Polarimetry

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Center for Frontiers in Nuclear Science

Brookhaven National Laboratory

Outline

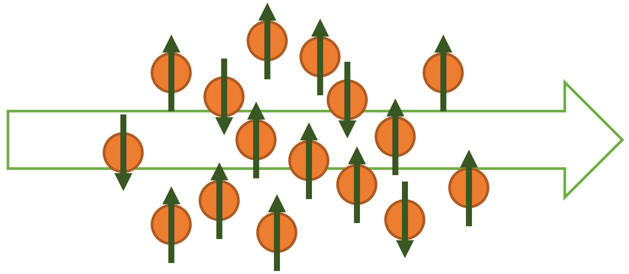
- Introduction: A Polarized Electron-Ion Collider
- I. Polarized Particle beams
- II. Proton Polarimetry
- III. Electron Polarimetry
- Conclusions

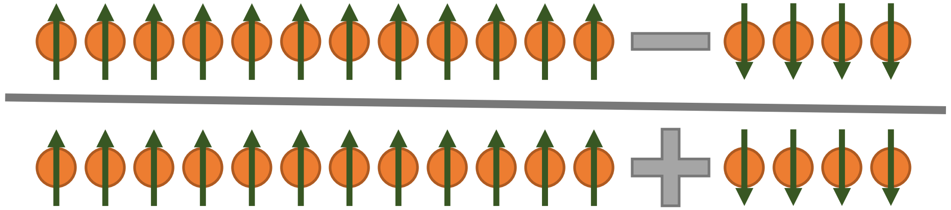
Polarimetry of High Energy Hadron Beams

Bunch Polarization

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).



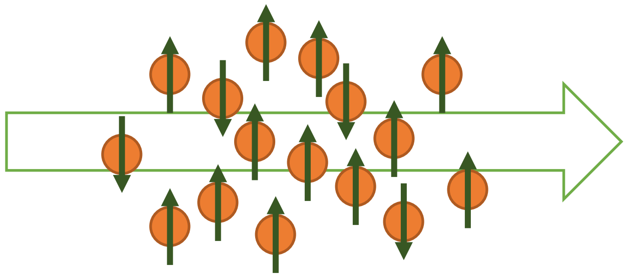


$$P = \frac{12 - 4}{12 + 4} = 50\%$$

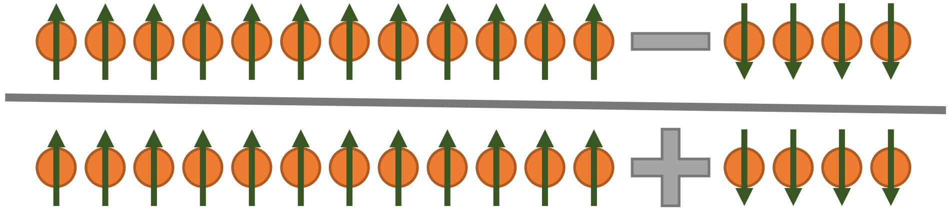
It doesn’t look that bad…

An experiment in and of itself

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 will have to devise a scattering experiment which is spin-dependent.
- We will 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: $\sigma^{\uparrow\downarrow} = \sigma_0 \pm \sigma_s$
- It is convenient to introduce an asymmetry: $\epsilon = \sigma^{\uparrow} - \sigma^{\downarrow} = 2\sigma_s$

The right frame

- The momentum and spin direction define a coordinate system.

Longitudinal $\boldsymbol{L}$

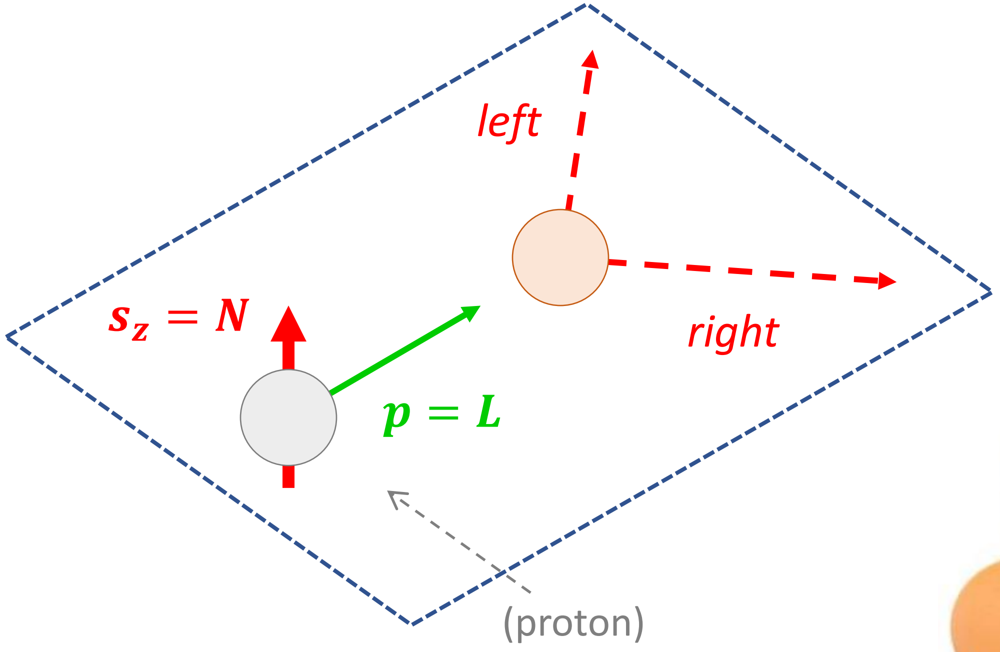
Normal $\boldsymbol{N}$

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

Bootstrapping…

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

$$\rho_f = \boldsymbol{M}\rho_i\boldsymbol{M}^*$$

$$\rho = \sum_n p_n \,|n\rangle\langle n|$$

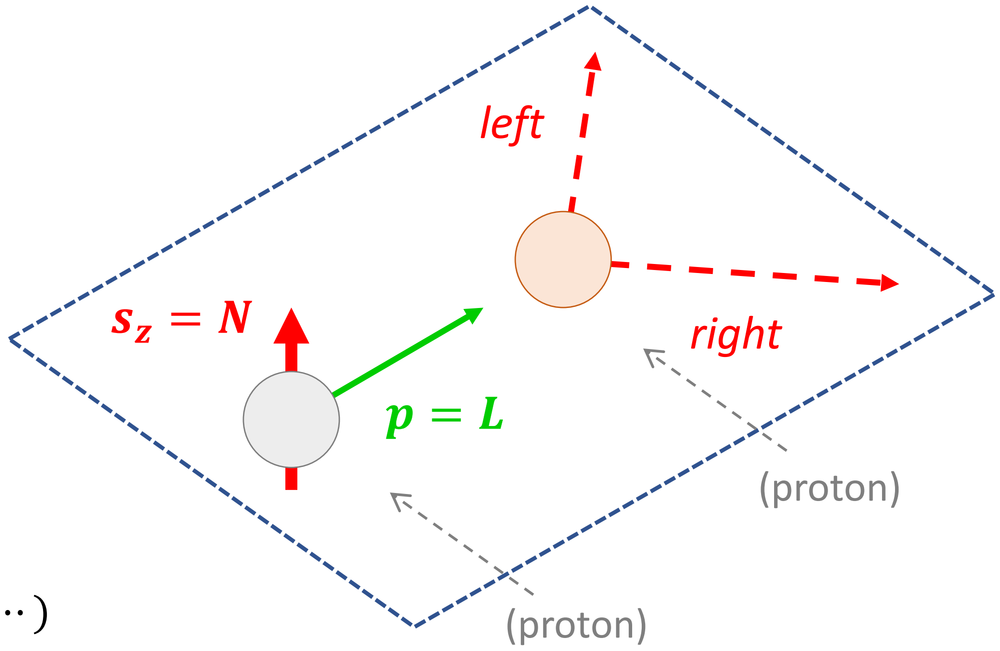
$$\boldsymbol{M} = \sum_{i,f} a_{f,i}\sigma_i \otimes \sigma_f$$

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

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

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

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



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

Bootstrapping…

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

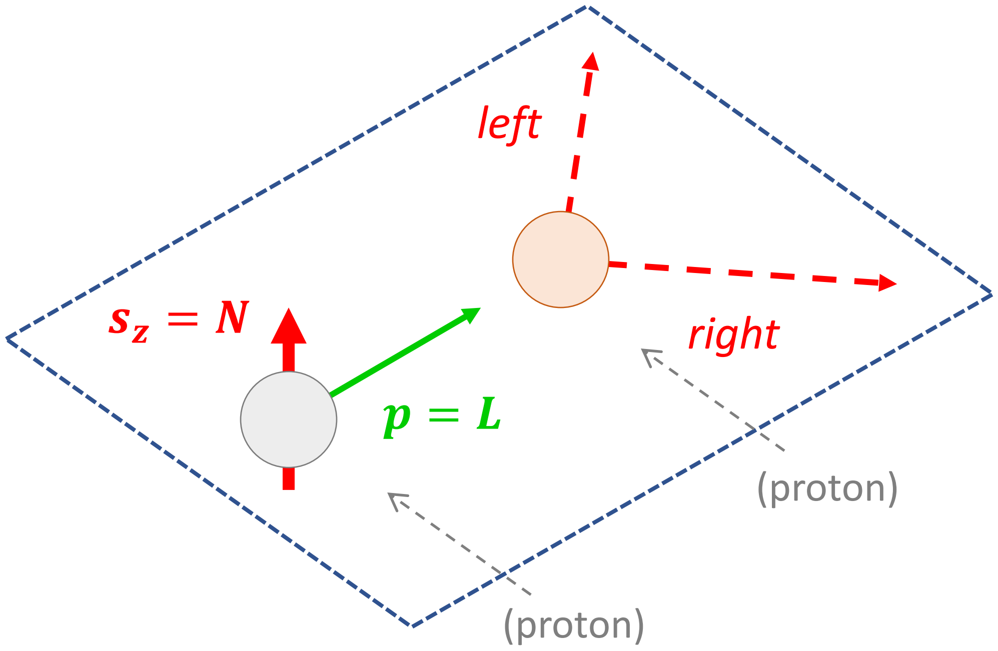
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left(1 + P_{beam}A_{00N0} + P_{target}A_{000N}\right)$$

ejectile, recoil, projectile, target

- For elastic scattering:

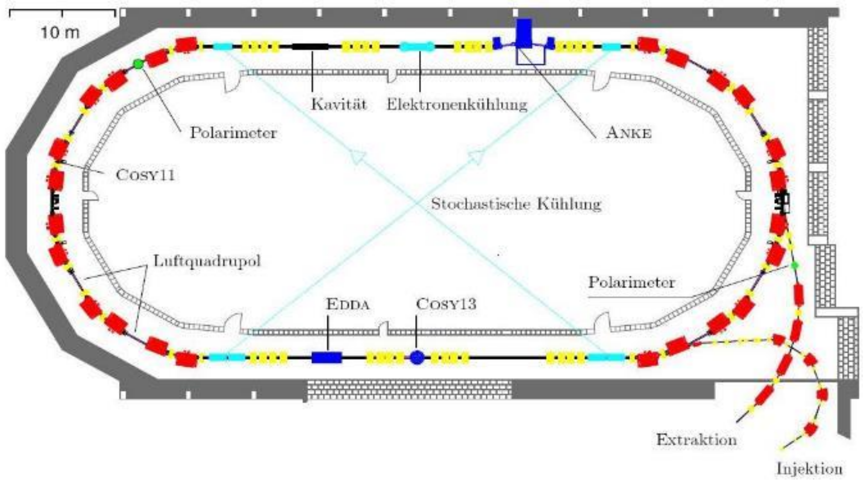
$$A_{00N0} = -A_{000N}$$

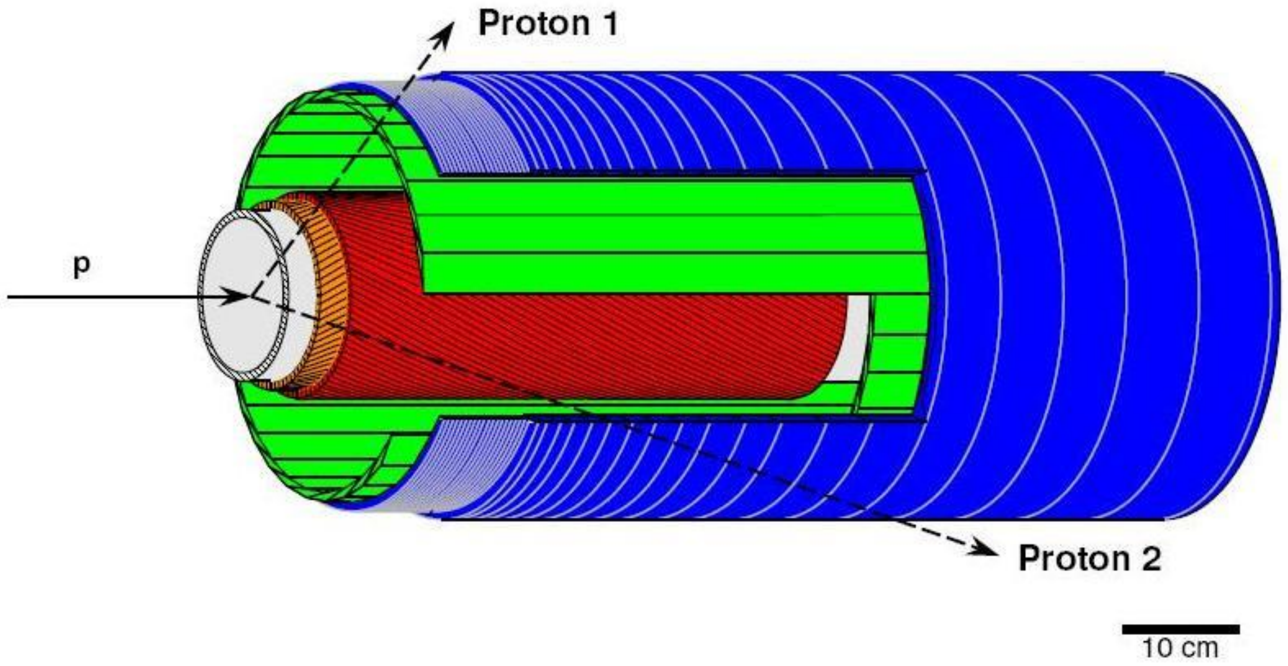
$$P_{Beam} = -\frac{\varepsilon_{Beam}}{\varepsilon_{Target}} P_{Target}$$



Elastic $p + p$ Scattering

- Example: EDDA @ COSY





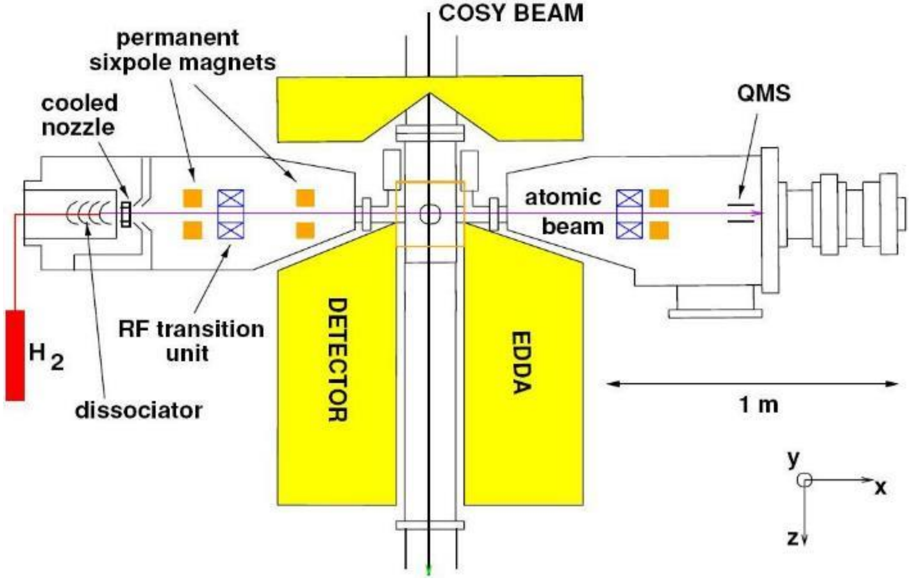
- Kinematic correlation in elastic scattering

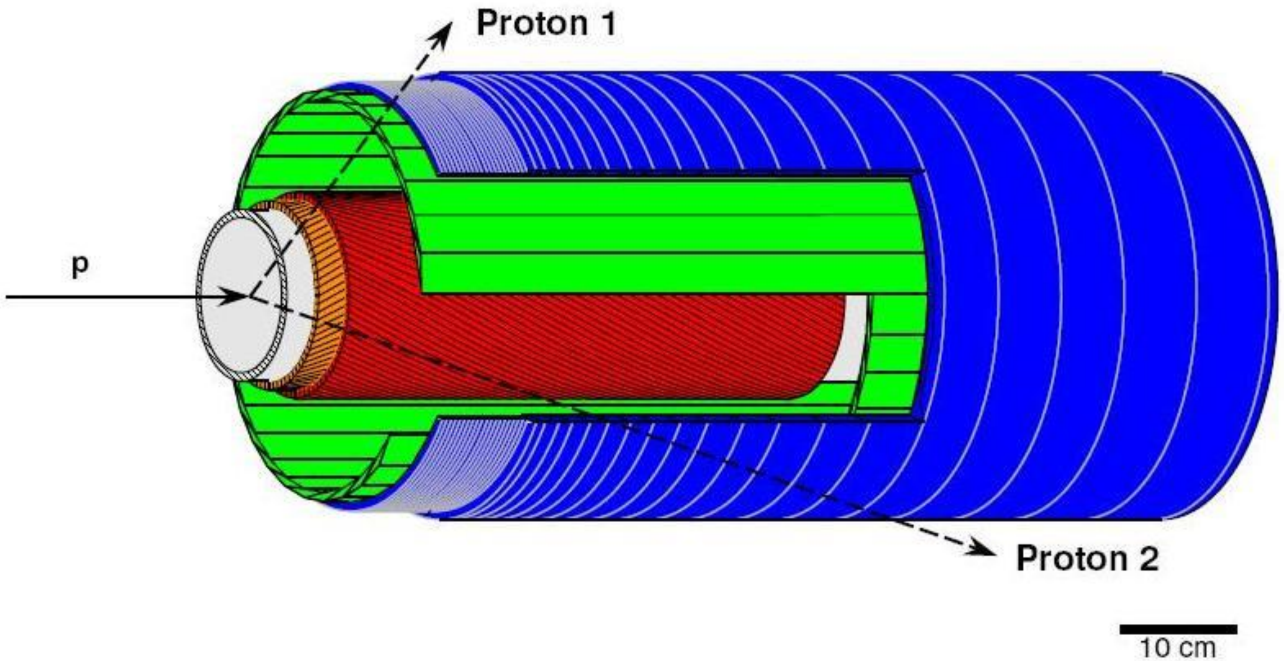
$$\varphi_1 - \varphi_2 = \pi$$
$$\tan\vartheta_1 \cdot \tan\vartheta_2 = 1/\gamma_{cm}^2$$

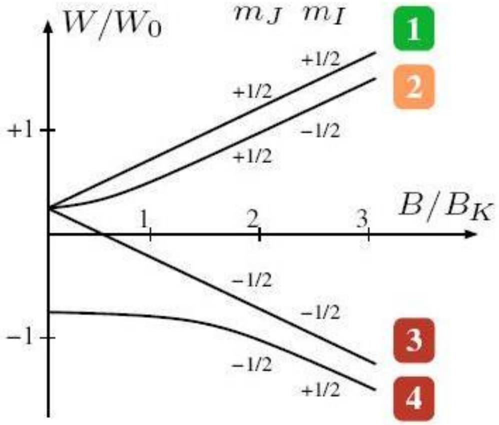
- EDDA detector
  - Scintillator hodoscope specifically designed for elastic $p + p$ scattering

Elastic $p + p$ Scattering

- Example: EDDA @ COSY







- Atomic hydrogen target
  - Selection of hyperfine state 1 (of 4)
  - Magnetic holding field $B_{x,y,z} \approx 10$ 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.

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

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

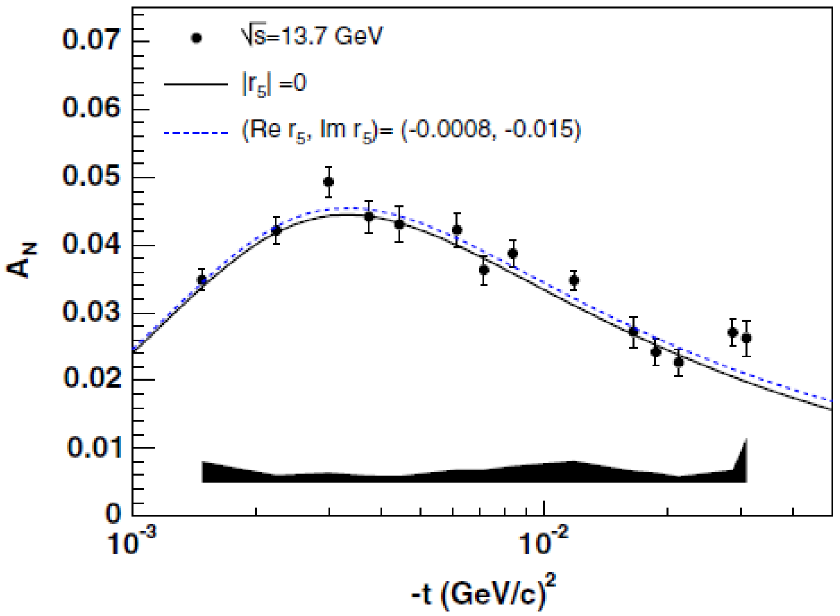
$$\varphi_2(s,t) = \left\langle +\frac{1}{2} + \frac{1}{2} \middle| \varphi \middle| - \frac{1}{2} - \frac{1}{2} \right\rangle$$

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

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

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

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

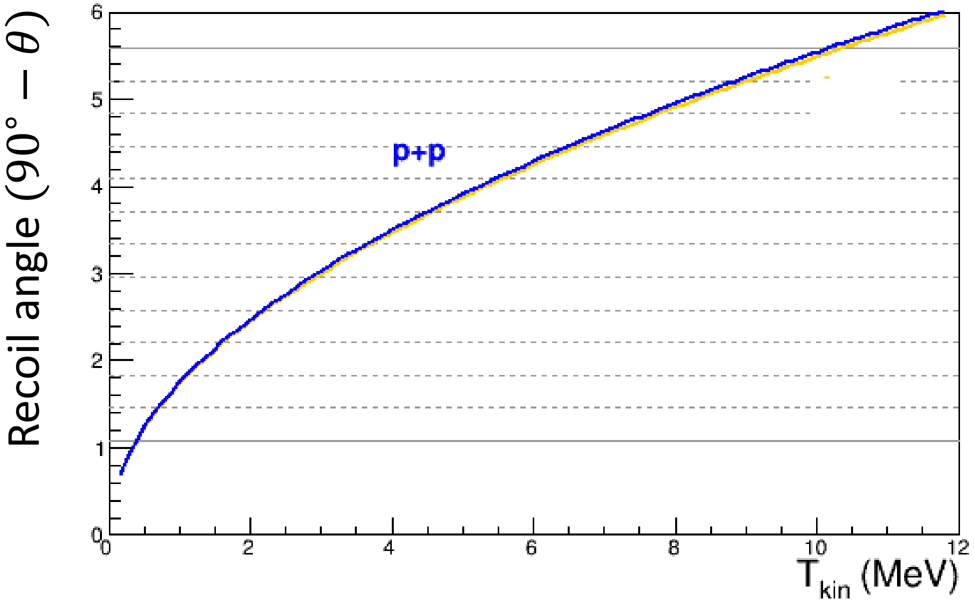


$$A_N \frac{ds}{dt} = -\frac{4\pi}{s^2} \mathrm{Im}\left[\varphi_5^{em*}(s,t)\varphi_+^{had}(s,t) + \varphi_5^{had*}(s,t)\varphi_+^{em}(s,t)\right]$$

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

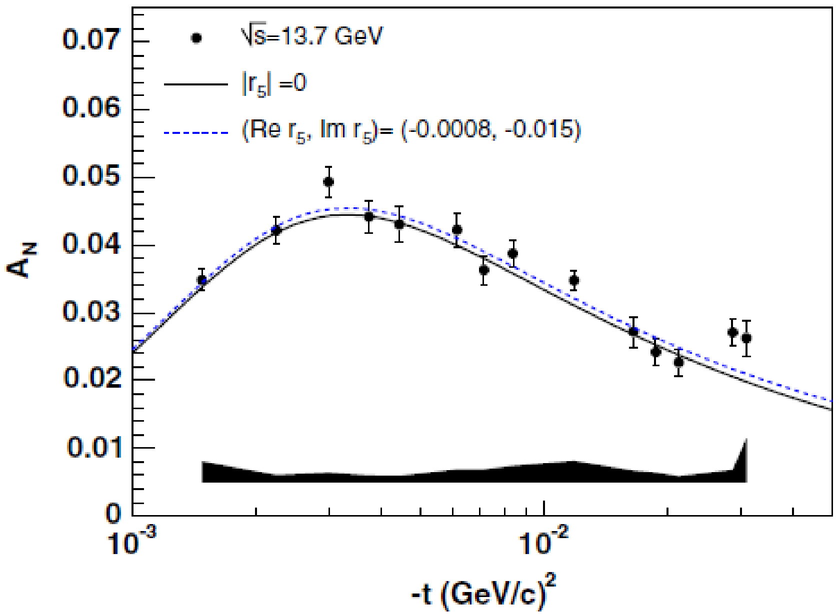
Elastic Scattering at RHIC energies

- 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.

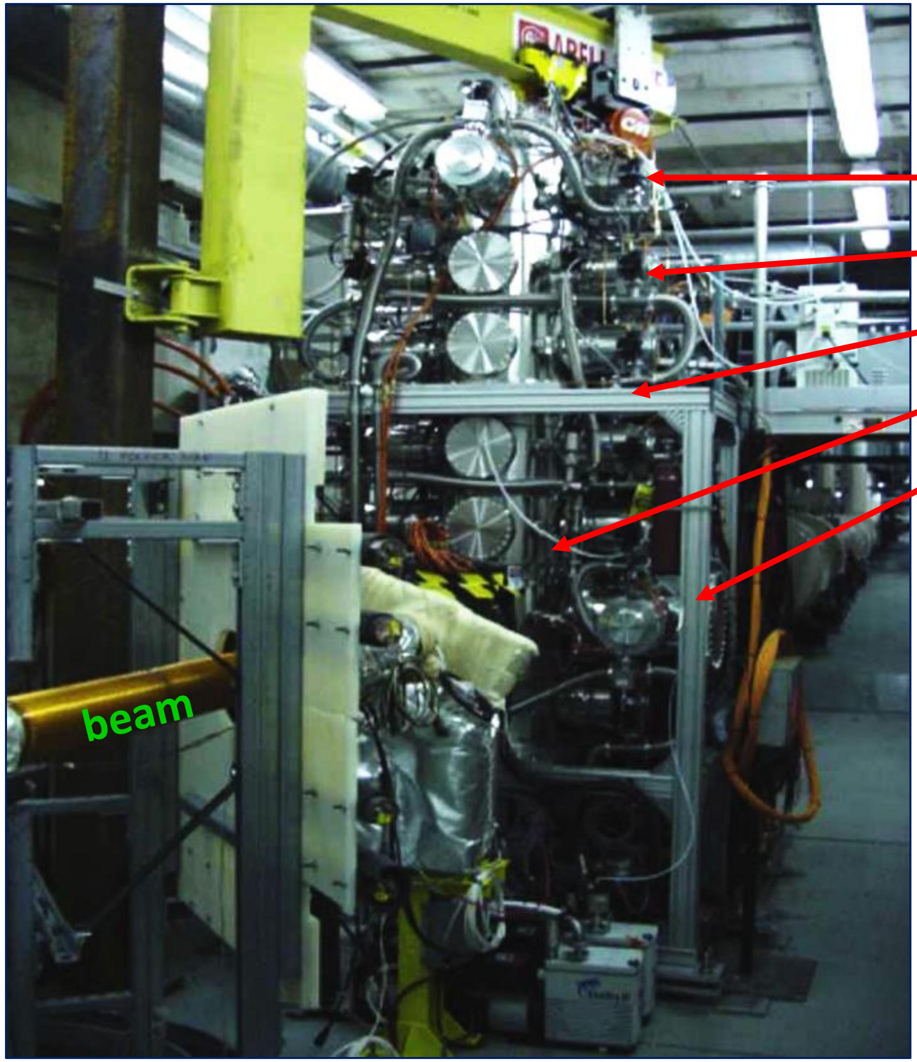


Kinetic energy of the recoil proton

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

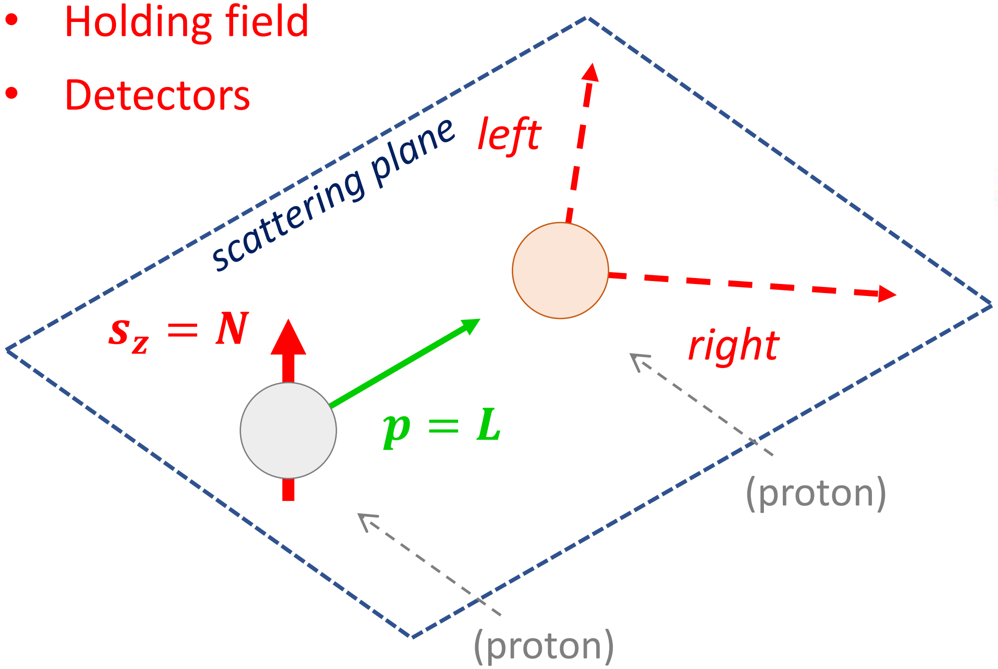


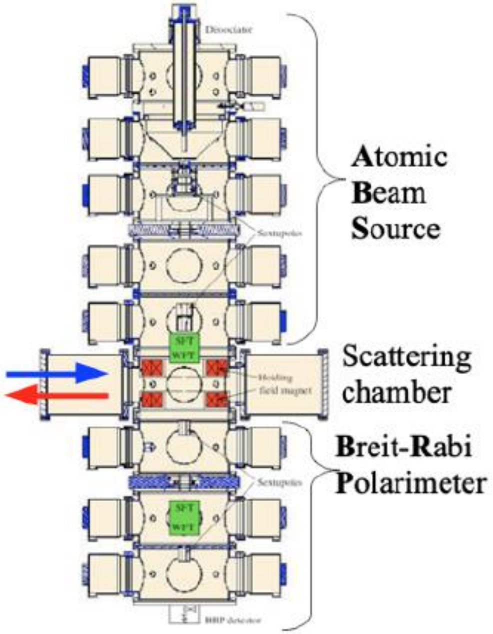
An Absolute Polarimeter at RHIC / EIC



- Polarized atomic hydrogen jet target (HJET)

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





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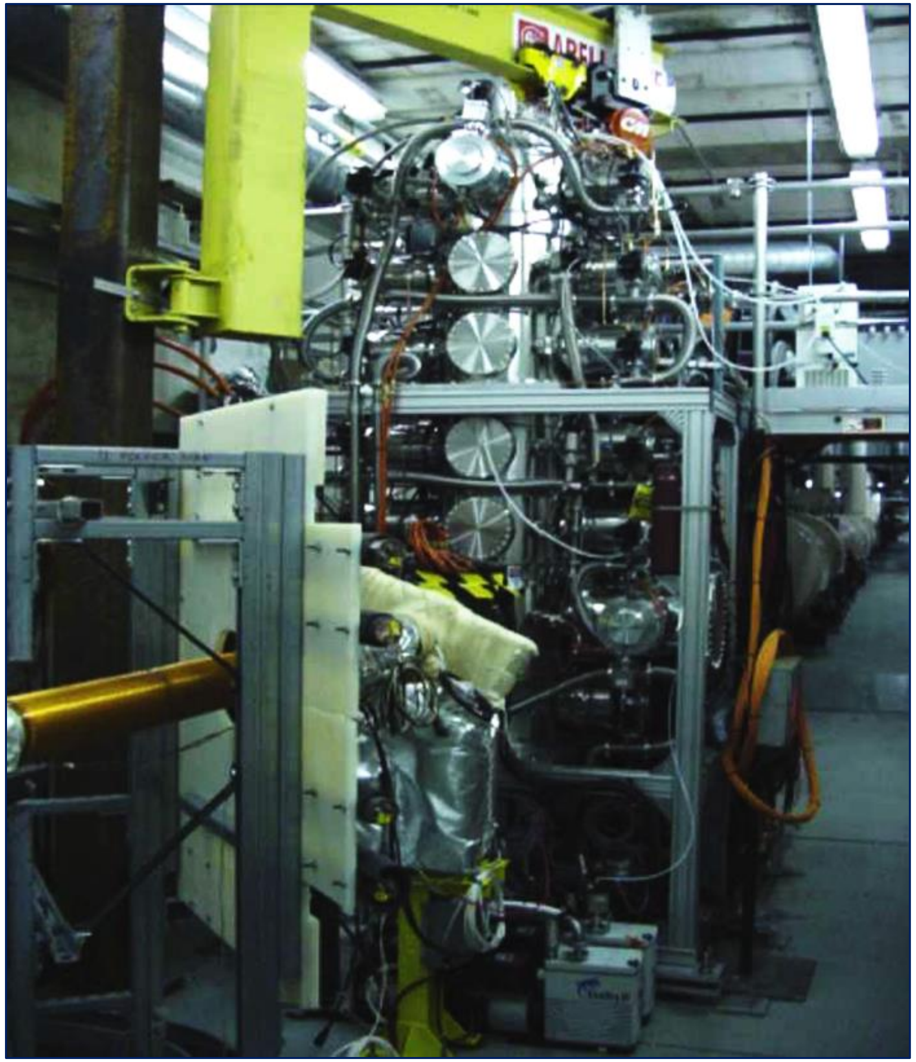
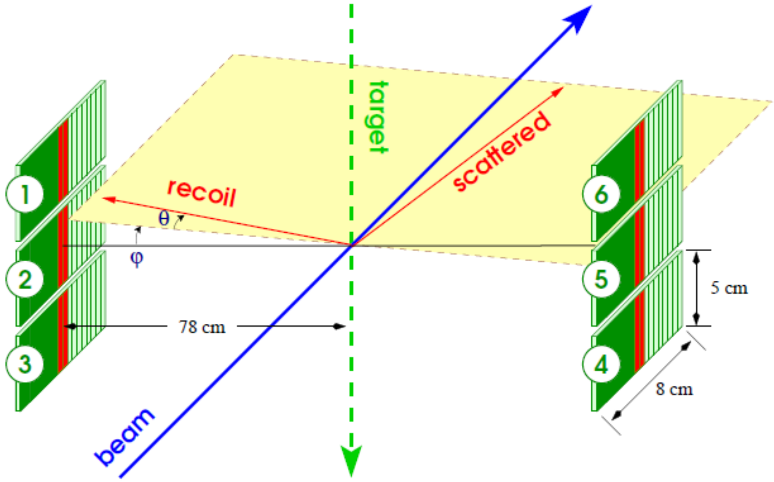
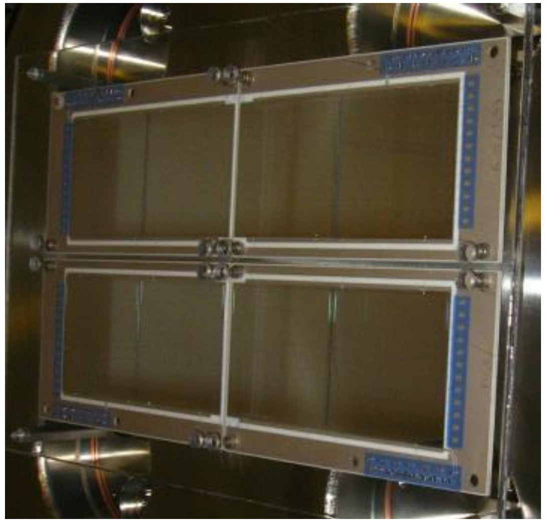
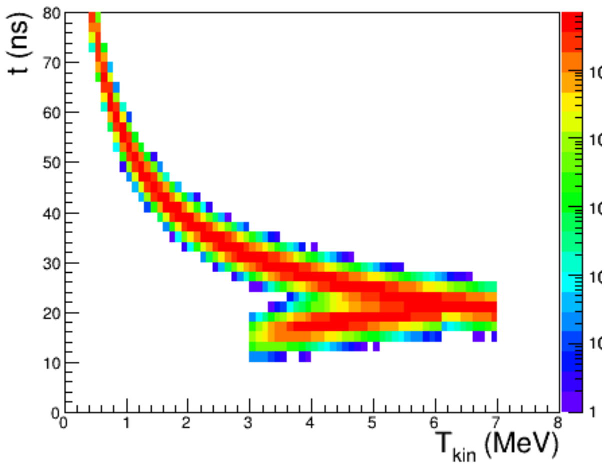


- Polarized atomic hydrogen jet target (HJET)
- Set of eight Hamamatsu Si strip detectors
- 12 vertical strips
  - 3.75 mm pitch
  - 500 μm thick
- Uniform dead layer ≈ 1.5 μm





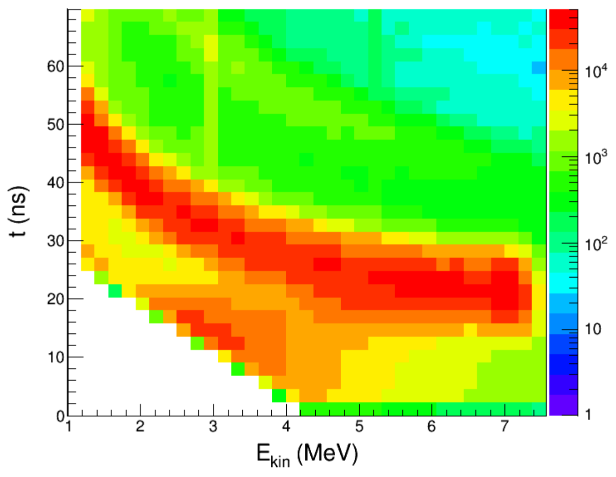
Proton Recoil Measurement



Expected elastic signal

Simple toy simulation with bunch length 3 ns

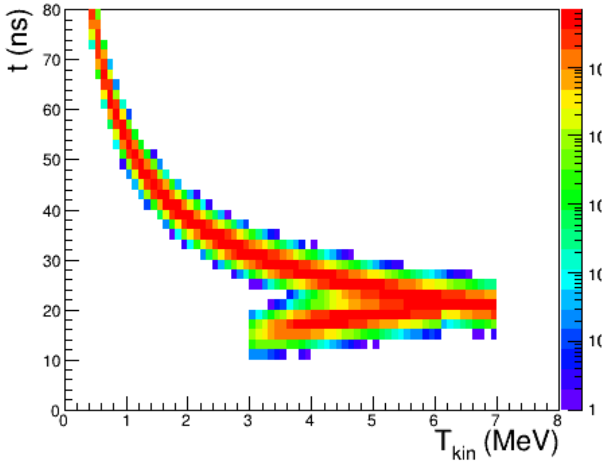
Non-relativistic: $T_{kin} = \frac{1}{2}mv^2$ → Time of flight is used for particle identification

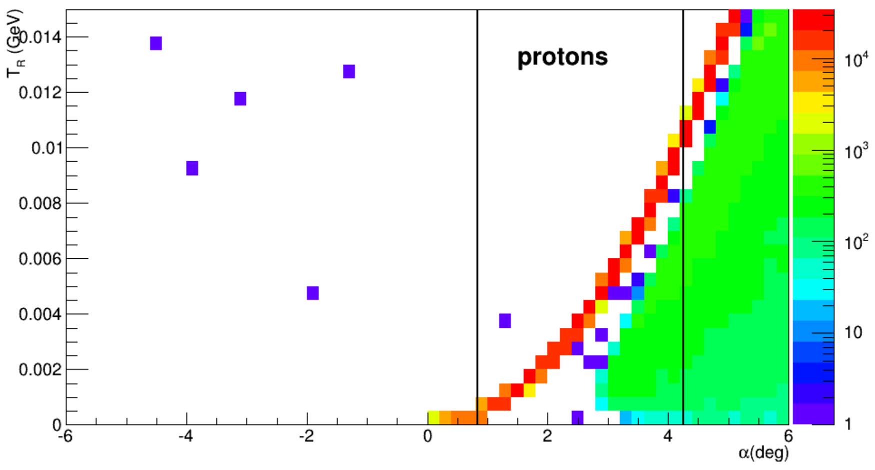


Real measurement

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

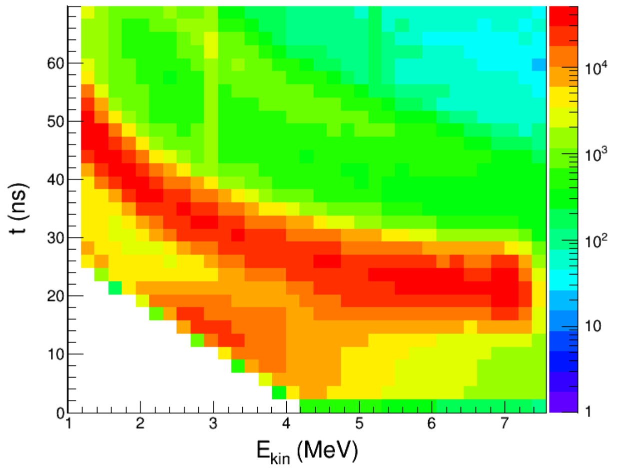
Proton Recoil Measurement

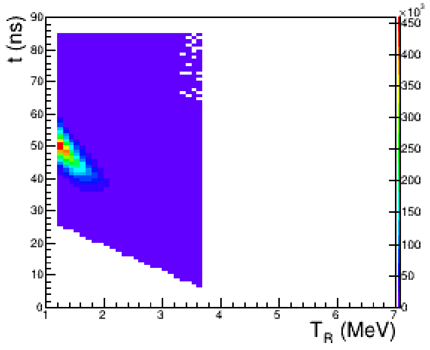


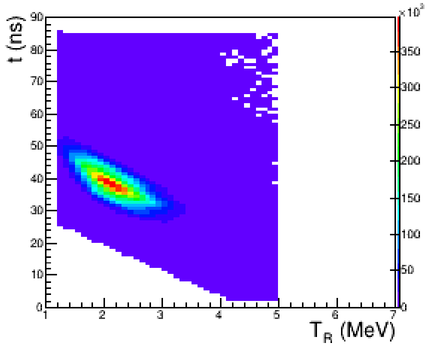


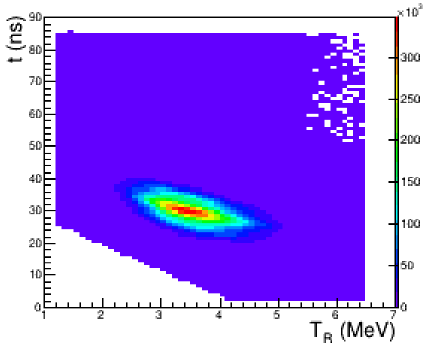
Time of flight is used for particle identification

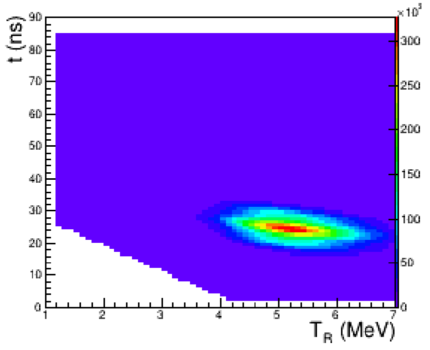
Recoil angle is used for kinematic correlation in elastic scattering











Absolute Beam Polarization

$$\varepsilon = A_N \cdot P$$

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

1

Polarization independent background

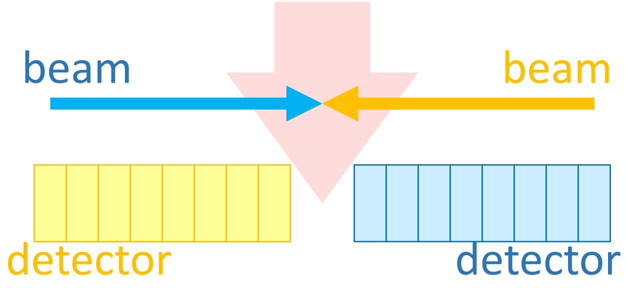
$$\varepsilon = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow} + 2 \cdot N_{bg}} \Rightarrow \frac{\varepsilon_B}{\varepsilon_T} = \frac{N_B^{\uparrow} - N_B^{\downarrow}}{N_T^{\uparrow} - N_T^{\downarrow}}$$

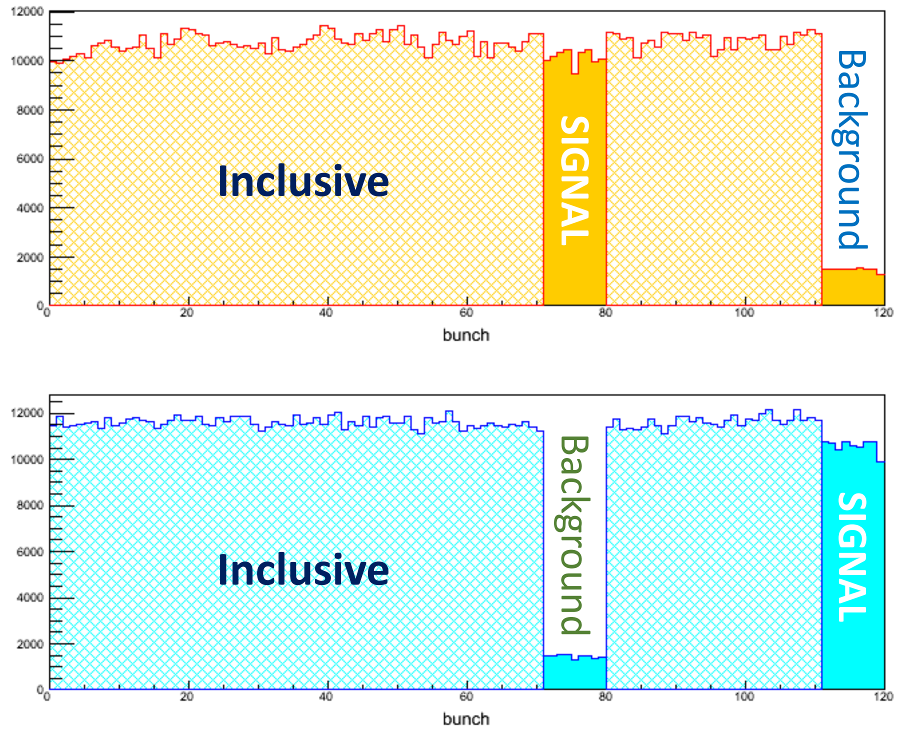
2

Polarization dependent background

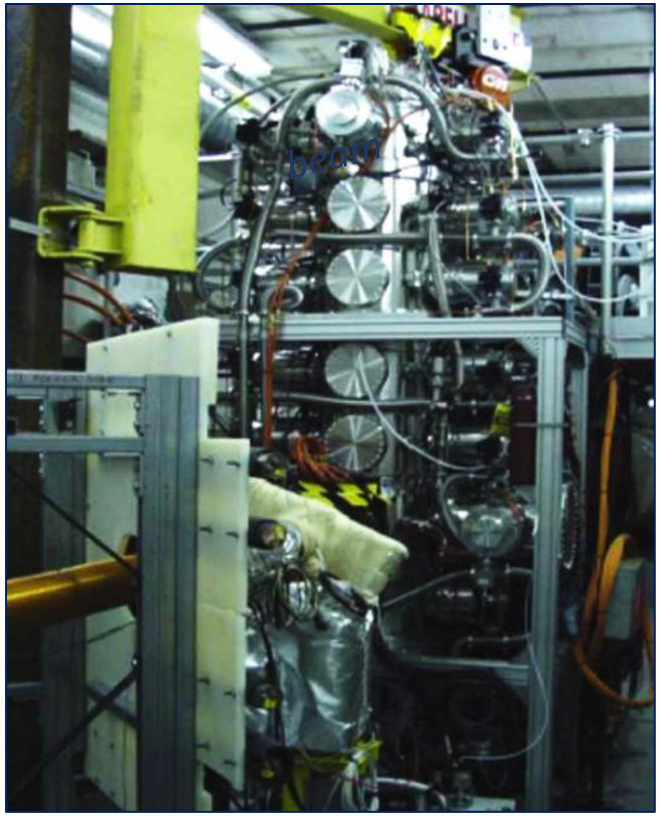
$$\varepsilon = \frac{\varepsilon_{inc} - r \cdot \varepsilon_{bg}}{1 - r}$$

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





A Suite of Polarimeters



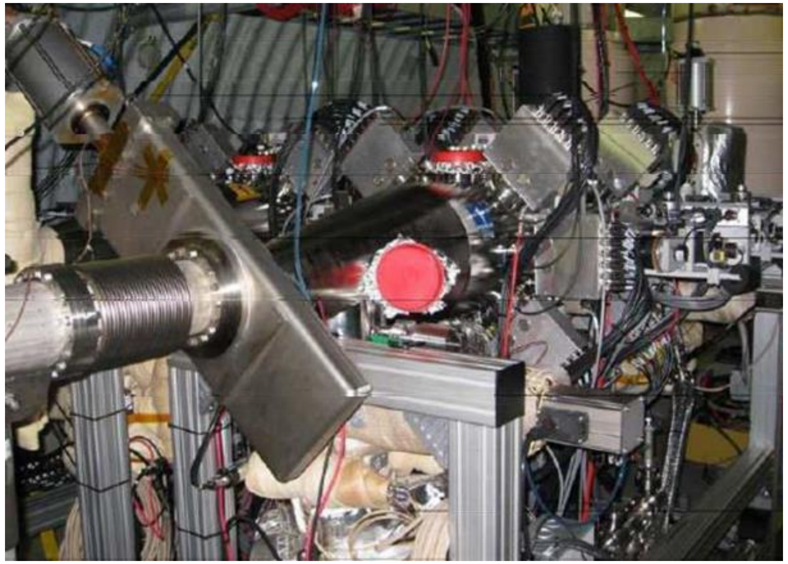
From our list of requirements:

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

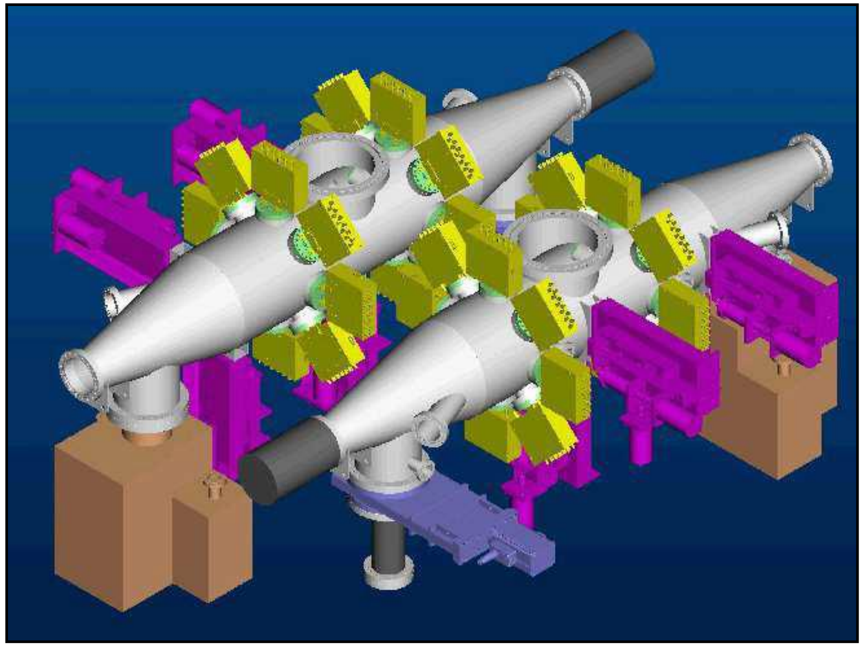
Polarized target

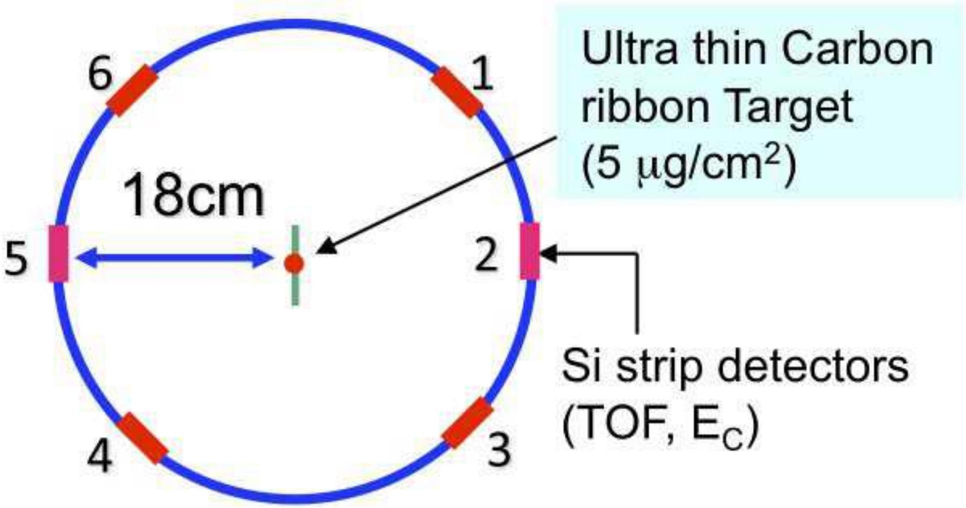
Continuous operation

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

normalization

Fiber Target Polarimeters

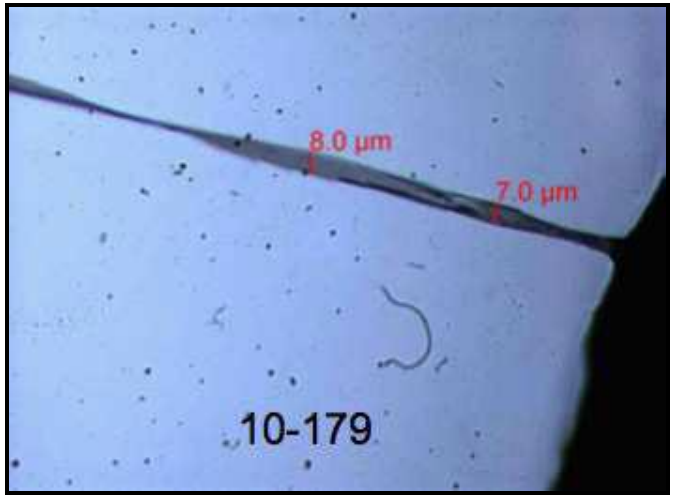


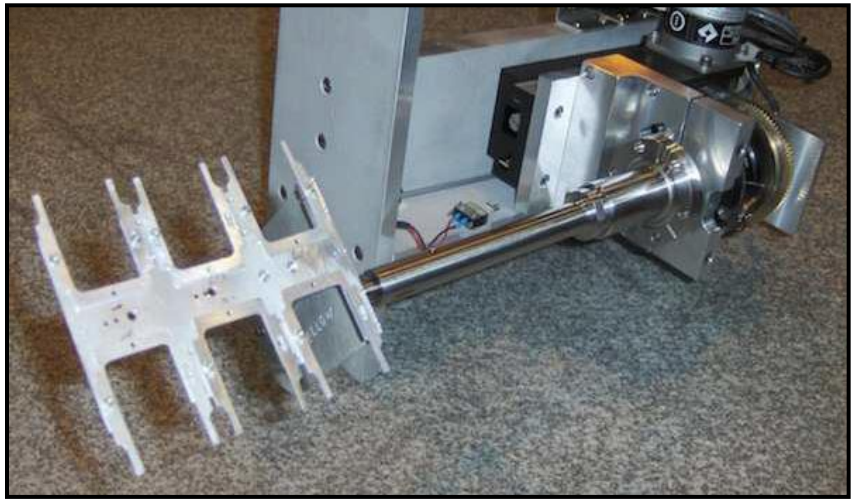


- Ultra-thin ribbon targets:

$$\approx 10\ \mu m\ x\ 100\ \text{nm}$$

- Target holder inside the beam pipe





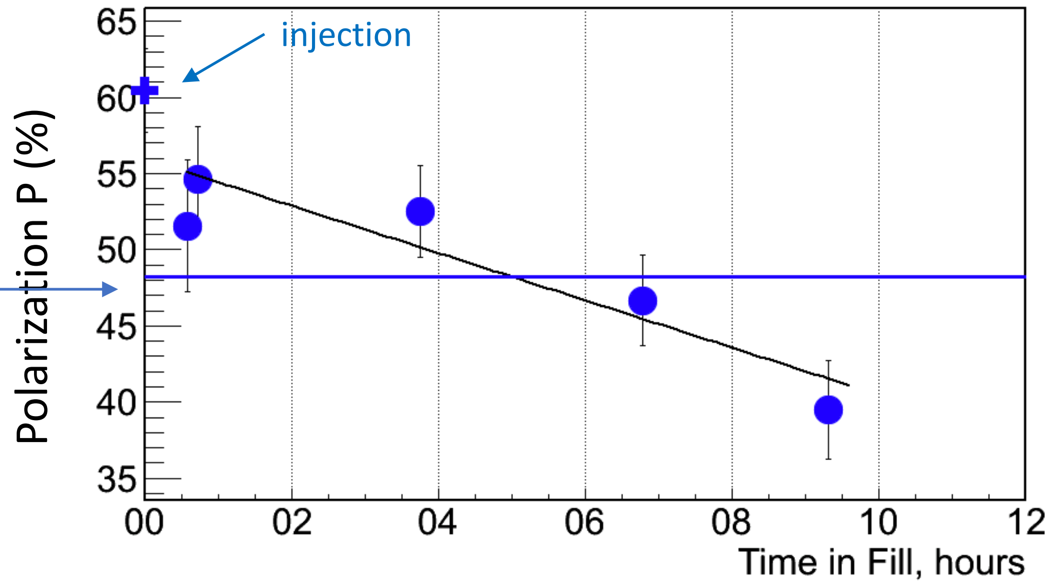
Polarization Decay

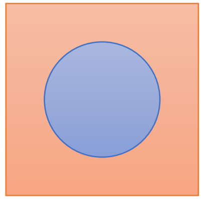
Polarization losses during the store are correlated to

- acceleration
- emittance
- profile

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

normalization with HJET





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

Polarization Decay

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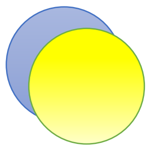
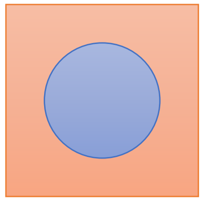
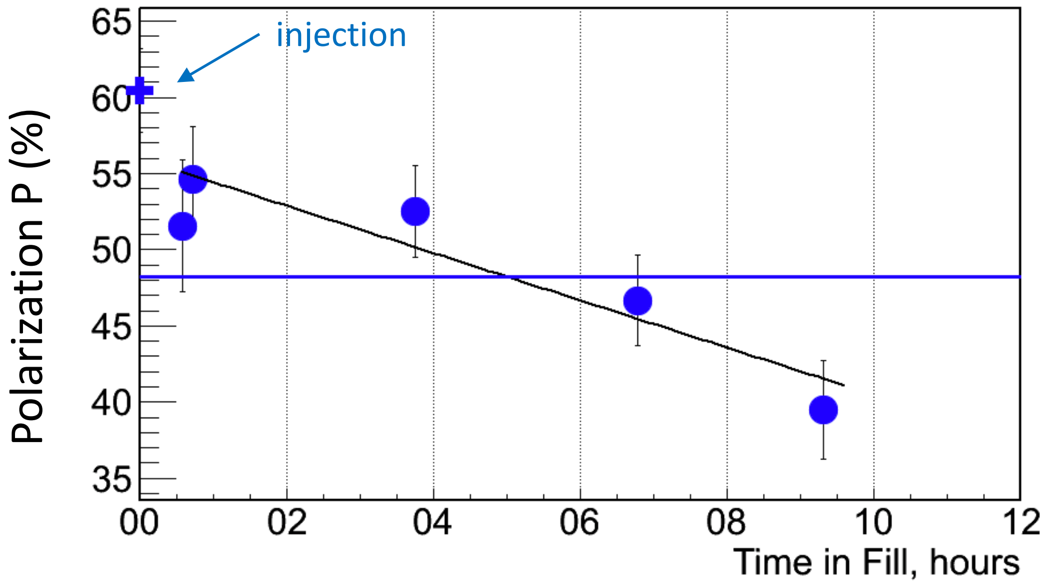
$$P = P_0 + \frac{dP}{dt} t$$



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



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



Important for experiments:

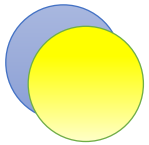
Luminosity changes throughout each store

Polarization Profile

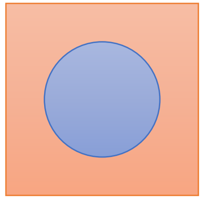
Polarization losses during the store are correlated to

- acceleration
- emittance
- profile

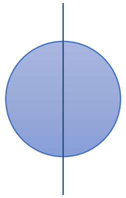
$$P = P_0 + \frac{dP}{dt}t \qquad \mathrm{R} = R_0 + \frac{dR}{dt}t$$



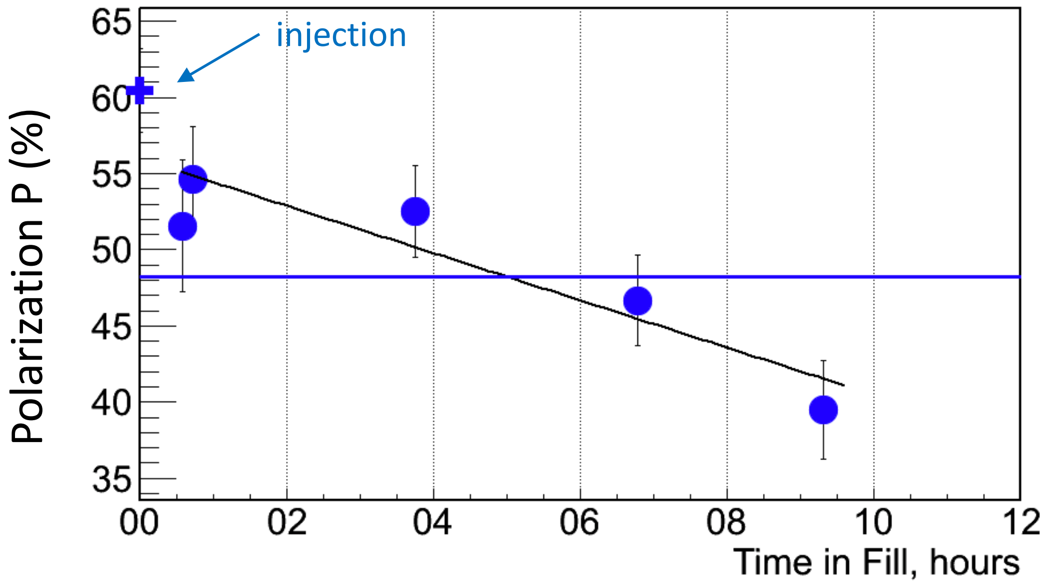
$$P_{coll} = \frac{\int dxdyP(x,y)I_B(x,y)I_Y(x,y)}{\int dxdyI_B(x,y)I_Y(x,y)}$$

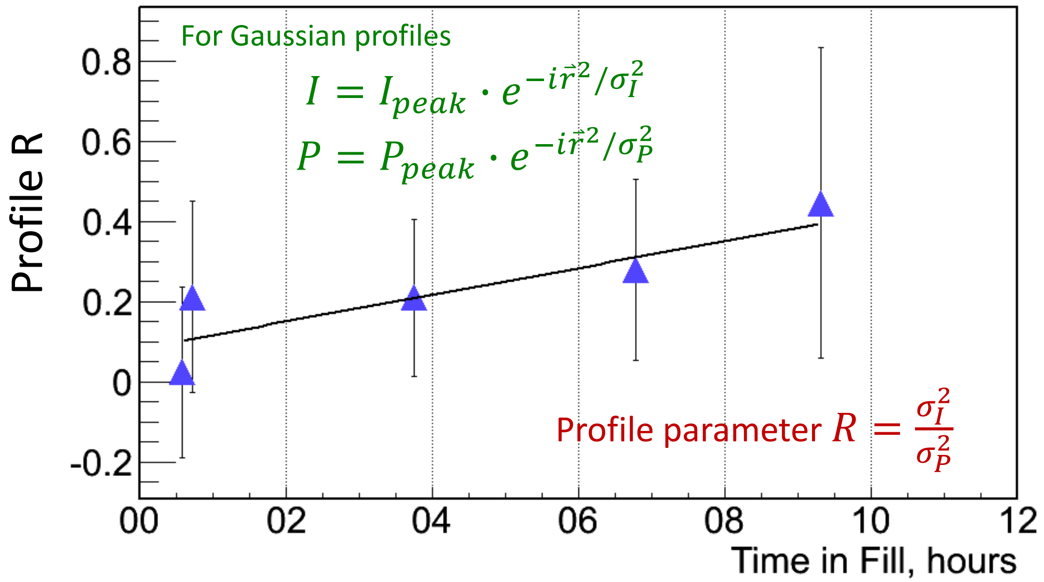


$$P_{jet} = \frac{\int dxdyP(x,y)I_B(x,y)}{\int dxdyI_B(x,y)}$$



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





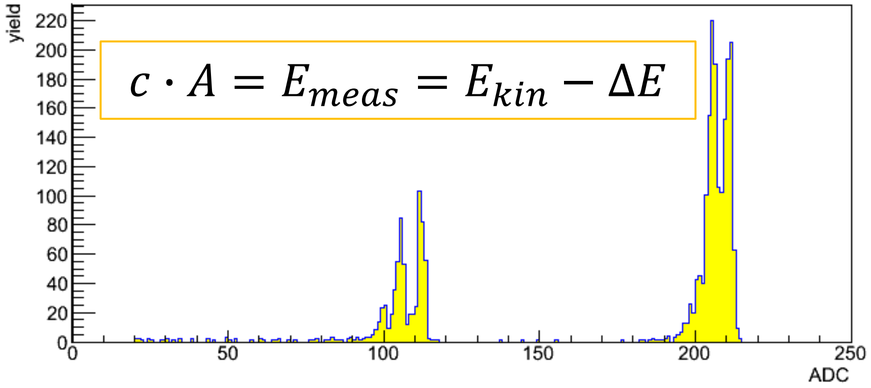
Limitations of the Measurement

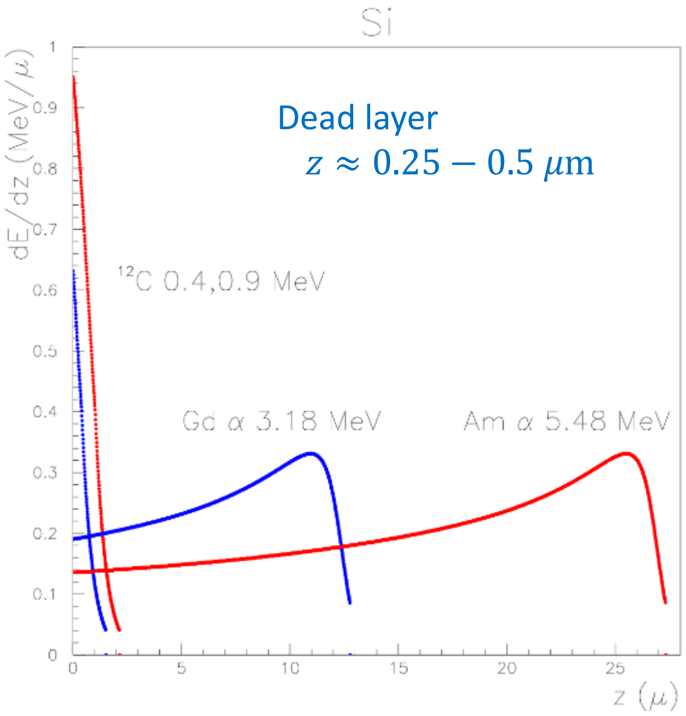
- Recoil particles have very low energy.
  - significant impact of the inactive detector parts (dead layer ΔE), especially for the Carbon measurement
  - Calibration with α-sources

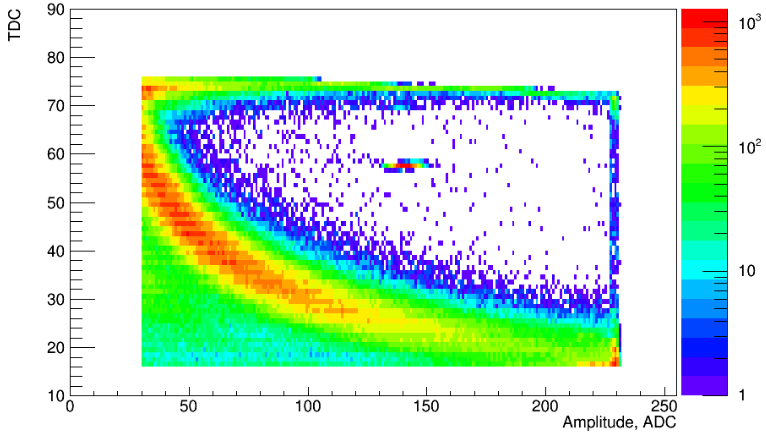
$$^{148}Gd(E_\alpha = 3.183 \text{ MeV})$$

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

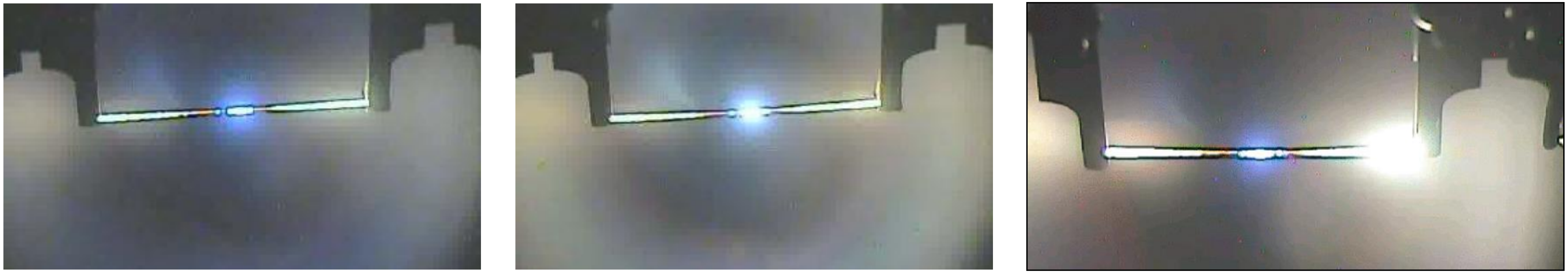
- Small angle scattering of recoil inside the target dilutes the kinematic correlation for elastic scattering.
  - Background dilutes the measured asymmetry (increases statistical uncertainty), but normalized with HJET
  - A_N drops above 1 MeV



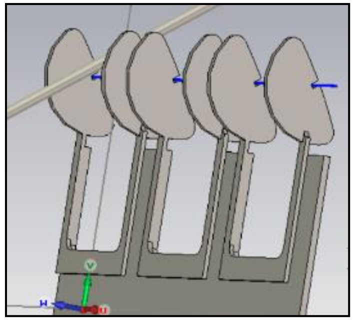


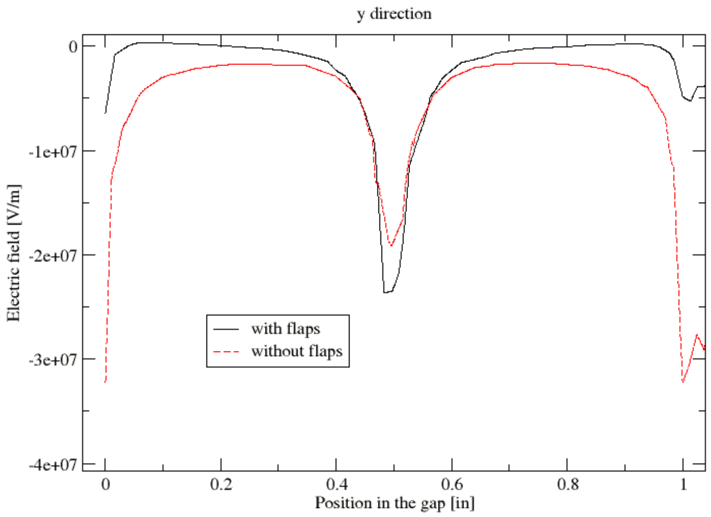


Target Lifetime



- 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

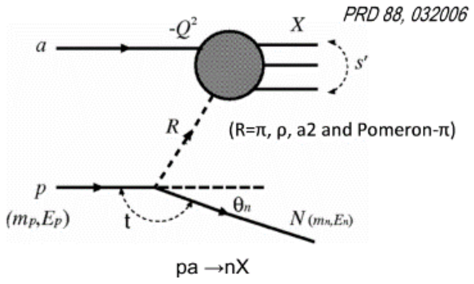


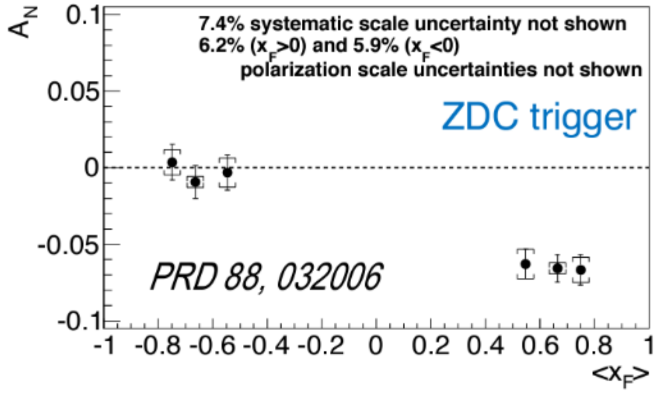


Simulation by J. Kewisch, BNL

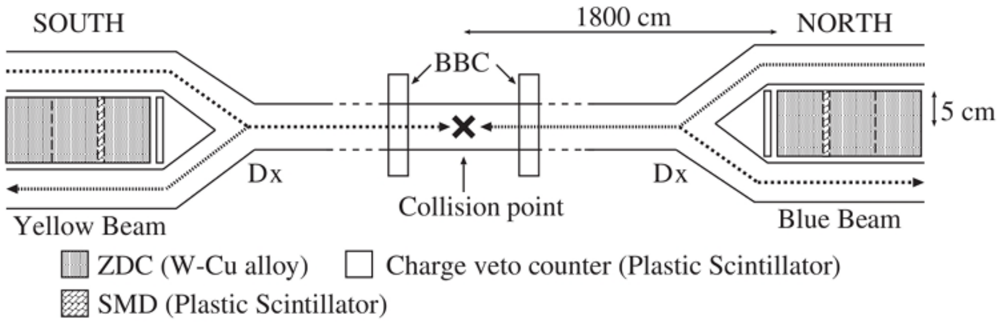
Local Polarimetry at RHIC

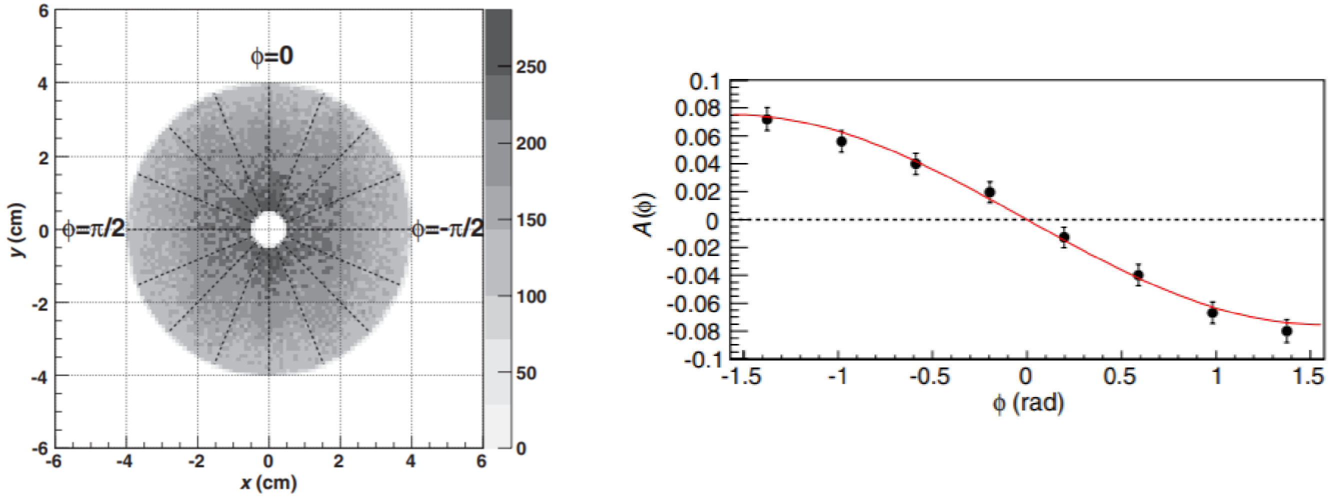
- Local polarimetry is primarily for confirming the direction of the polarization vector at the experiment.
  - Observe suppression of asymmetry or change of direction
  - Very forward going production of neutrons in $p+p$ collisions
  - First established at RHIC-IP12, standard method for RHIC experiments





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





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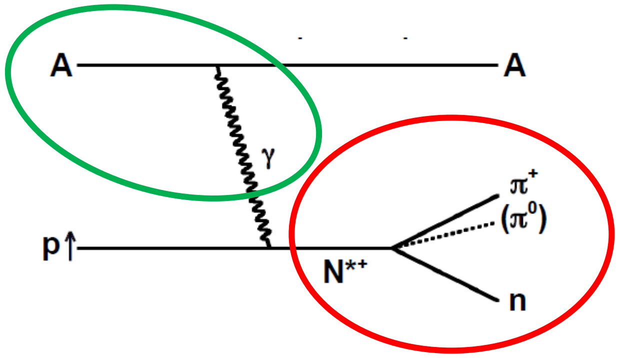
Potential for Future Applications

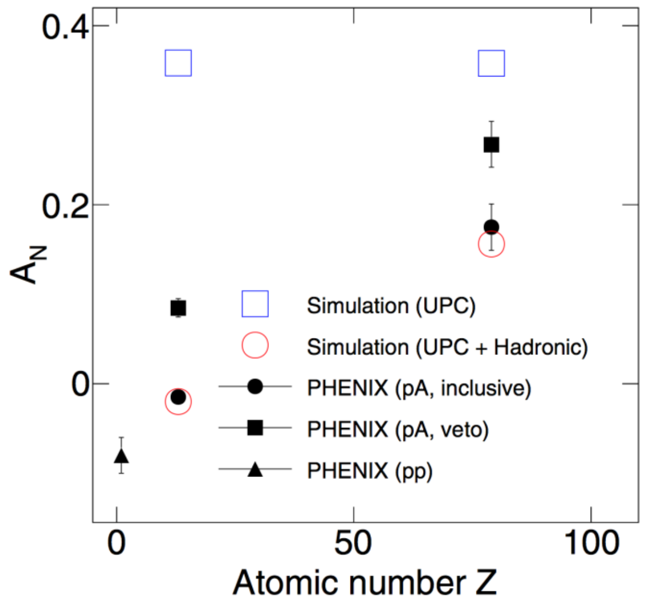
- Nuclear dependence of very forward going neutrons
    - Very large asymmetry (with opposite sign)
    - Select low multiplicity with beam-beam counters
    - Ultra-peripheral collision extension to π/a_1 model
    - Photon flux from STARlight
      Klein et al., Comput. Phys. Comm. 212 (2017) 258
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

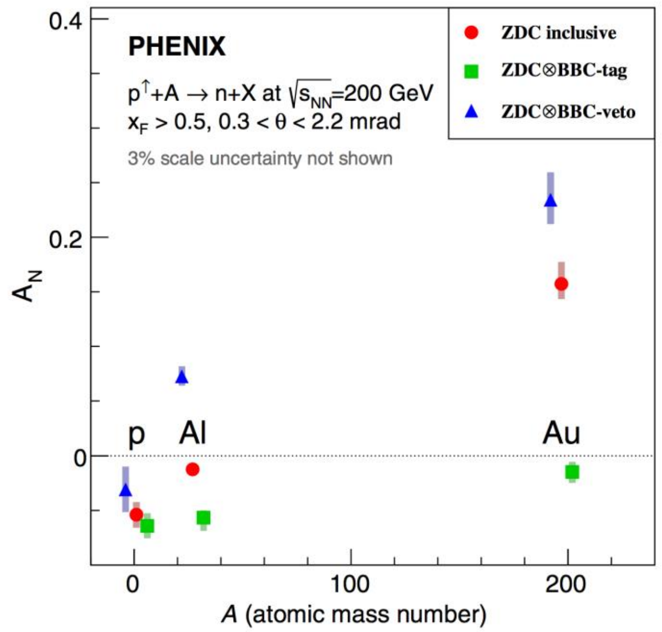
$p^{\uparrow} + p$

$p^{\uparrow} + Al$

$p^{\uparrow} + Au$

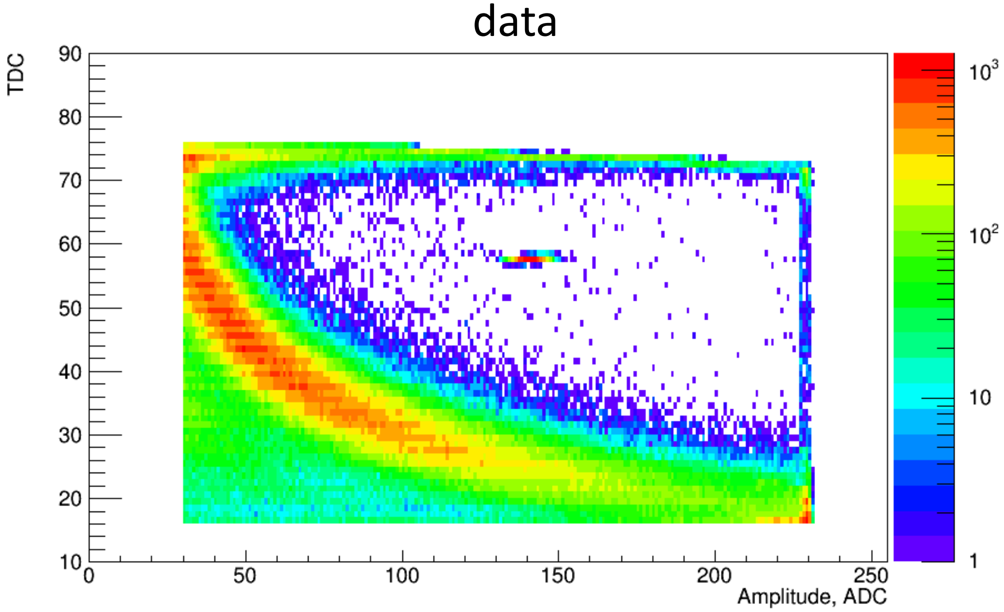


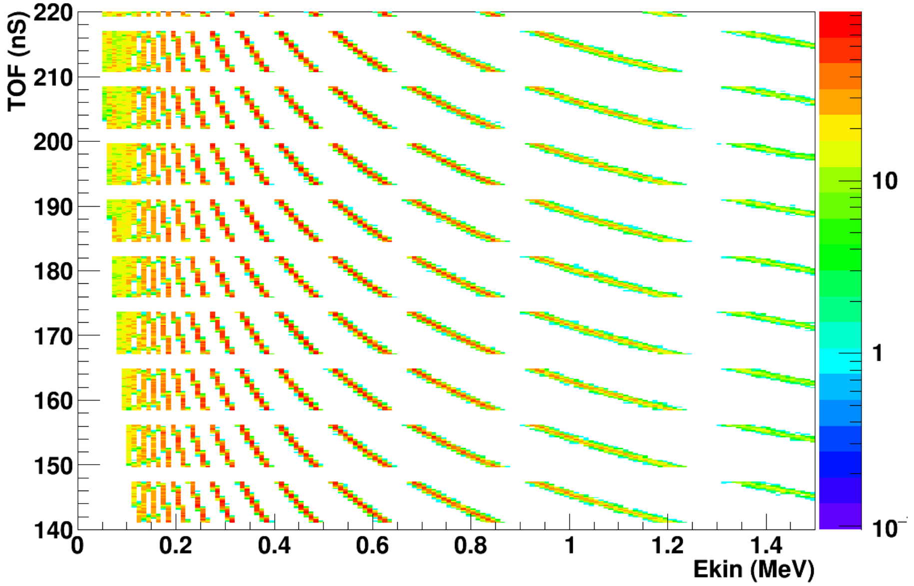


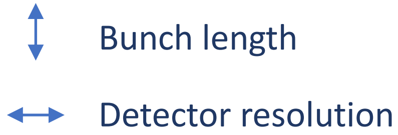


Phys. Rev. Lett 120 (2018) 022001
Phys. Rev. C 95 (2017) 044908

From RHIC to EIC







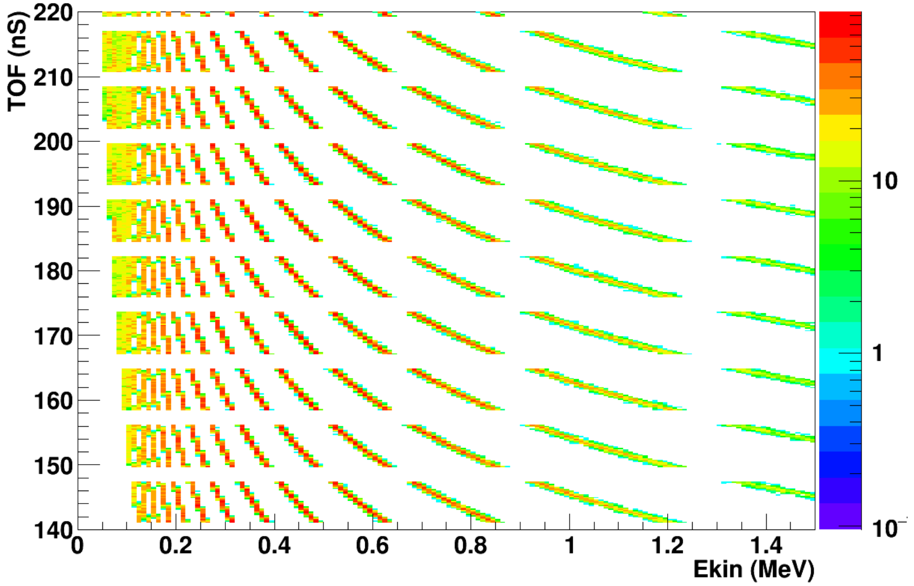
120 bunches → 1320 bunches

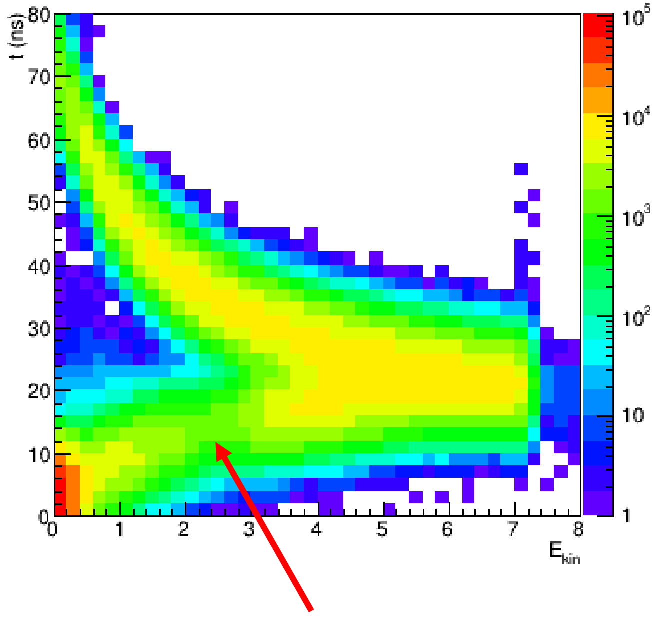
Bunch spacing 106 ns → 9.6 ns

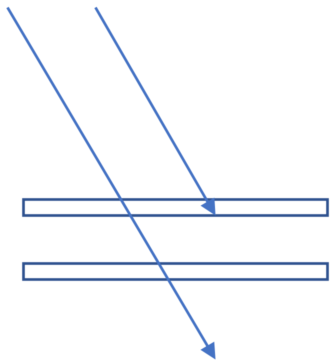
Bunch length $3.5\ \mathrm{ns} \rightarrow\ 0.3\ \mathrm{ns}$

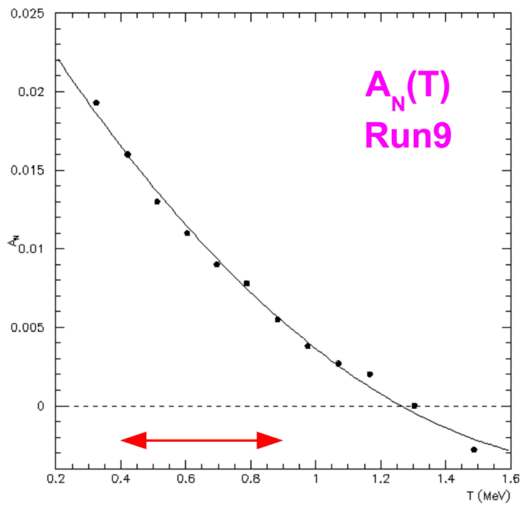
From RHIC to EIC

- 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



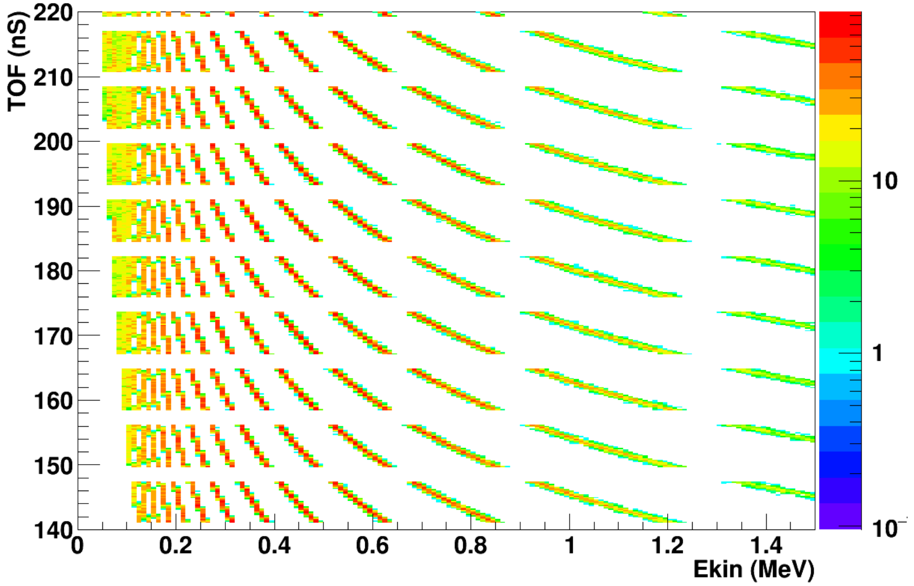


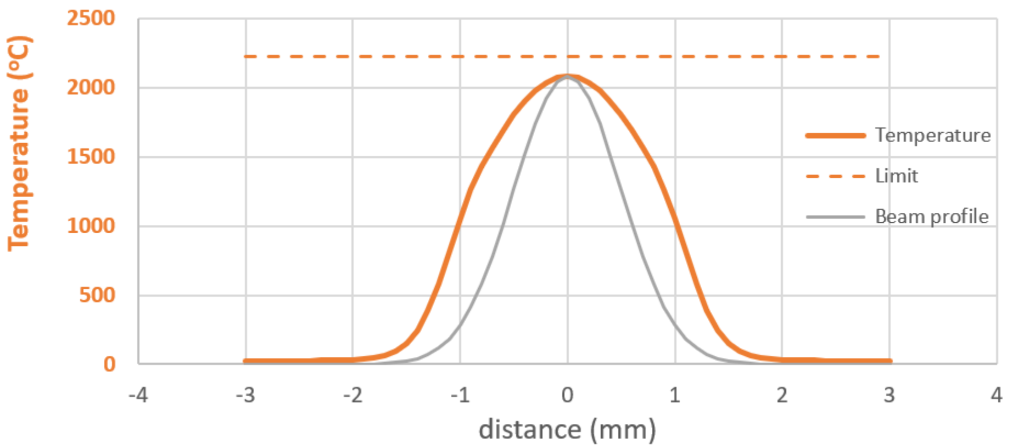




From RHIC to EIC

- 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

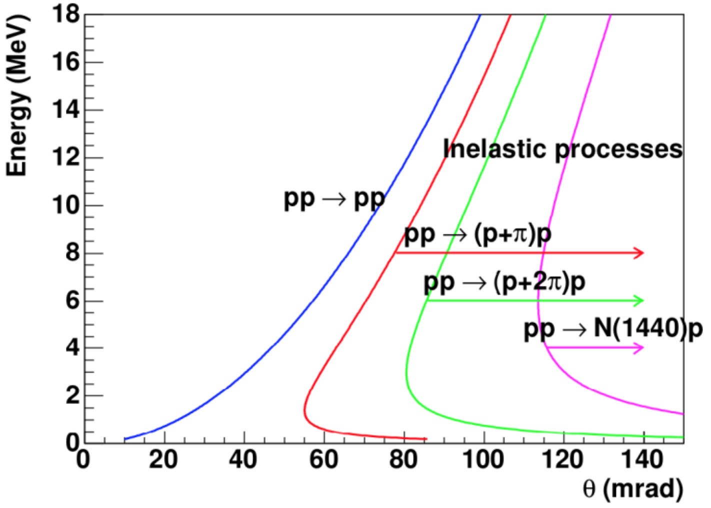
Polarized Light Ion Beams

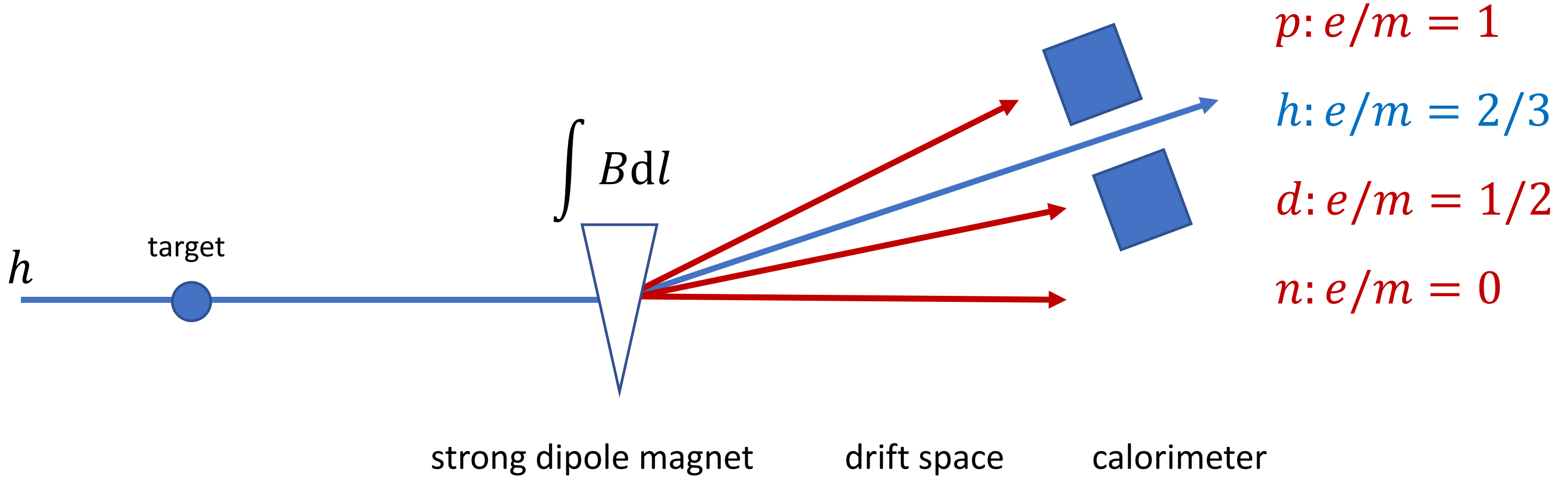
- Polarized d and ^3He beams are not part of the EIC baseline design.
- Absolute polarization will (likely) require a polarized ^3He target.
    - Elastic scattering is necessary for the sign-flip of the analyzing power

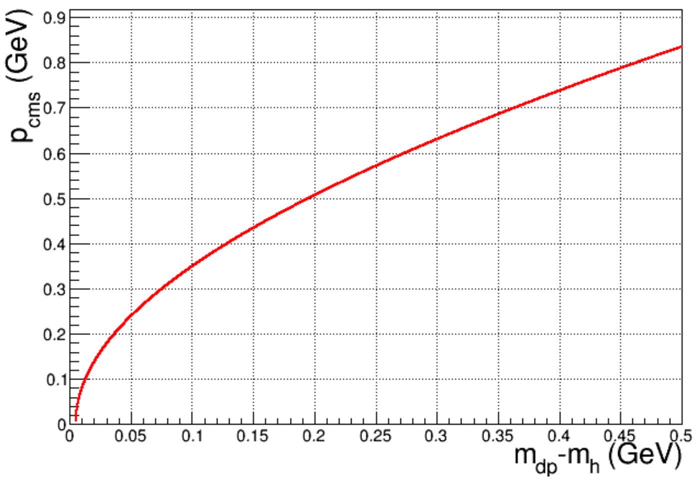
$$A_{00N0} = -A_{000N}$$

    - Breakup energy is only 5.5 MeV: problematic if beam breaks up $h \to pd$
    - Tag/veto breakup products downstream of the polarimeter

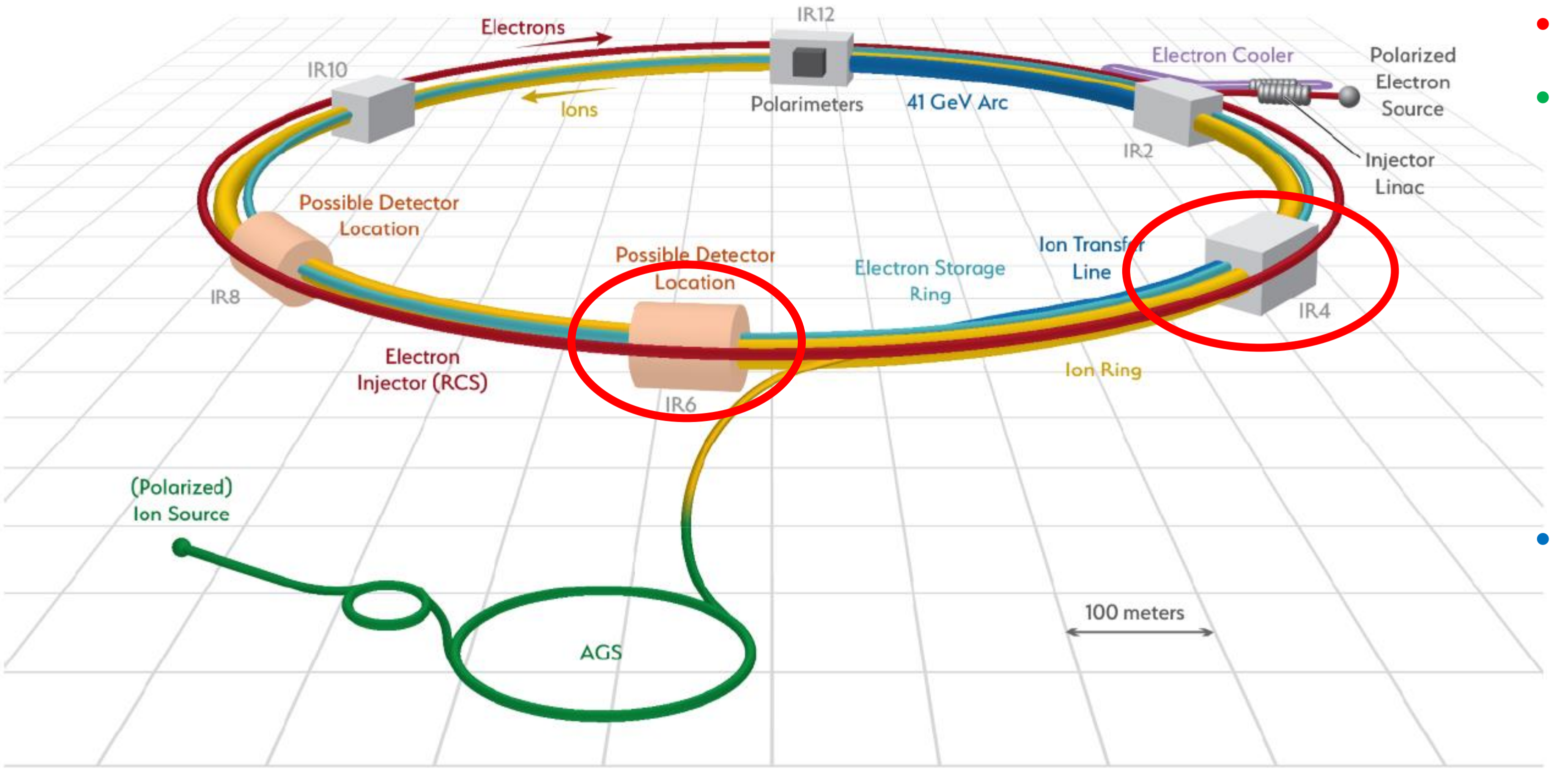
threshold for $pp \to pp\pi$

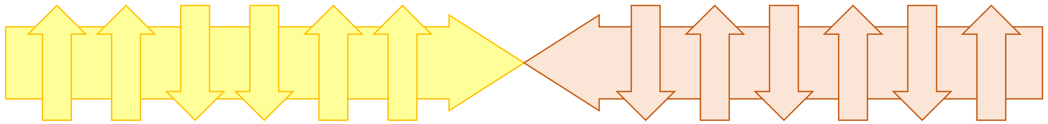






Recap: Hadron Polarimetry



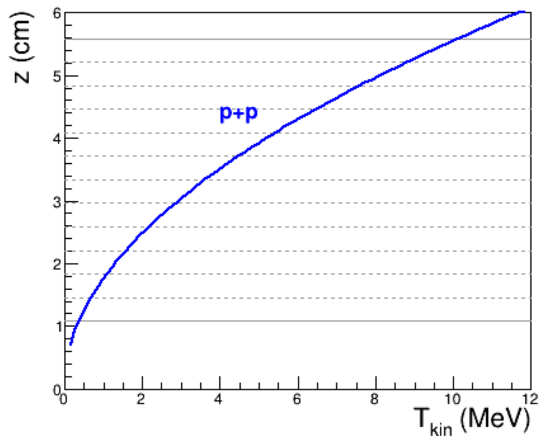


- Proton beam energies: $50 - 275$ GeV
- Combination of devices for
  - Non-destructive
  - Absolute polarization
  - Fast measurements during store
  - Bunch profile
  - Local polarimetry at experiment
- Potential for future polarized light ion beams
  - Location allows for upgrades to the polarimeter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

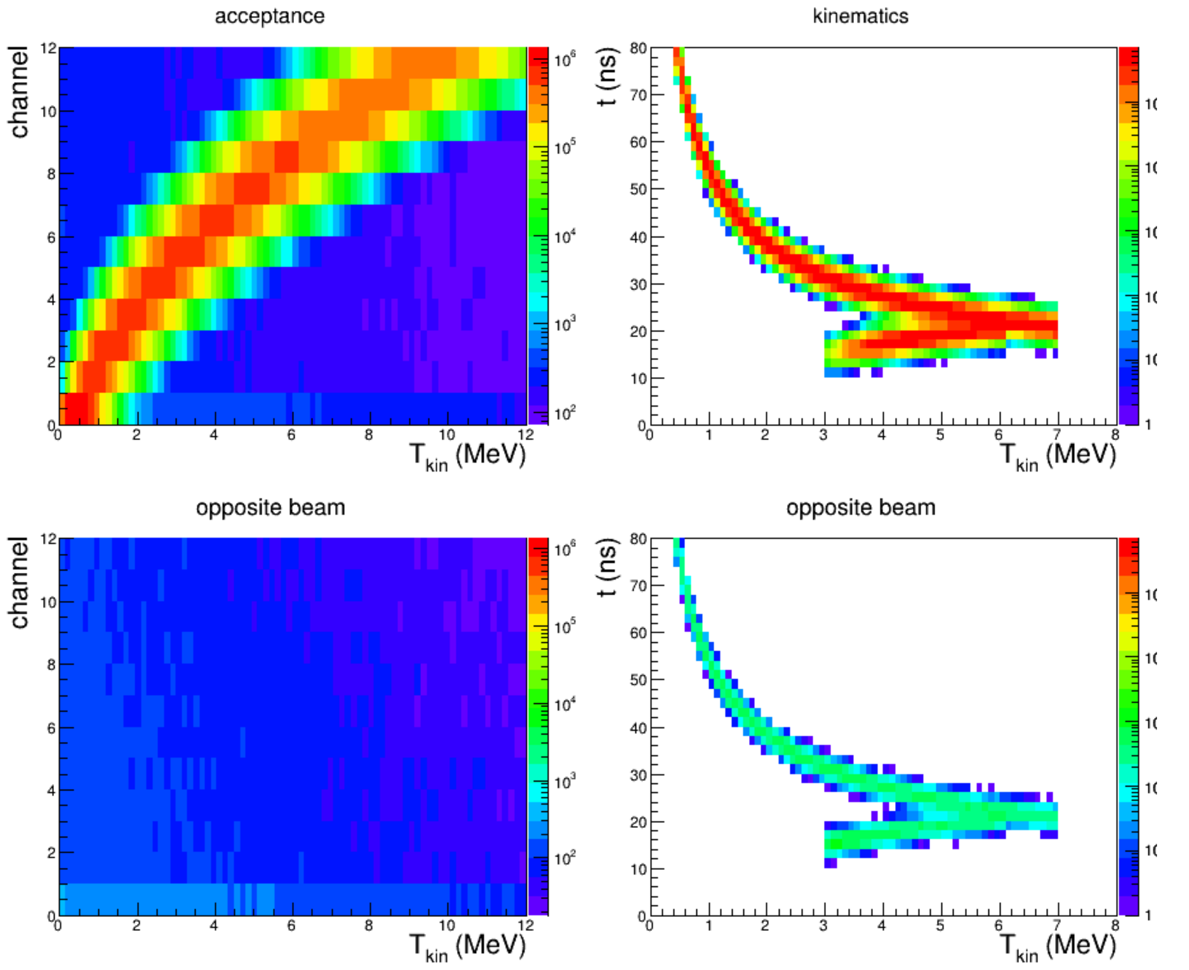
Backup

Toy Simulation

- Recoil angle calculated from kinetic energy
- Assume fairly slow exponential cross section as function of energy
- Deposited energy from punch through particles calculated with empirical model (NIST)
- Size of atomic beam target and molecular component
- Effect of opposite beam (upstream contribution from molecular target)



bunch length σ_B = 1.0 ns
target width σ_T = 0.3 cm
molecular width σ_M = 9.0 cm
molecular fraction r = 1%



Main uncertainties:

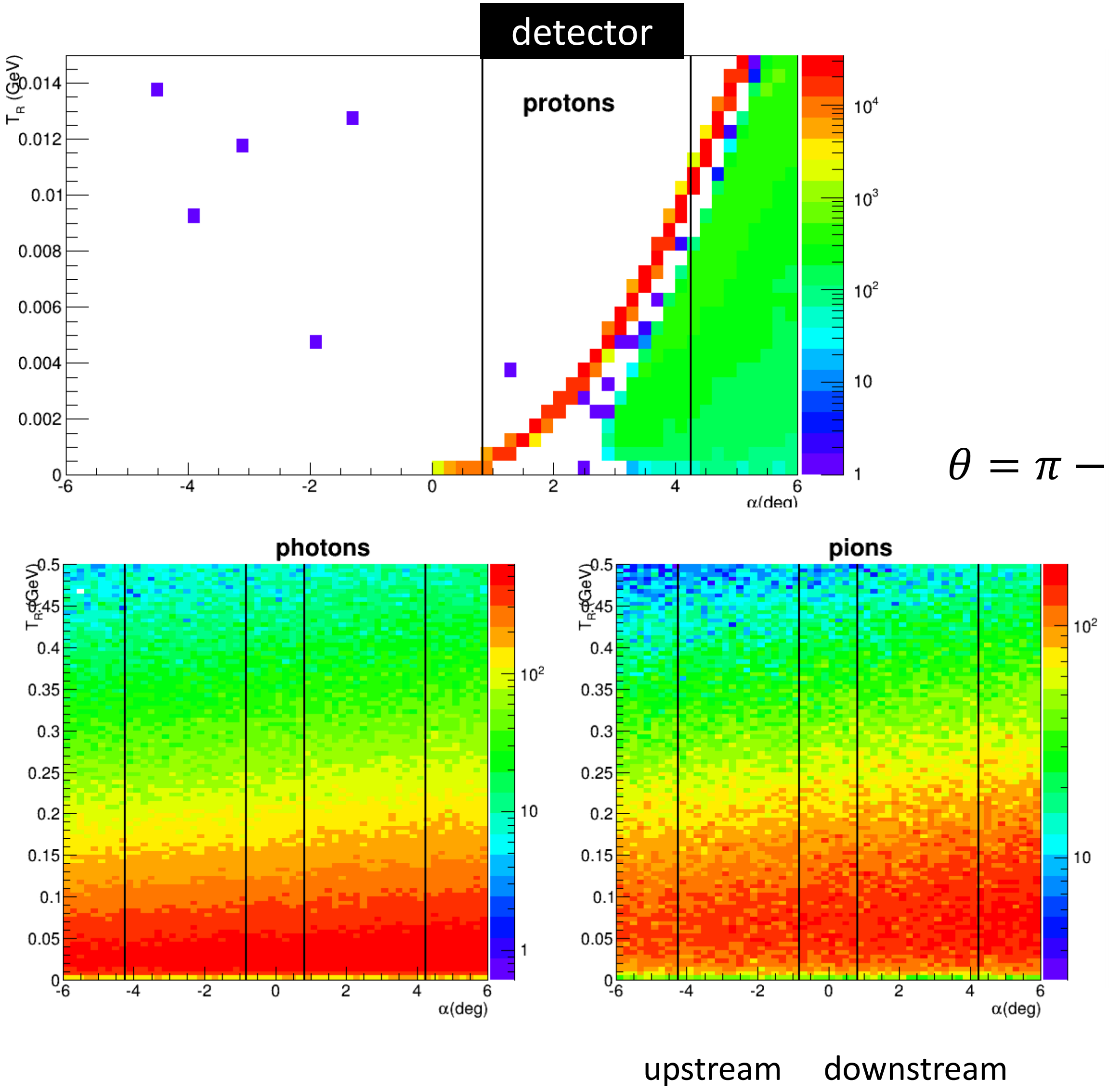
- Bunch length
- Target thickness (z)
- Molecular background (z)

Other uncertainties:

- Energy resolution
- Strip pitch

PYTHIA Studies

- p+p at $\sqrt{s} = 21.6$ GeV with boost
  - Equivalent to 250 GeV beam on fixed target
- PYTHIA 6.4.28, Tune 320
  - QCD 2 → 2
  - Elastic
  - Diffractive
- Fast background
  - pions, (*photons*) up to a few GeV
  - Kinematic correlation lost
- For this study, the vertical size of the detector is not relevant (no asymmetry measurement, keep full azimuthal range φ)

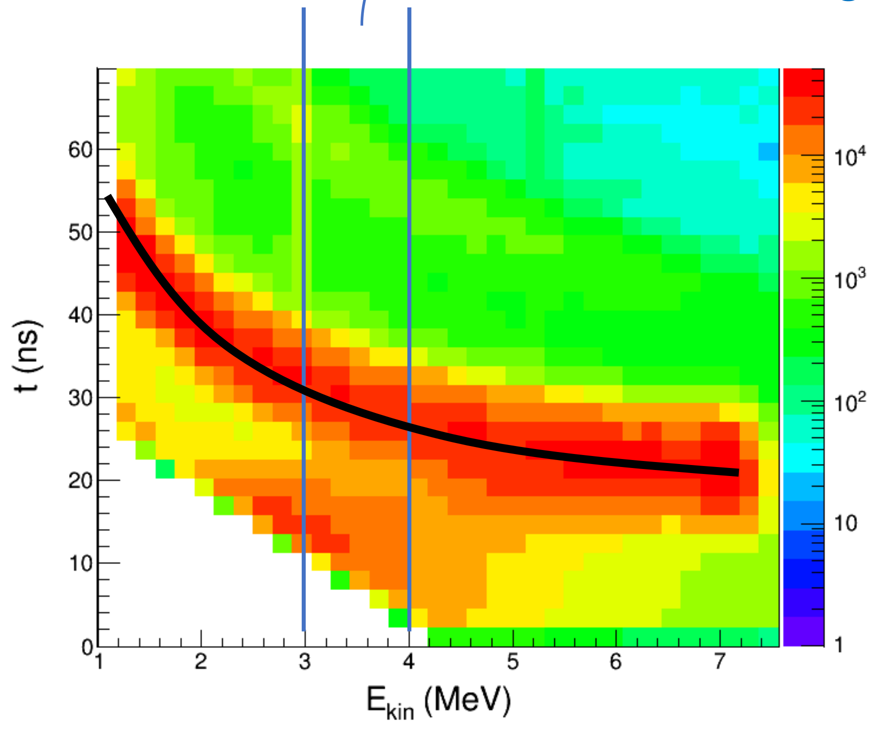


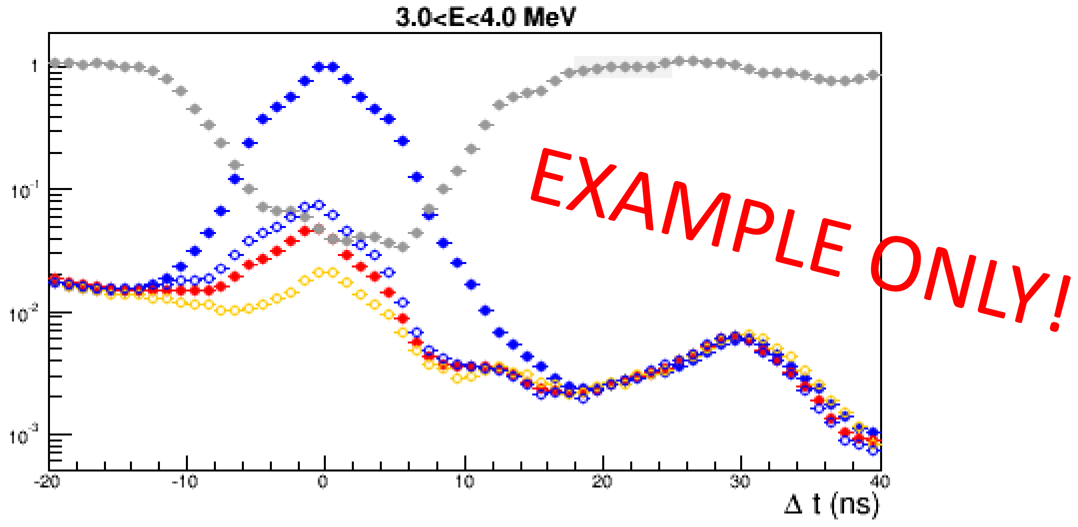
$\theta = \pi - \alpha$

Combine signal and background into time-of-flight vs. deposited energy

How to quantify the background

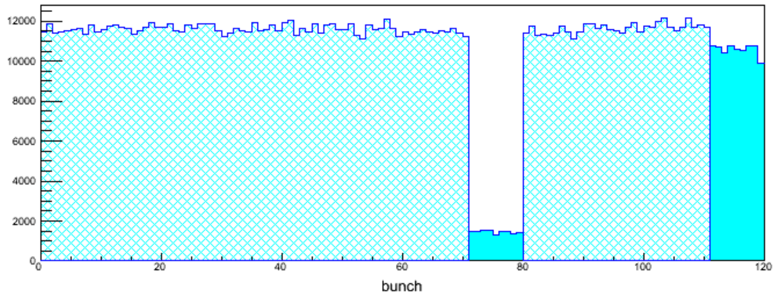
- Slice in kinetic energy
- Compare
  - signal
  - punch through
  - background





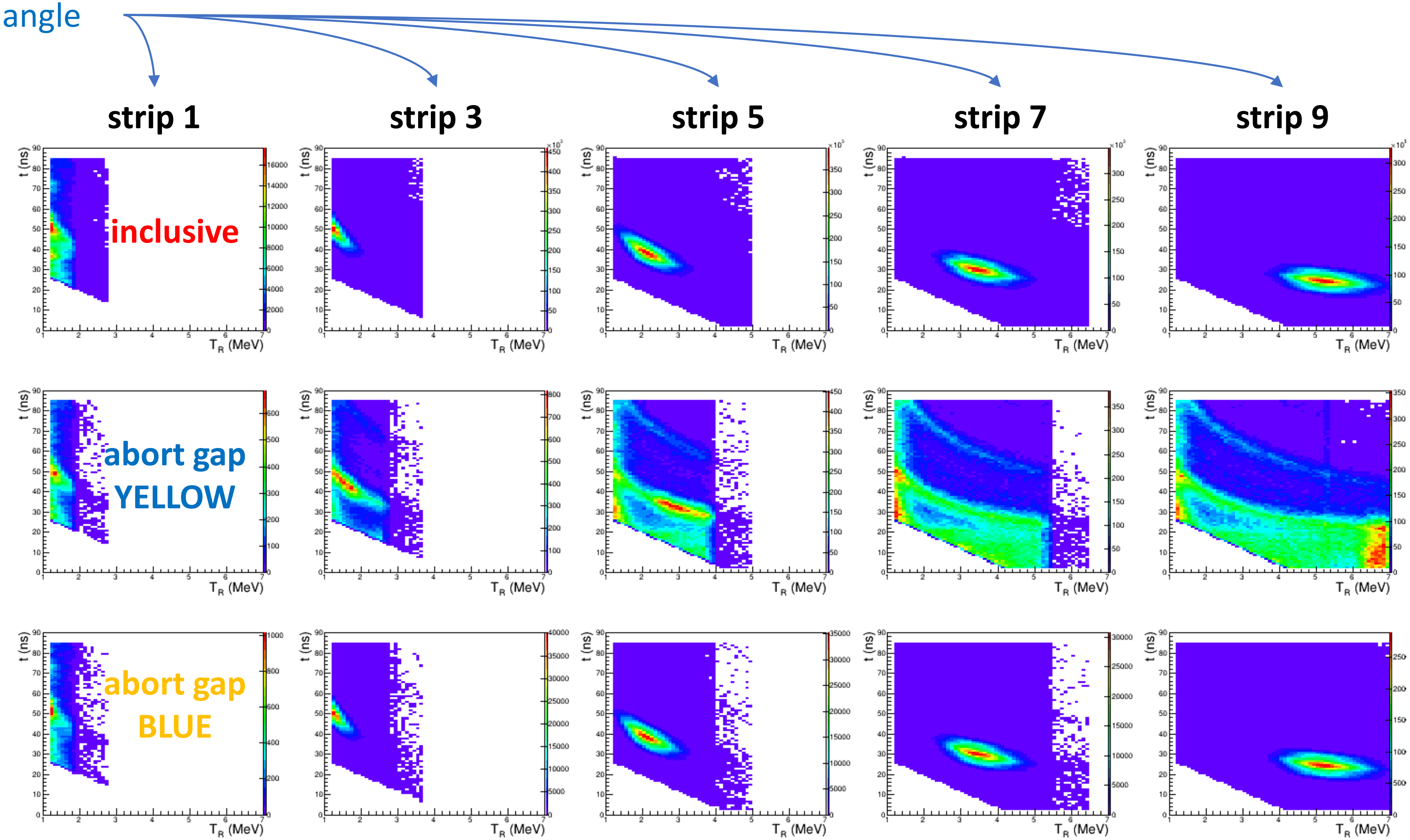
$$\Delta t = t_{meas} - t_{calc}$$

	$m_{miss} \approx m_P$	$m_{miss} \neq m_P$
Inclusive	●	○
Abort gap	○	
Signal		●



Kinematics of the Recoil Proton

different recoil angle



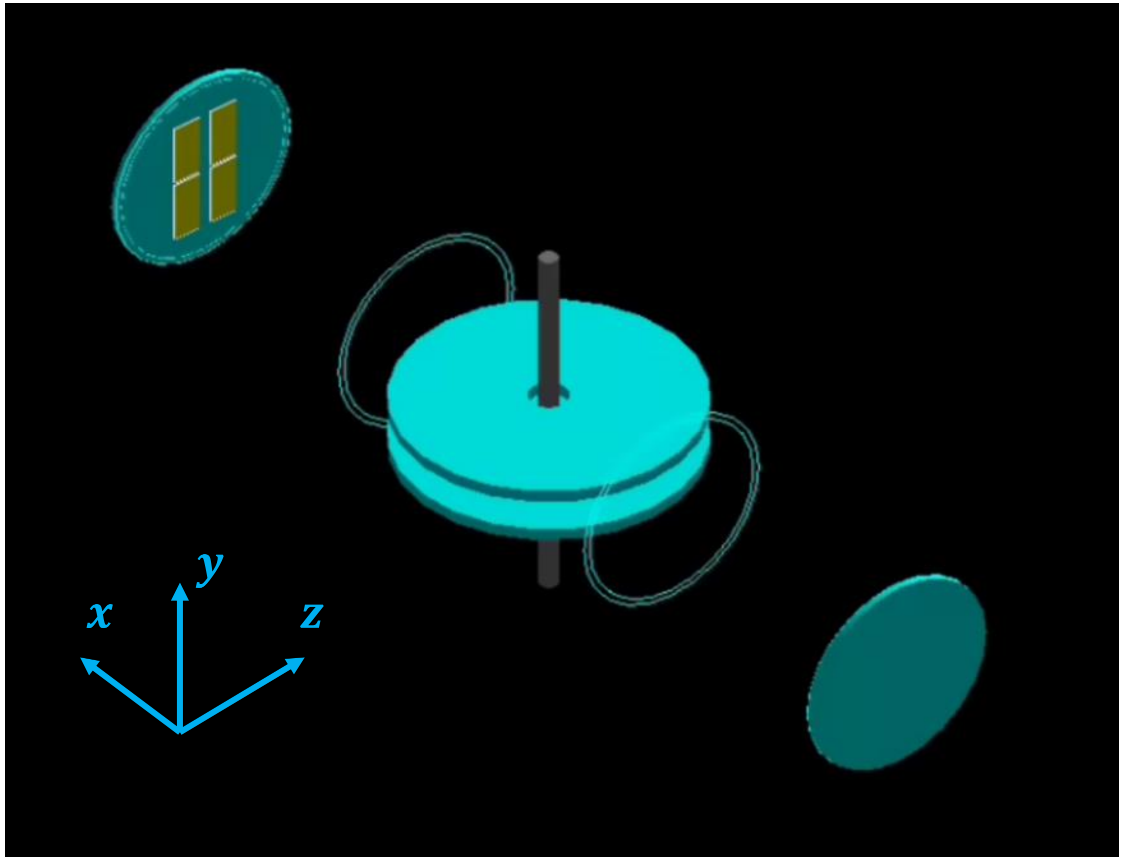
DST files are available with jetTree:

- tof
- ekin
- strip (α)

Will need to rerun a few fills without the manual tof/ekin cut

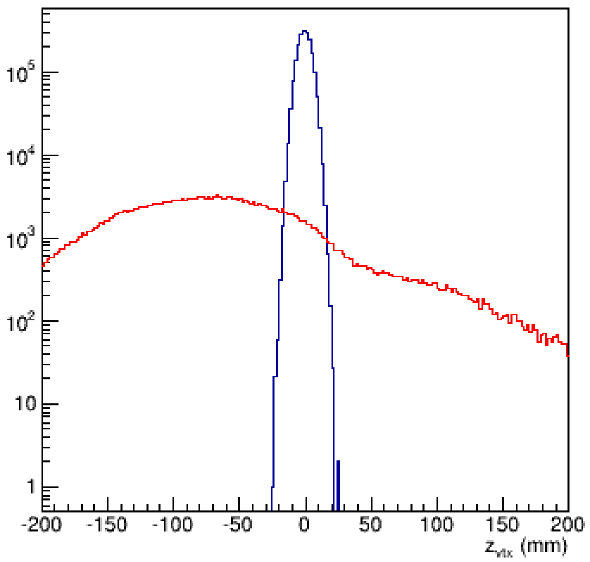
Polarimeter Simulation

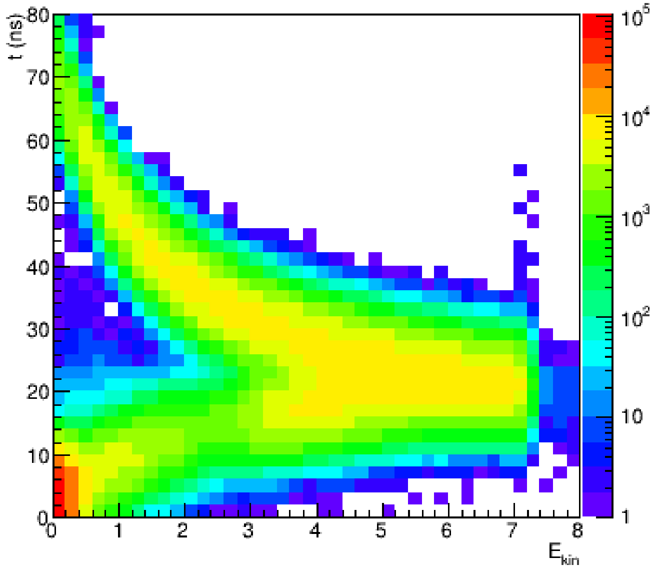
- Full detector in GEANT4
  - $400\ \mu m$ Silicon, $8\ \mu m$ dead layer
  - No strip segmentation (no pile-up seen in data)
- Detector chamber and flanges
- Atomic hydrogen jet target
  - $\rho \approx 0.4 \cdot 10^{-11}\ \mathrm{g/cm^3}$
- Parameterized magnetic holding field
- Beam bunch length ($3.5\ \mathrm{ns}$)
- Vertex distribution ($5\ \mathrm{mm}$, $10\ \mathrm{cm}$)
- PYTHIA input
  - Single beam

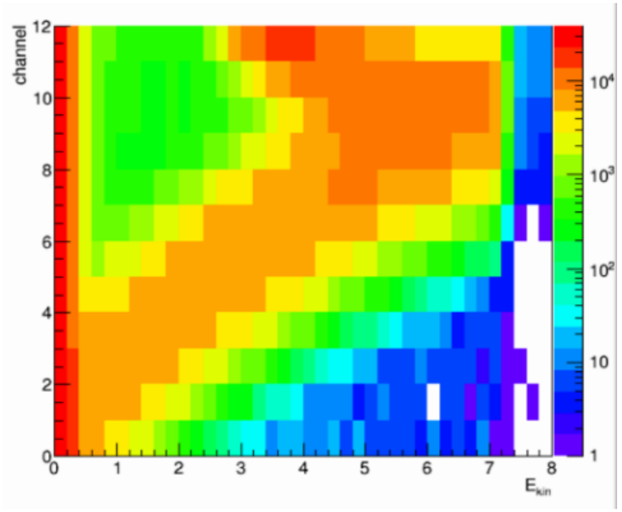


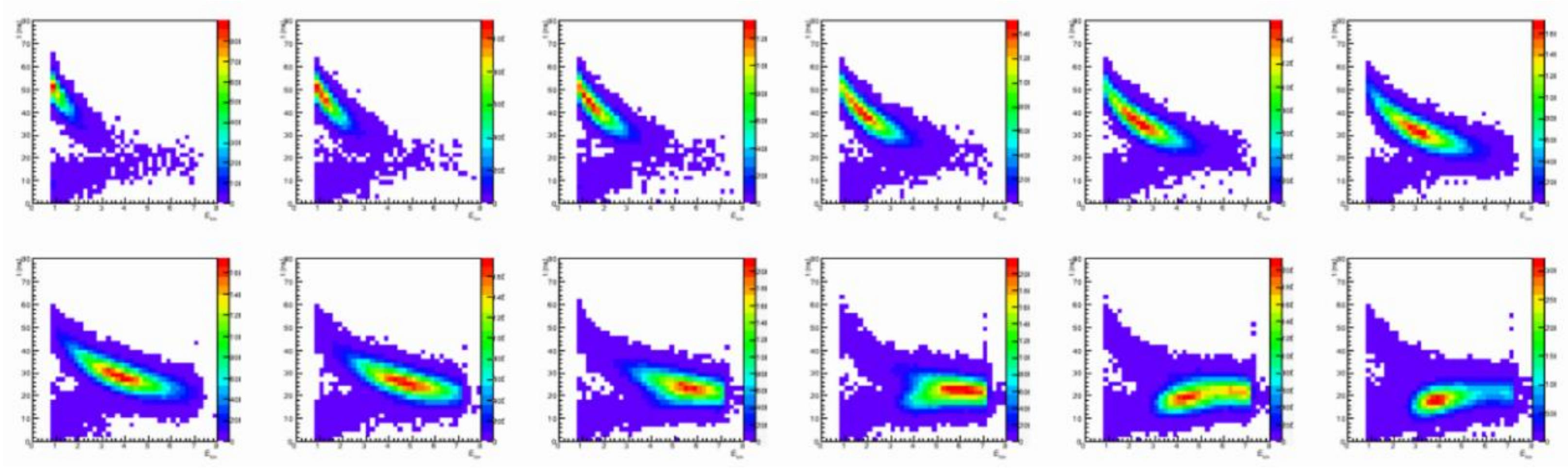
Simulation Results

- 100M + 10M filtered PYTHIA events
  - Tracks within 30^o of detector center
  - About 2M + 250k hits
  - Rarely more than one track per event
- Simulation reproduces the basic features
  - Kinematic correlation (elastic scattering)
  - Signal and background (particle id)









Simulation Results

- Punch-through particles
  - Fast, little energy deposit
- Very few recoil protons in upstream detector
  - Compare target width with detector length
- Contribution from widely distributed molecular hydrogen
  - Wide range of punch-through particles
  - Skewed vertex distribution due to detector acceptance
- Test measurements in RHIC Run 2022
  - Modifications to detector setup to veto punch-through particles