Carbon polarimeter	Forward neutrons
Absolute beam polarization	+	[+]	✗	[✗]
Polarization decay	[+]	+	+	+
Transverse profile	✗	✗	+	[✗]
Longitudinal profile	+	+	+	✗
Polarization vector	[✗]	+	+	+
Bunch polarization	✗	✗	+	✗

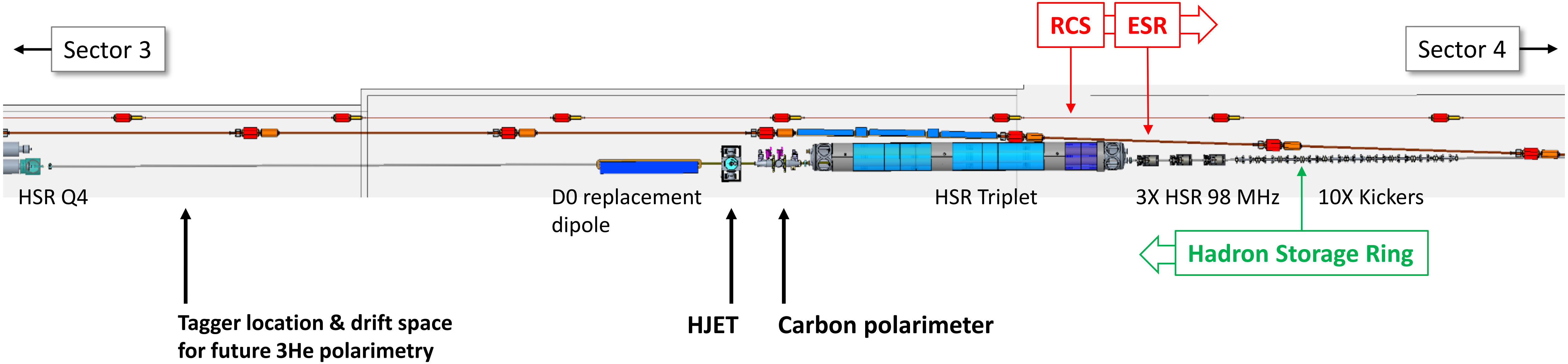
(*) Increased systematics
(*) A_N can be calculated, but needs to be confirmed; full background subtraction

(*) less accurate than pC

(*) depends on the target

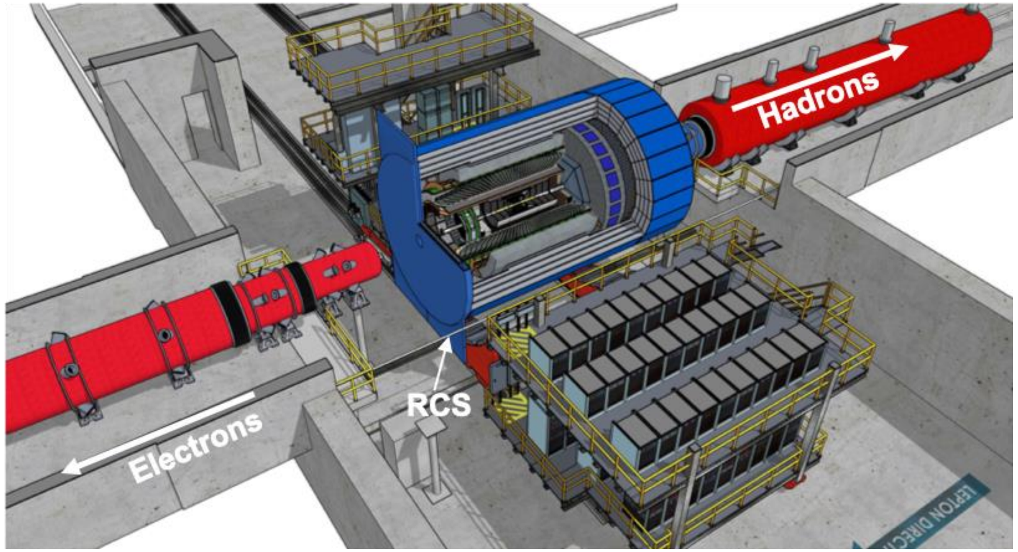
(*) limited space for detectors with current magnet configuration

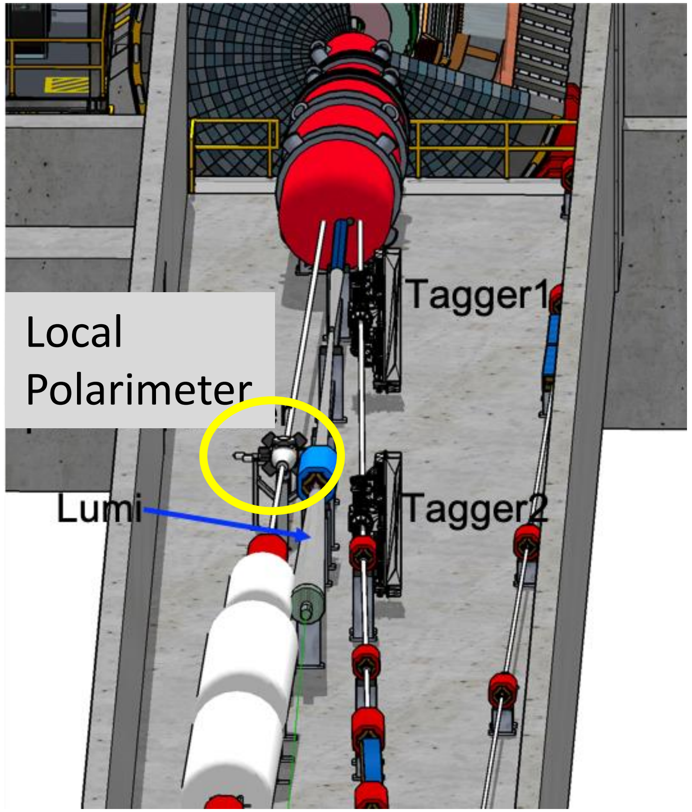
Polarimeters are an integral part of the EIC



Local Polarimeter for EPIC

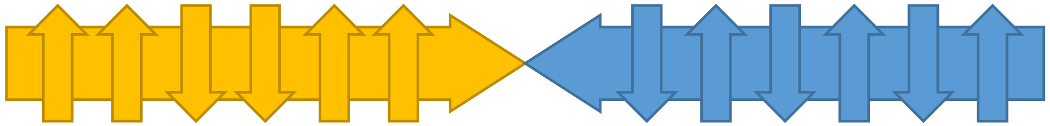
- Spin rotators for longitudinal polarization
- Crab cavities for increased luminosity in collision
- Limited space in hall / straight section
- Polarimeter in incoming hadron beam

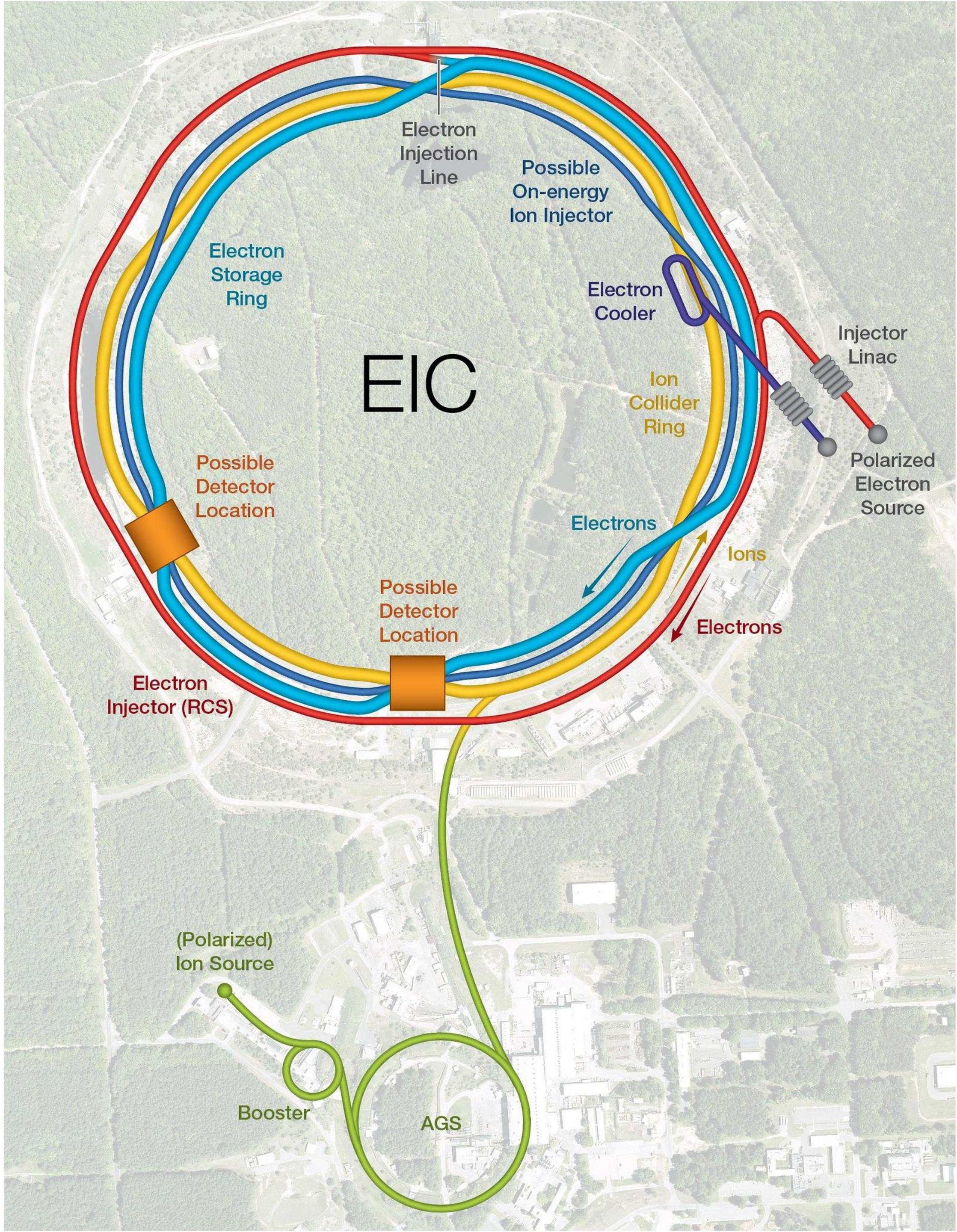




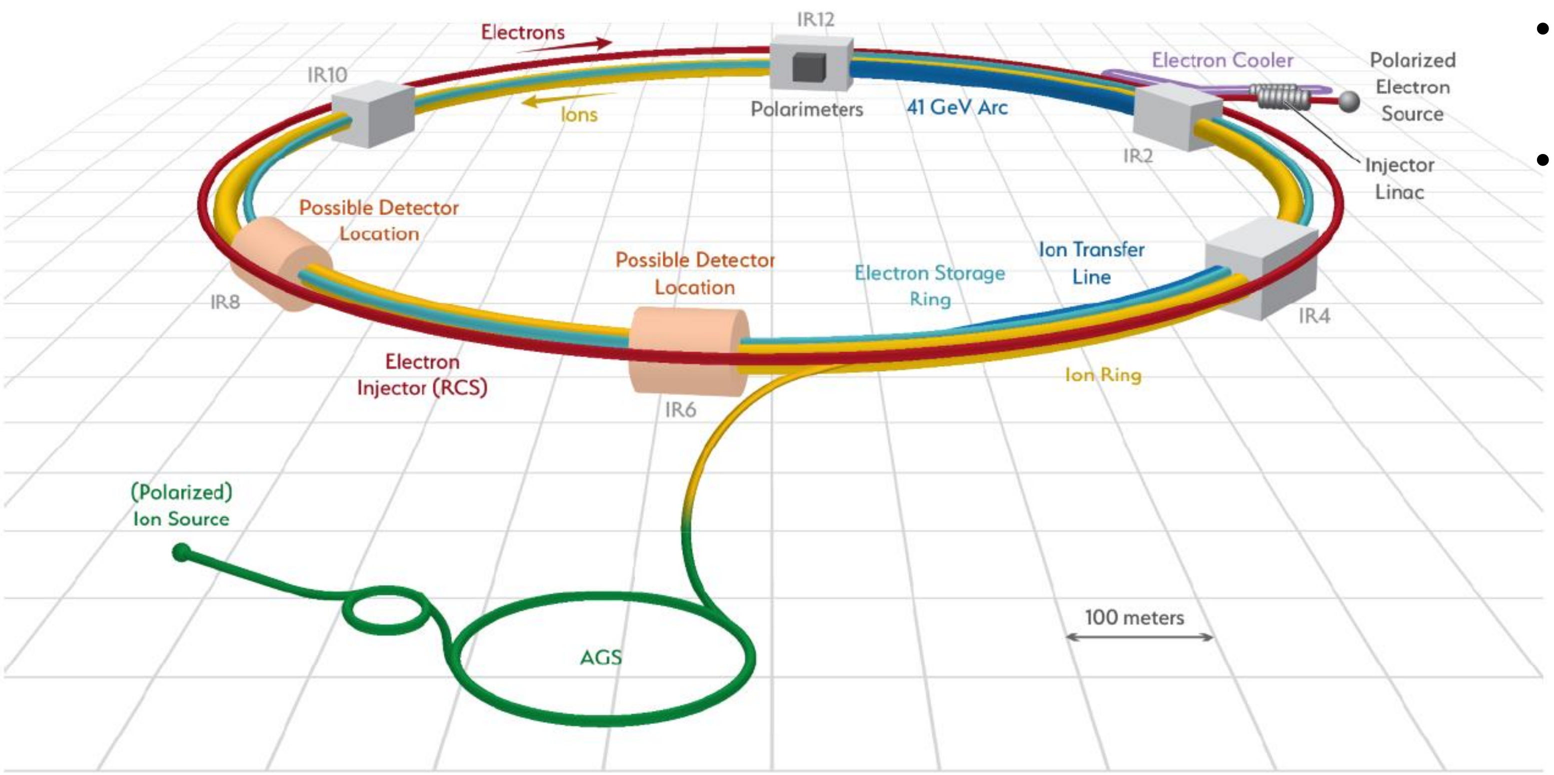
Recap: Hadron Polarimetry

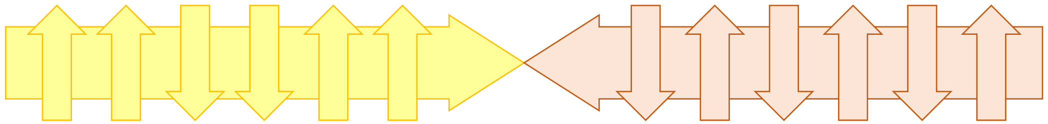
- Proton beam energies: $50 - 275\ \mathrm{GeV}$
- Combination of devices for
  - Non-destructive
  - Absolute polarization
  - Fast measurements during store
  - Bunch profile
  - Local polarimetry at experiment
- Potential for future polarized light ion beams
  - Location allows for upgrades to the polarimeter setup





A Polarized Electron-Ion Collider





- The EIC will be the first dedicated polarized electron-ion collider.
- Polarimetry is an integral part of the collider design to meet the demands of the physics goals.