Hadron Polarimetry for the EIC

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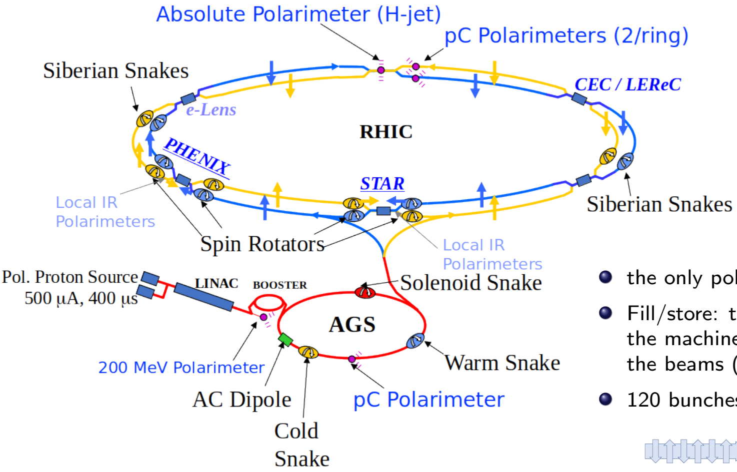
BROOKHAVEN NATIONAL LABORATORY

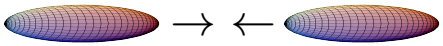
U.S. DEPARTMENT OF ENERGY | Office of Science

Relativistic Heavy Ion Collider



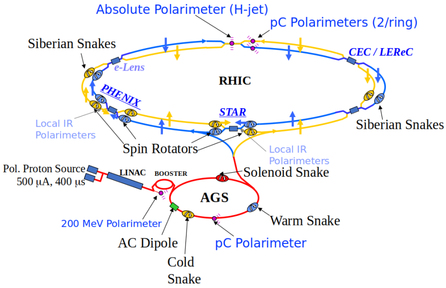
- the only polarized proton collider
- Fill/store: time unit over which the machine is filled and collides the beams ($\sim$ 8 hours)
- 120 bunches (106 ns spacing)

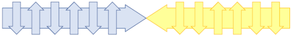
- 10^{11} protons per bunch
- Bunches have extension in x, y, s



Proton polarimetry at RHIC

- **There is no physical process that can be calculated from first principles that can be used in ion polarimetry**
- Requirements: **precision**, **polarization profile** and **lifetime** to know **polarization in collisions**
- **Two-tier measurement**:
  - one for the **absolute polarization** (with low statistical power)
  - one for **relative polarization** (with high statistical power)

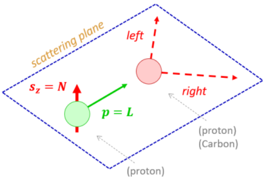




120 bunches (106 ns spacing)
10^{11} protons per bunch
Store $\sim$ 8 hours

Absolute polarimeter: H-jet polarimeter

- A **polarized proton jet, with known polarization** used as target for **elastic scattering in Coulomb-nuclear interference (CNI) region** by beam $\vec{p}$. Asymmetry: $\varepsilon = A_N P$.



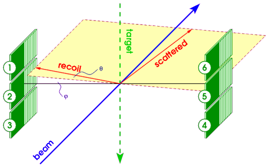
- The analyzing power A_N doesn't have to be known and allows the **self-calibration** of the polarimeter

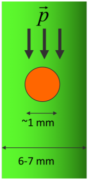
- Beam polarization given by

$$P_{\text{beam}} = \frac{\varepsilon_{\text{beam}}}{A_N} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} P_{\text{target}}$$

$$\varepsilon = \frac{N_L - N_R}{N_L + N_R}$$

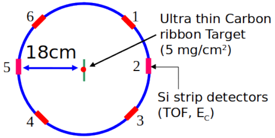
- Silicon strips detect the recoil protons



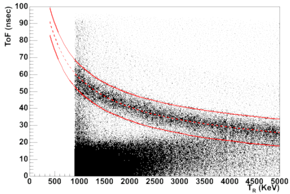


Fast and precise polarimeter: pC polarimeter

- **Non-polarized, ultra-thin carbon ribbon** ($w = 10$ μm), used as target for **elastic scattering in the CNI region** by beam $\vec{p}$
- Azimuthal asymmetries $\varepsilon(\phi)$ measured
- A_N from normalization to the H-Jet; dependence with energy agrees well with models
- Beam polarization: $P_b = \dfrac{\varepsilon(\phi)}{A_N \cdot \sin(\phi)}$
- Silicon strips detect the recoil carbon nuclei, measurements of 20-30 s in target scan mode

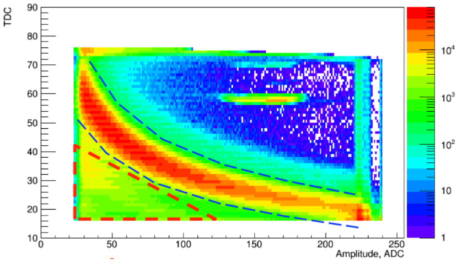


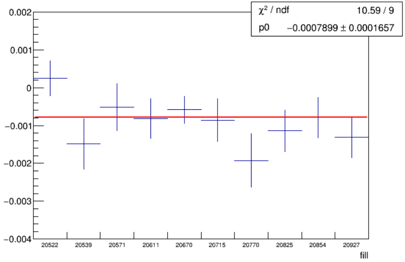
Time of flight vs kinetic energy



From RHIC to the EIC

- Requirements for the EIC: **bunch by bunch polarization measurement with 1% uncertainty**
- Challenges: **less time between bunches** (with respect to RHIC), **possibly polarized prompt background** to elastic scattering signal events





Background asymmetry, 10 measurements of
RHIC pC polarimeters in 2017

From RHIC to the EIC (2)

- AGS and RHIC will continue running until 2025 $\Rightarrow$ can be used for **tests**
- Test on RHIC polarimeters, using **second layer of silicon strips**, planned for 2021 $\vec{p}\vec{p}$ run, to understand the feasibility of vetoing prompts (now being tested in one silicon detector of the AGS pC polarimeter)
- Tests of ***dd*** **scattering at the RHIC Jet polarimeter** and of $\vec{h}$ **on the AGS carbon polarimeters** can be done the next years to measure rates, analysing power A_N values and to evaluate the viability of d polarimetry at the EIC (since 2015, tests were done at the RHIC H-Jet with different nuclear beams)
- Other solid (e.g. gold) and gaseous (e.g. xenon) **target materials**, usage of other technologies, including better **timing resolution** and lower **electronics background**, should be considered

Possible tests for hadron polarimetry at the AGS and RHIC

Tests at BNL for hadron polarimetry of EIC

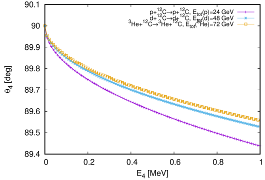
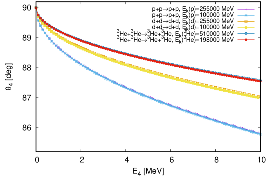
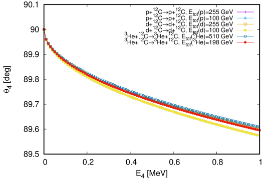
Beam	Target	Ring/ Polarimeter	Energy/ nucleon	Comments
He-3	C	AGS/C	24 GeV	Was already done, useful to know rates (including background)
Polarized He-3	C	AGS/C	24 GeV	Useful to get the scaling factor of the A_N
He-3	He-3	RHIC/X	166 GeV	Useful to know rates (including background)
He-3	Polarized He-3	RHIC/X	166 GeV	Useful to get the scaling factor of the A_N
Polarized He-3	Polarized He-3	RHIC/X	166 GeV	Useful to get the A_N
He-3	C	RHIC/C	166 GeV	Useful to know rates (including background)
D	C	AGS/C	24 GeV	Useful to know rates (including background)
D	D	RHIC/Jet	100 GeV	Useful to know rates (including background)
D	Polarized D	RHIC/Jet	100 GeV	Useful to get the scaling factor of the A_N
D	C	RHIC/C	100 GeV	Useful to know rates (including background)

Maximum energies provide the smallest analysing powers, hence are better suited for tests.
X – dedicated setup attached to bottle with gas

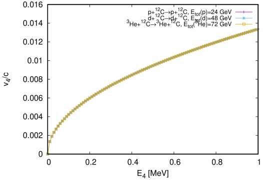
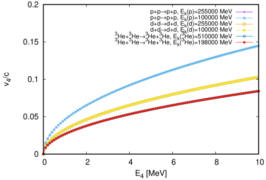
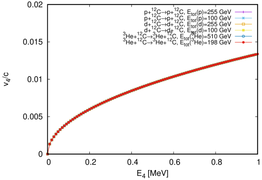
- Tests of *dd* **at the RHIC H-Jet** and of $\vec{h}$ **on the AGS carbon polarimeters** are more prioritary, others could be done later

Kinematics

θ_4 (angle of recoil particle with respect to beam direction) vs its energy

pC AGS	H-Jet	pC RHIC
		

v_4/c (relative velocity of recoil particle) vs its energy

pC AGS	H-Jet	pC RHIC
		

[From: https://skisickness.com/2010/04/relativistic-kinematics-calculator/]

- **Similar kinematics (detector geometry and time of flight)** of light ions and pp

Polarized light ion beams, analysing power

- Simplest model for elastic scattering:

$$A_N \propto k$$

- **Breakup of light ions** has to be taken into account, e.g. by vetoing fragments

- Polarimetry using elastic scattering in the CNI region in D-D or D-C **very difficult**

$k_p = 1.793,\ k_{^3He} = -1.398,\ k_D = -0.143$

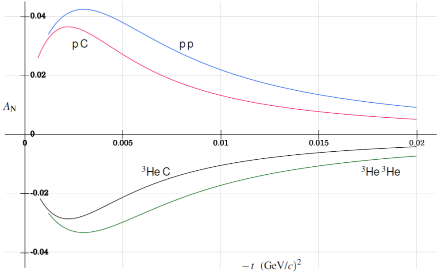


Figure 1: Analyzing power A_N versus the squared momentum transfer variable (-t) for the elastic scattering processes (from the top): (1) proton proton, (2) proton carbon, (3) helium-3 carbon, (4) helium-3 helium-3, assuming that $\sigma_{tot}(hC) = 2\sigma_{tot}(pC)$, that $\sigma_{tot}(hh) = 4\sigma_{tot}(pp)$, and that ρ, δ, R_S, I_S, and finite nuclear size effects are negligible.

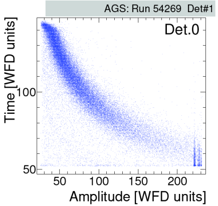
[N. Buttimore]

- A **test with a jet of polarized deuterons with known polarization** can be done in the next few years **at the H-Jet**

Helium-3 beams

- Gas of **polarized helium-3** nuclei (helion) was used as **fixed target** at HERMES [Nucl. Instr. & Methods A367 1995 9699], JLab and Jülich
- A helium-3 beam was **tested sucessfully at the AGS C polarimeters**, can be repeated with higher intensity beam
- "Event rate gain for helion due to elastic cross section is estimated to be $A^{2/3} = 3^{2/3} = 2.08$. The actual observed gain is about 2."

Helion-carbon scattering at C polarimeters of the AGS:



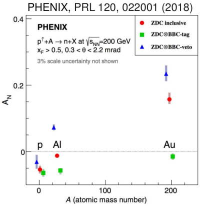
[H. Huang *et. al.*, Proceedings of IPAC2014, Dresden, Germany, doi:10.18429/JACoW-IPAC2014-WEPRO071]

- Source of polarized ^{3}He is available; a **test with polarized ^{3}He in C polarimeters of the AGS** can be envisioned

Alternative approach

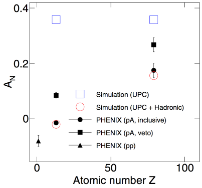
- A **large asymmetry** was measured by PHENIX in **forward neutrons from $\vec{p}$ on nuclei** (Al and Au)
- γ from high Z nucleus scatters on $\vec{p}$ target; parameterizations of $\gamma + \vec{p} \rightarrow n + \pi^+$ (MAID**) and photon flux (STARlight*) describe PHENIX results:

Data:

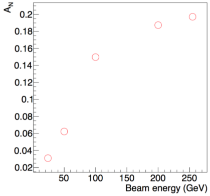


Model vs data

[G. Mitsuka, PRC 95, 044908 (2017)]



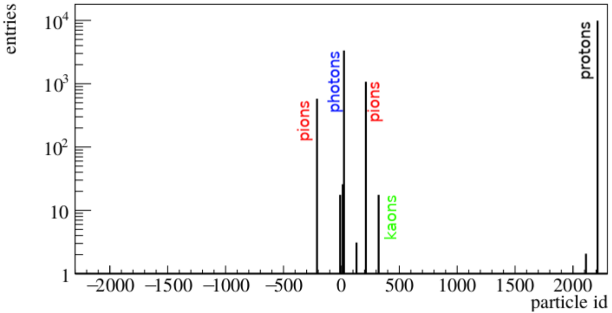
Simulation (pAu):



- **Polarimeter: high Z target (*e.g.* Xe gas jet) in $\vec{p}$ beam**
- Would require a calorimeter to detect neutrons at low angles
- Open questions: can a thin jet ($\sim$ 100 μm) of Xe gas be produced and allow enough statistics for lifetime of P and profile measurements?

(*) Klein et al., Comput. Phys. Comm. 212 (2017) 258 (**) Drechsel et al., Eur. Phys. J. A 34 (2007) 69

Pythia simulations of the present RHIC H-Jet polarimeter

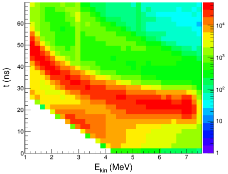


- phythiaRHIC (Phythia6), $E_1 = 255$ GeV, $E2 = 0.00001$ GeV; 5×10^6 events, acceptance of the H-Jet silicon detectors
- MSEL=0
  MSUB(91)=1 ! Elastic
  MSUB(92)=1 ! Singly diffractive (XB)
  MSUB(93)=1 ! Singly diffractive (AX)
  MSUB(94)=1 ! Double diffractive
  MSUB(95)=1 ! Low-pT scattering

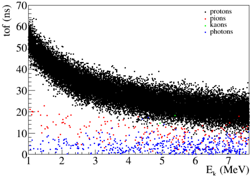
  MSUB(96)=1 ! Semihard QCD 2 $\rightarrow$ 2
- Most common particles in the final state: protons, pions, photons, kaons

Pythia simulations of the present RHIC H-Jet polarimeter

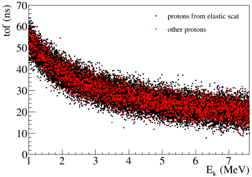
2017 H-Jet data

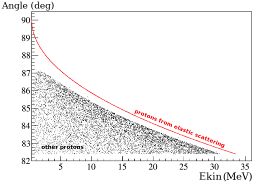


Pythia pp simulations



- Bunch length of 3.7 ns used to produce the smearing
- “Banana” shape reproduced
- It’s possible to separate elastic and inelastic scattering protons based on angle and kinetic energy for the H-Jet





Summary

- **Hadron polarimetry is crucial for the EIC spin physics program**
- The EIC conditions present **challenges, as the shorter time between bunches**, and **more stringent requirements (bunch by bunch polarization measurements)**
- Pythia simulations reproduce the "banana" shape of the TOF vs kinetic energy for the H-Jet data
- pA simulations with DPMJET-III are underway
- We should make the best usage of the available unique conditions at AGS and RHIC until 2025
- APEX (accelerator physics experiment) request being prepared, all input is much appreciated!

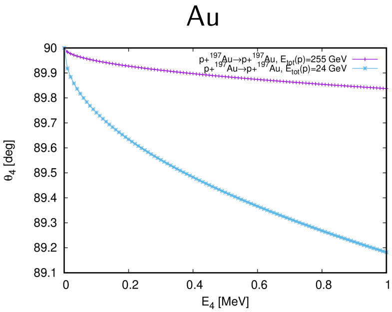
BACKUP

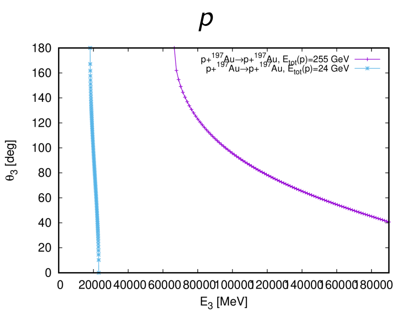
Gold as a substitute for carbon in pC polarimeters?

- Leeds University has found a way of making a gold sheet just two atoms thick so that there should be few multiple scattering events were the sheet (or sheets) whisked by to avoid depletion. The recoil angle may then act as a constraint. (Nigel Buttimore) ["Scientists create the world's thinnest gold", https://phys.org/news/2019-08-scientists-world-thinnest-gold.html]

- "I had alerted Andrei Poblaguev to the possibility of a gold polarimeter. As you may know, he pointed out that, most likely, inelastic $pAu \rightarrow pAu^*$ scattering rather than elastic $pAu \rightarrow pAu$ had been measured. For a gold target polarimeter one would have to theoretically understand the difference between detecting recoil protons and recoil gold. Also, the desirable recoil Gold energy of 8 keV may be too small by comparison with the HJET electronic noise of about 20 keV. I suppose that electrostatic acceleration of the recoiling Au (to increase energy and lower time-of-flight) is not possible."

Kinematics of pAu final state particles for AGS and RHIC energies

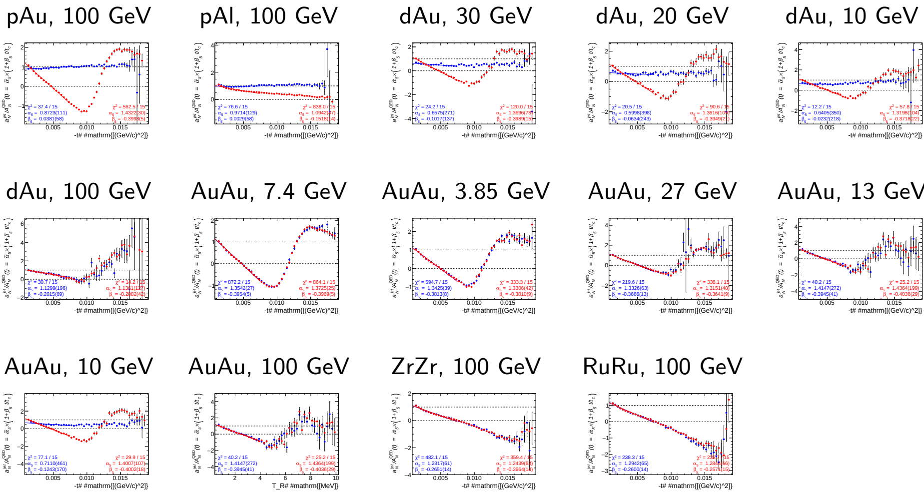




[From: https://skisickness.com/2010/04/relativistic-kinematics-calculator/]

Tests (parasitic measurements) at the H-Jet since 2015

[Andrei Poblaguev, mail 7/Jan/2020]



- pAu(100) single spin asymmetry changes sign, depends on beam energy