Hadron Polarimetry
at an
Electron-Ion Collider

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18th International Workshop on
Polarized Sources, Targets and Polarimetry

September 23-27, 2019
Knoxville, TN

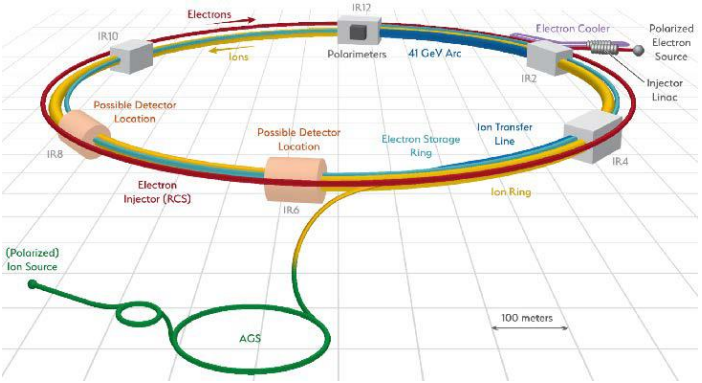
BROOKHAVEN NATIONAL LABORATORY

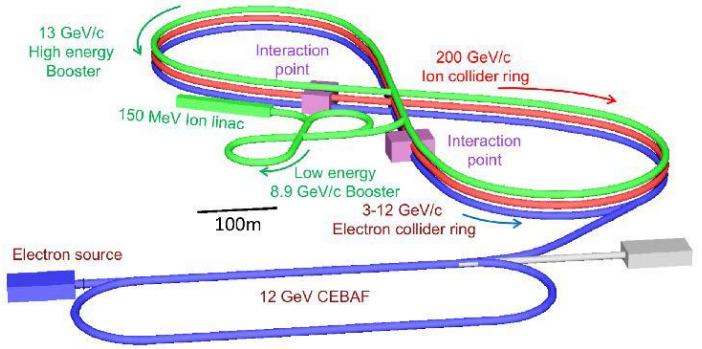
U.S. DEPARTMENT OF ENERGY | Office of Science

OAK RIDGE National Laboratory

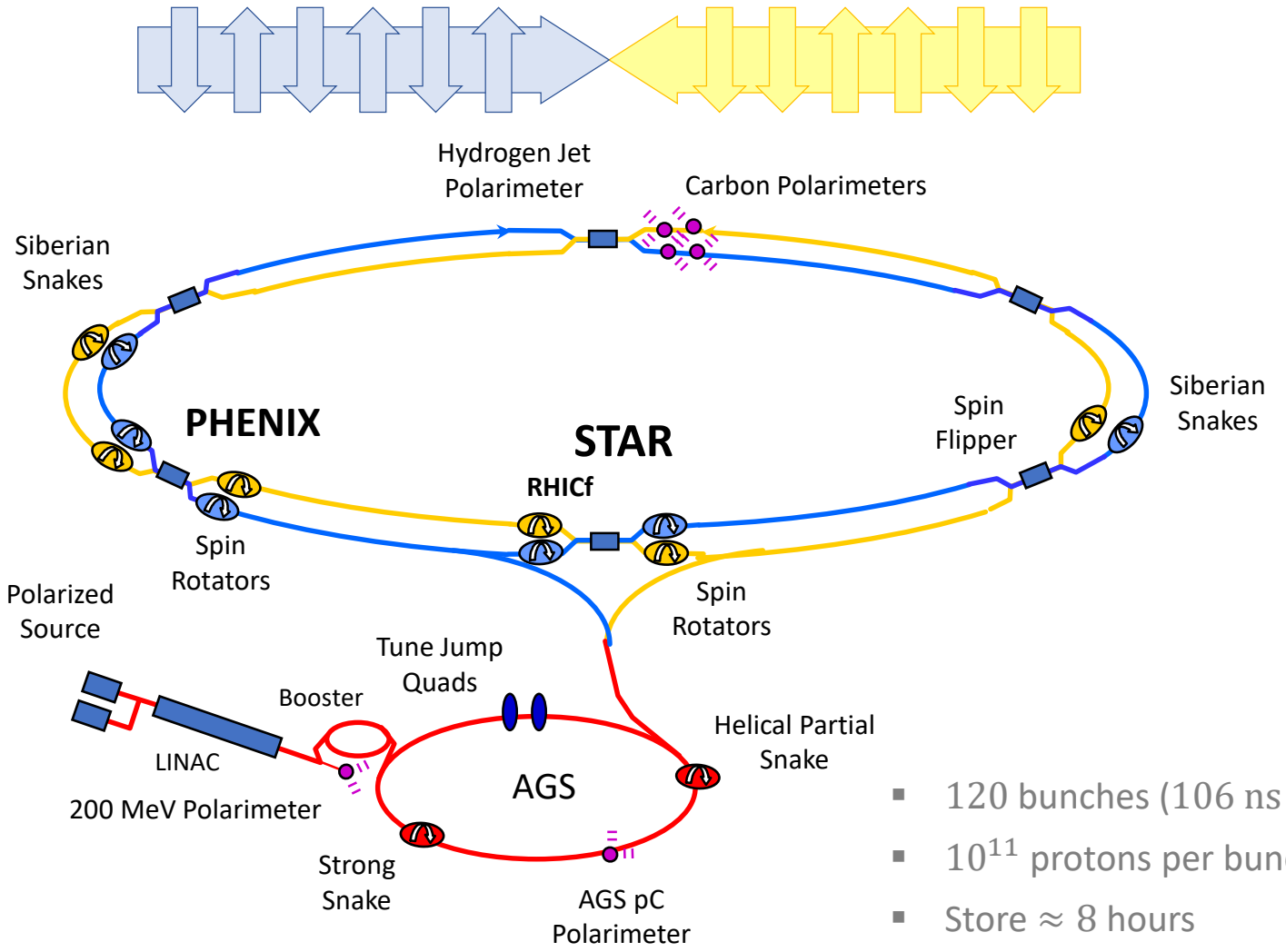
Requirements for an Electron-Ion Collider

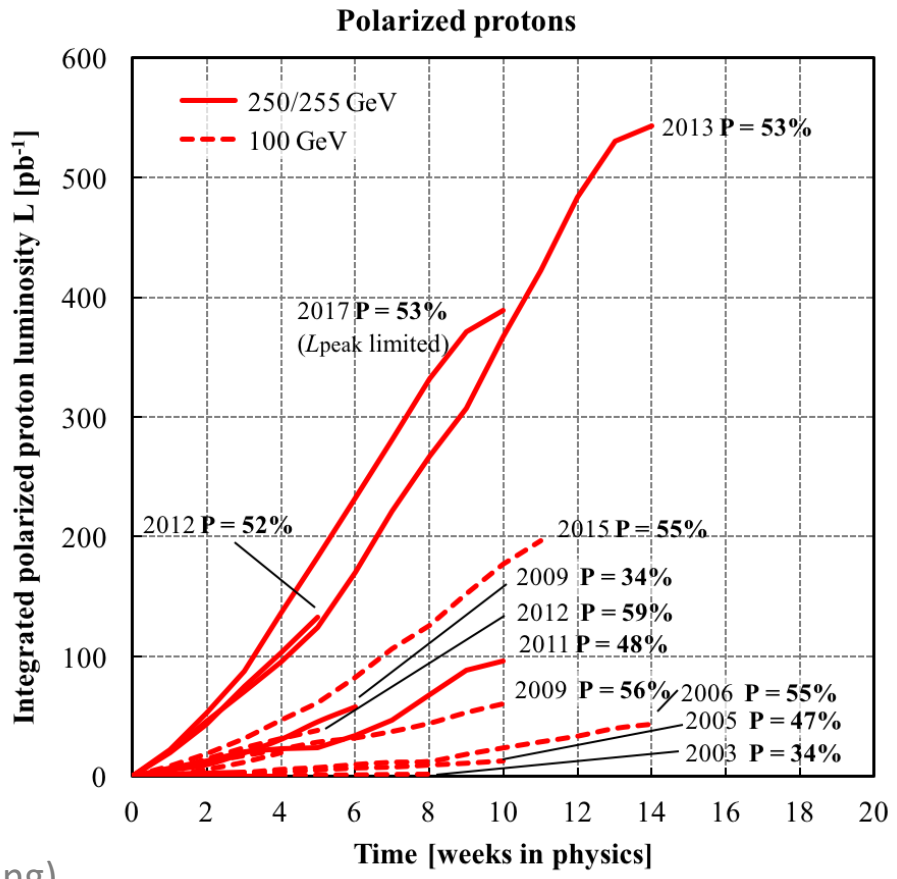
- Physics observables
  - High beam polarizations: electrons & protons
- High EIC Luminosity → small systematics ≈ 1%
- Flexible bunch polarization orientation
- Polarimeter ⟺ polarization in collision
  - Bunch polarization profile in x, y, z
  - Polarization lifetime
  - Polarization per bunch
- First collider with polarized deuterium and ^3He beams
- Luminosity measurement depends on beam polarization
  - Need theory input





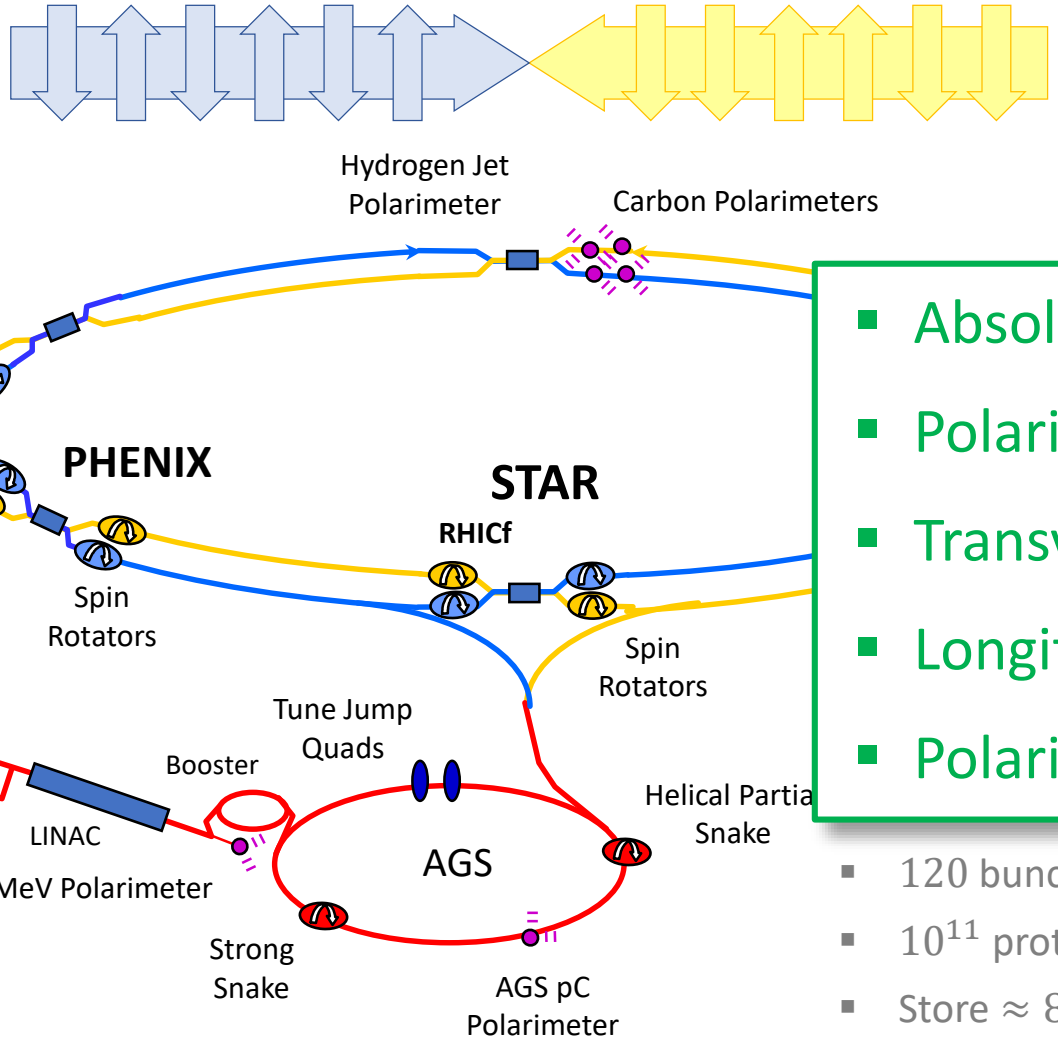
Polarized Protons at RHIC

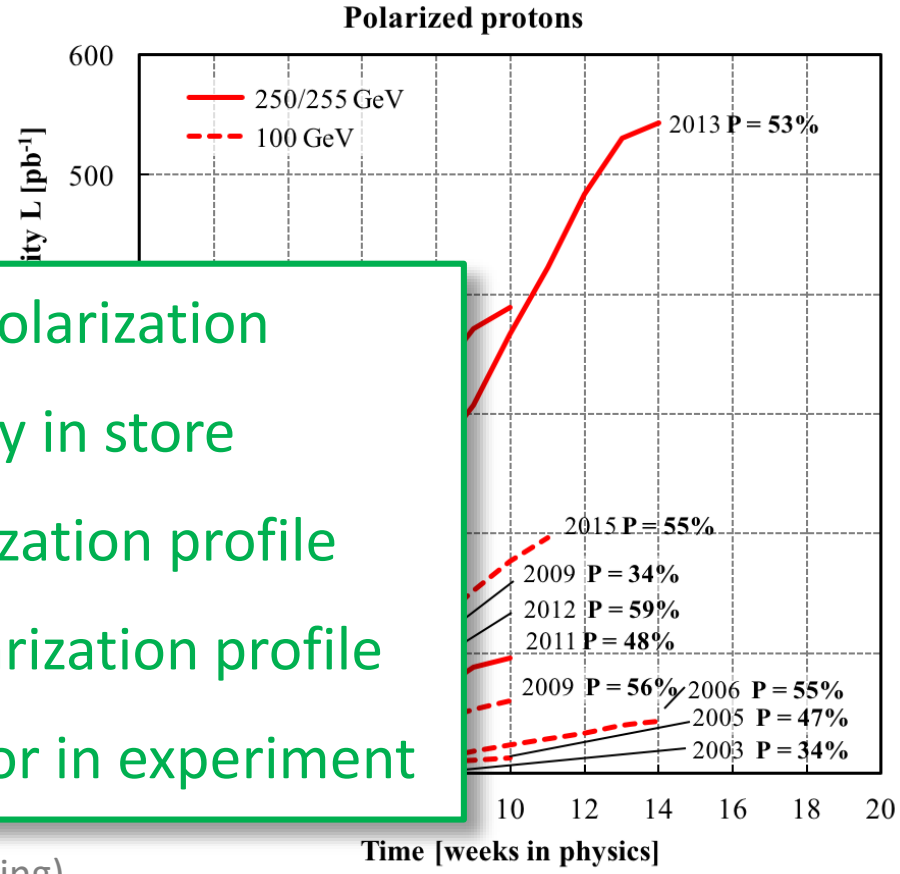




- 120 bunches (106 ns spacing)
- 10^{11} protons per bunch
- Store ≈ 8 hours

Polarized Protons at RHIC





- Absolute beam polarization
- Polarization decay in store
- Transverse polarization profile
- Longitudinal polarization profile
- Polarization vector in experiment

- 120 bunches (106 ns spacing)
- 10^{11} protons per bunch
- Store ≈ 8 hours

Acceleration of Polarized Hadron Beams

Magnetic moment precession in magnetic fields:

- Thomas-BMT equation
- Lorentz force

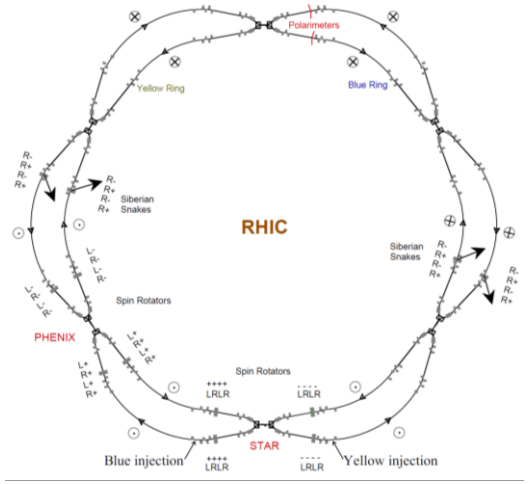
$$\frac{d\vec{P}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \times \vec{P}$$

$$\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\vec{B} \times \vec{v}$$

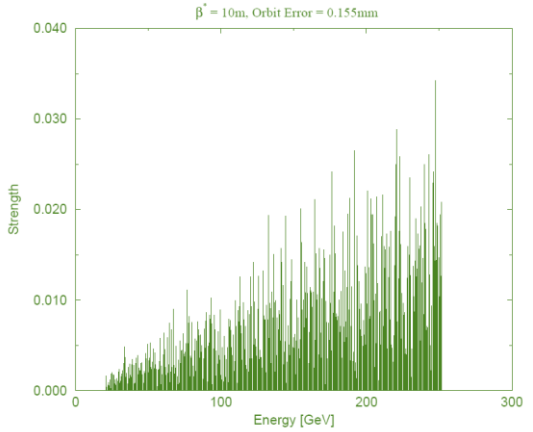
$$G = 1.7928$$

$$\gamma = E/m$$

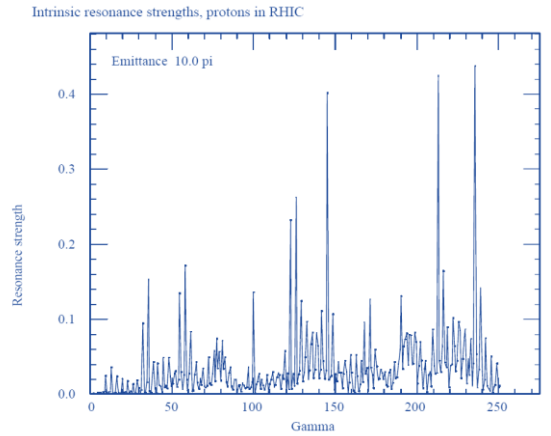
$$\nu_{spin} \equiv G\gamma$$



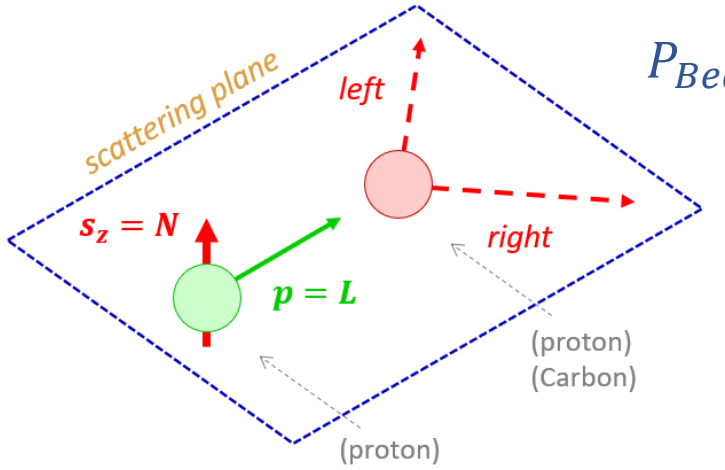
- Imperfection resonances
  - $\nu_{spin} = n$
  - integer n



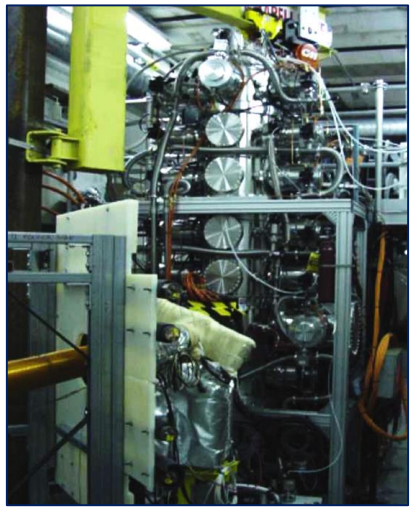
- Intrinsic resonances
  - $\nu_{spin} = kP + \nu_y$
  - integer k
  - superdiodicity P
  - vertical betatron tune ν_y

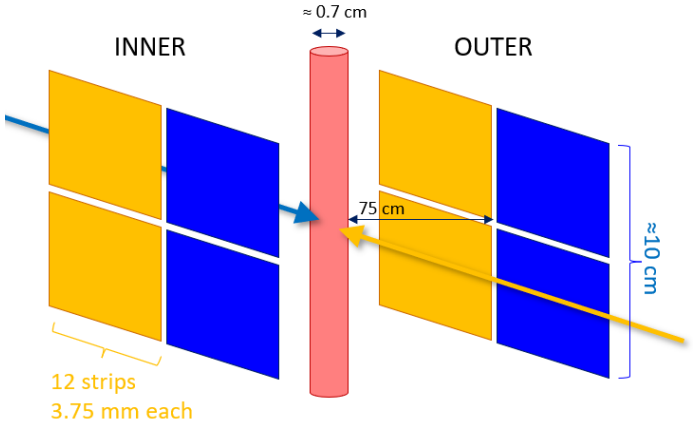


Proton Polarimetry at RHIC



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



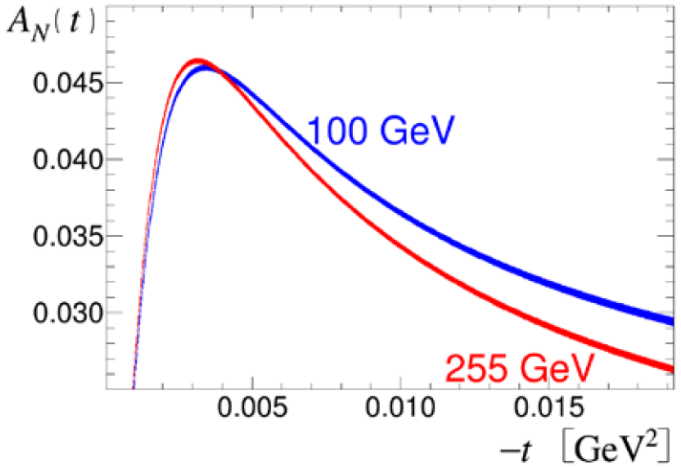


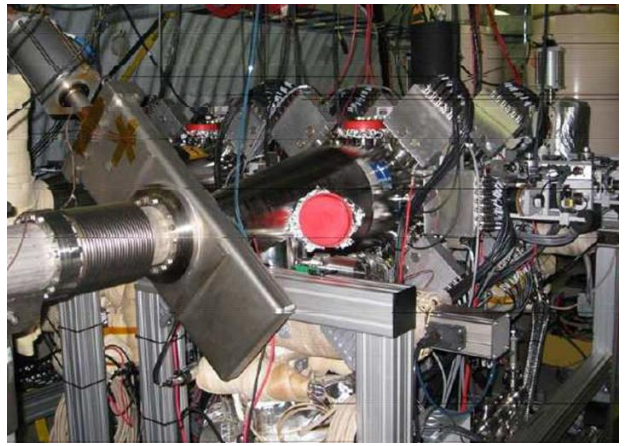
$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

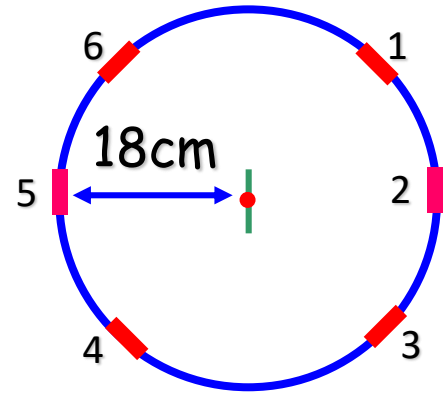
$$\varepsilon = A_N \cdot P = \frac{N_L - N_R}{N_L + N_R}$$

(*) perpendicular to polarization vector

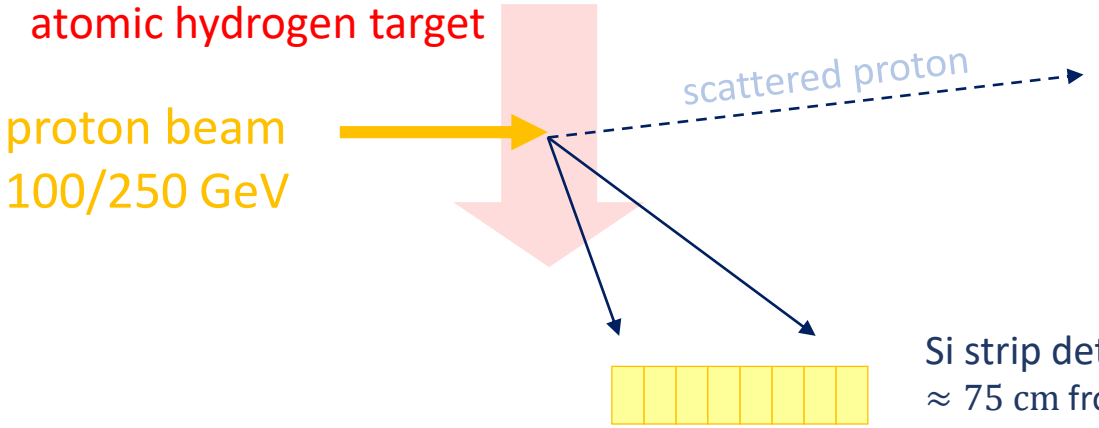
accepted for publication in PRL





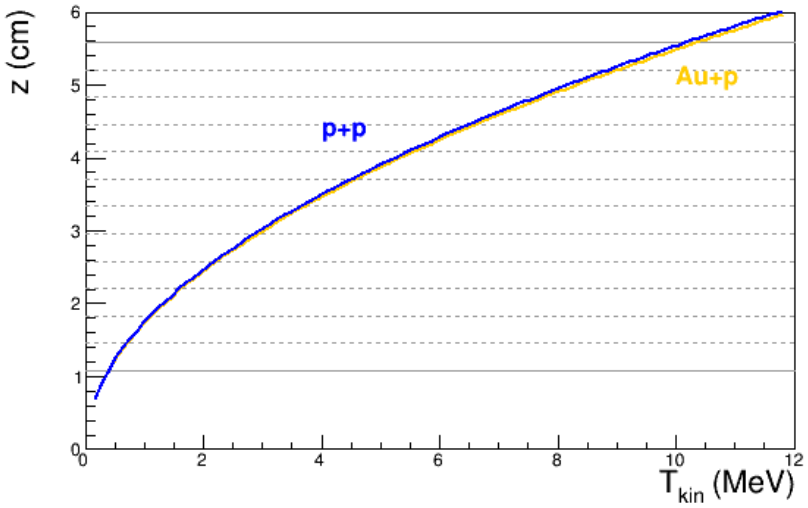


Elastic Proton Scattering

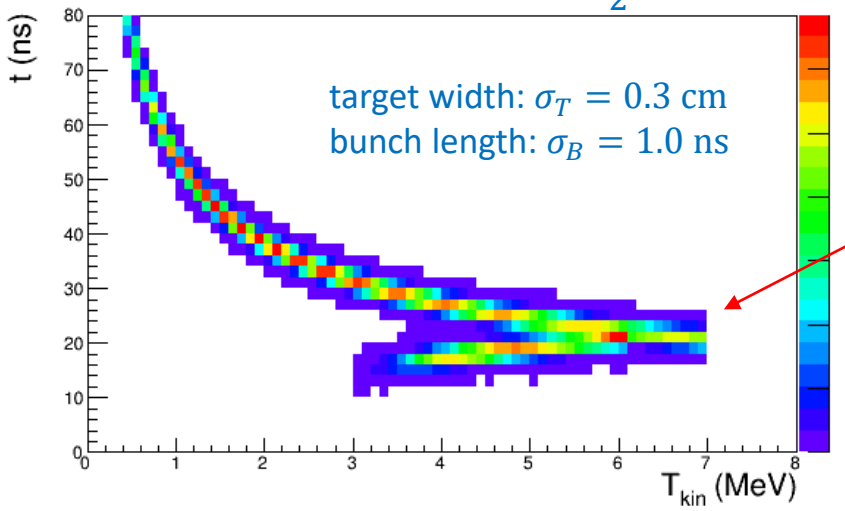


Si strip detectors
≈ 75 cm from interaction point

Recoil proton from elastic scattering



Non-relativistic: $T_{kin} = \frac{1}{2}mv^2$



detector thickness

Polarization Decay and Bunch Profile

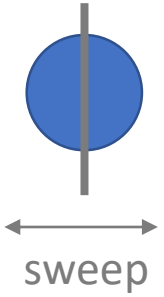
Experiments

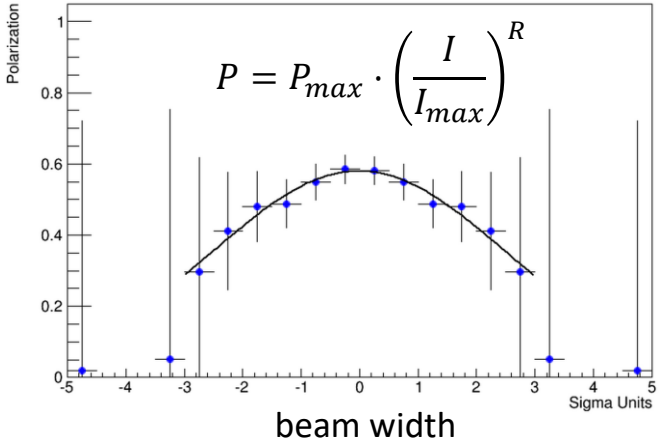
$$P = \frac{\int P(x,y,t) \cdot I_B(x,y,t) \cdot I_Y(x,y,t) dxdydt}{\int I_B(x,y,t) \cdot I_Y(x,y,t) dxdydt}$$

HJET Polarimeter

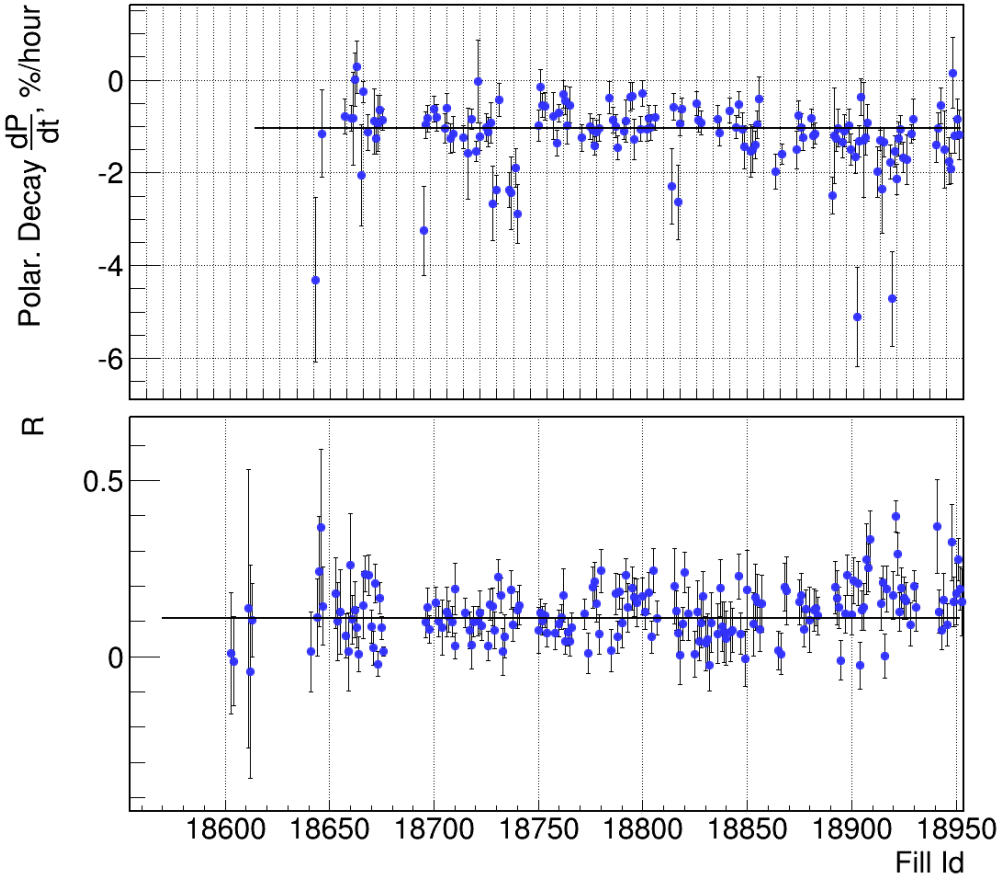
$$P = \frac{\int P(x,y,t) \cdot I(x,y,t) dxdydt}{\int I(x,y,t) dxdydt}$$

Carbon Polarimeter





beam width



Polarization Decay and Bunch Profile

Experiments

$$P = \frac{\int P(x,y,t) \cdot I_B(x,y,t) \cdot I_Y(x,y,t) dxdydt}{\int I_B(x,y,t) \cdot I_Y(x,y,t) dxdydt}$$

HJET Polarimeter

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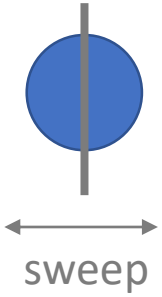

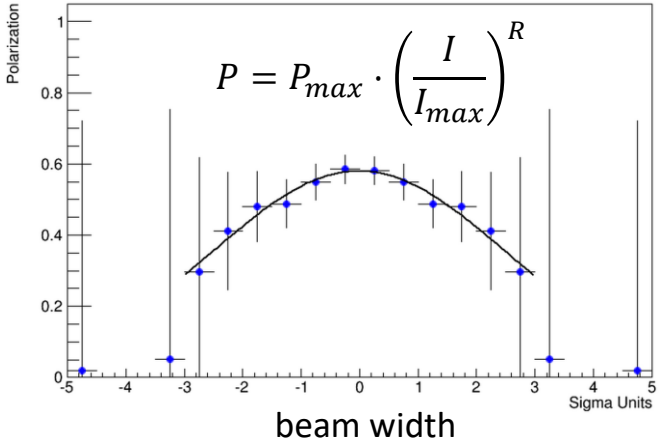

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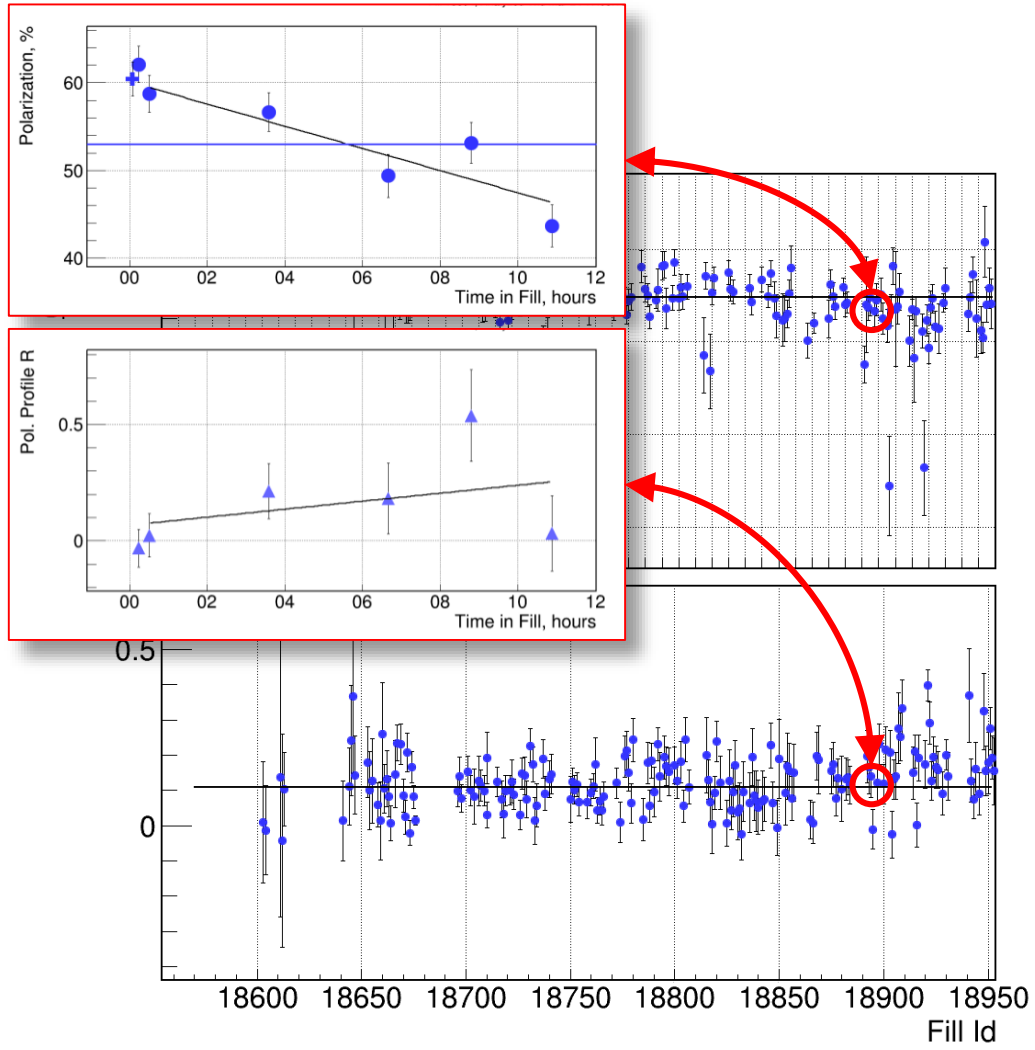
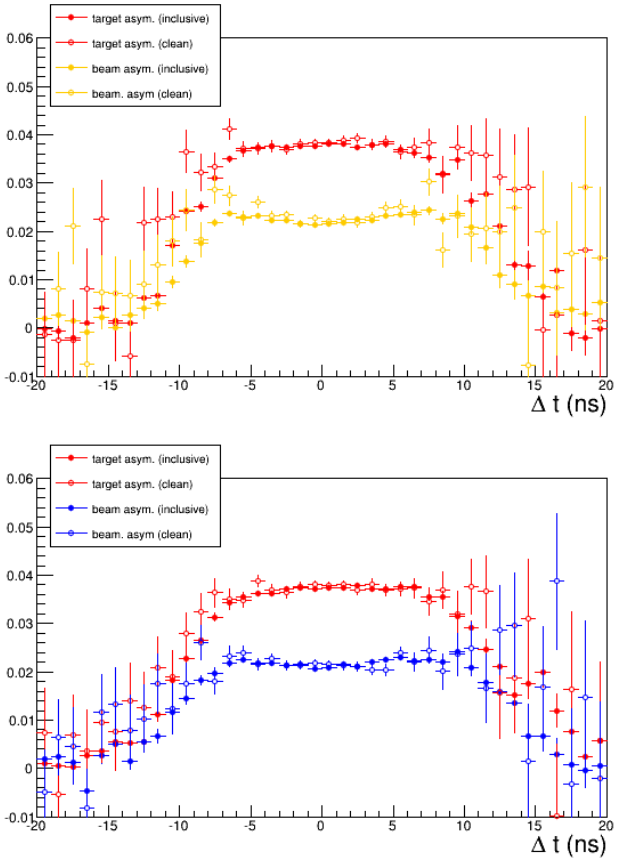
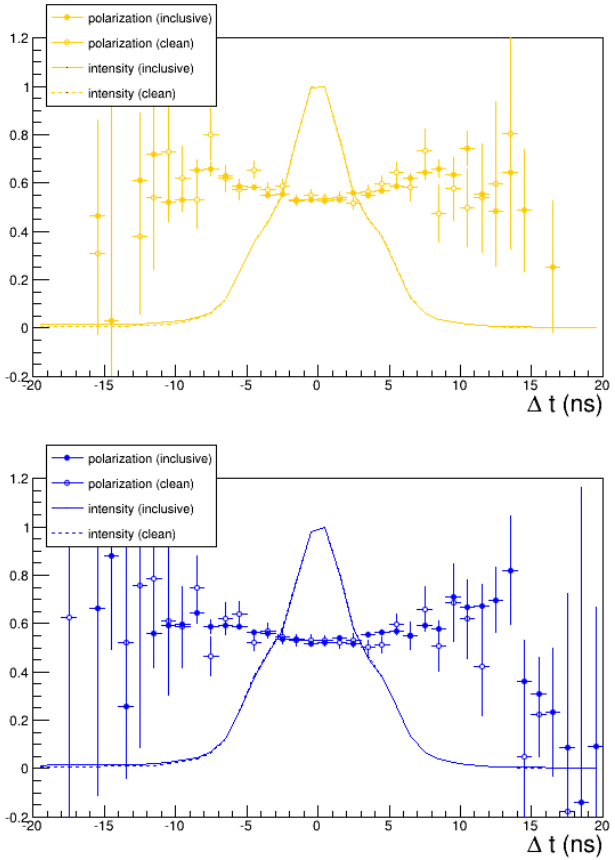


Longitudinal Bunch Profile

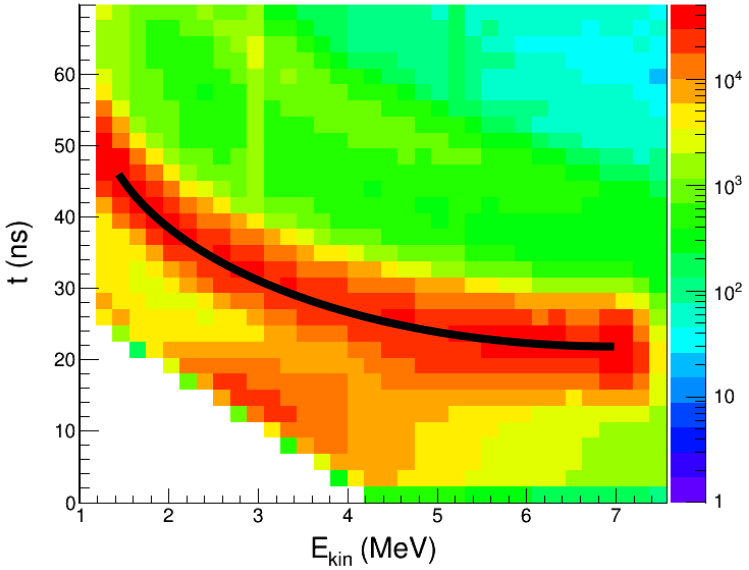
Asymmetries in JHET



Bunch polarization in HJET

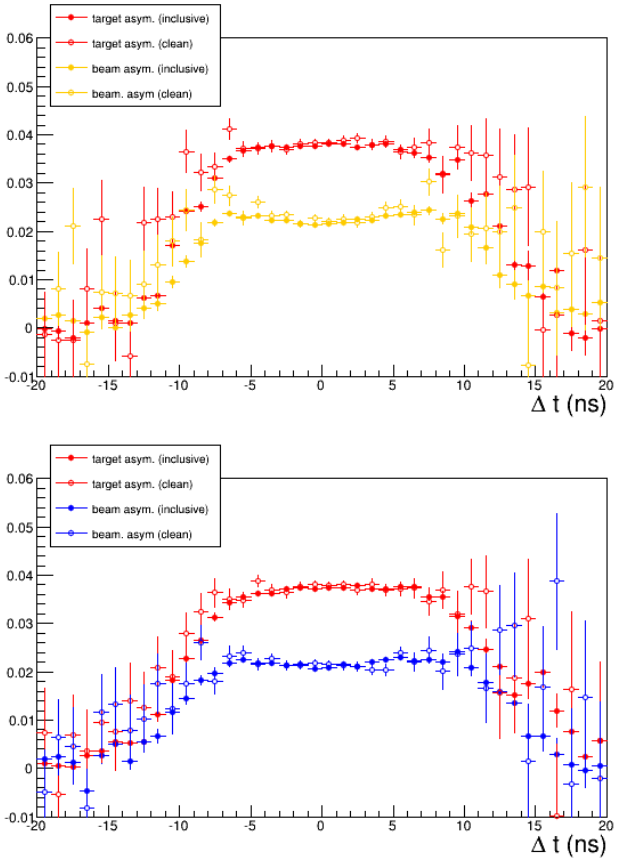


Longitudinal bunch profile:
Time of flight difference from the elastic recoil

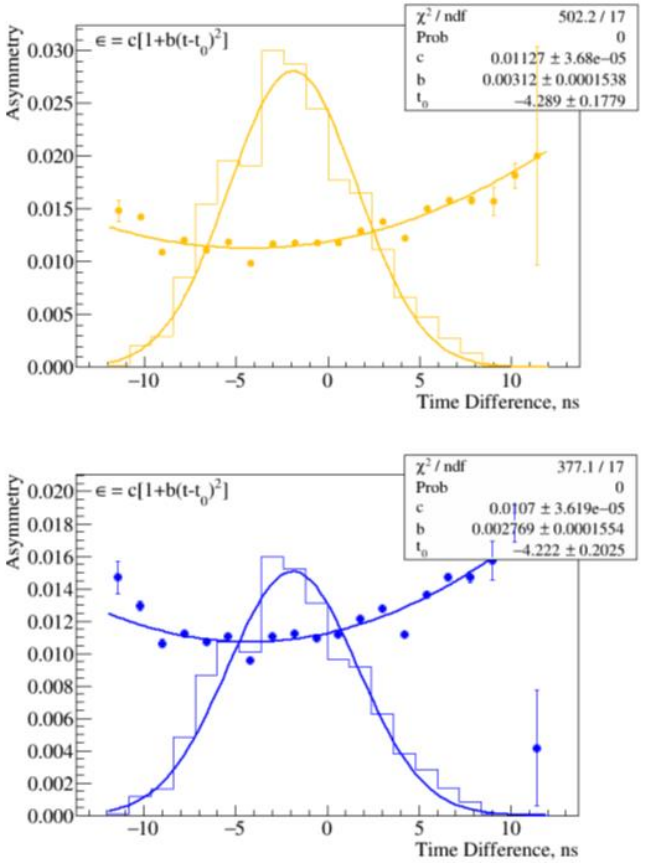


Longitudinal Bunch Profile

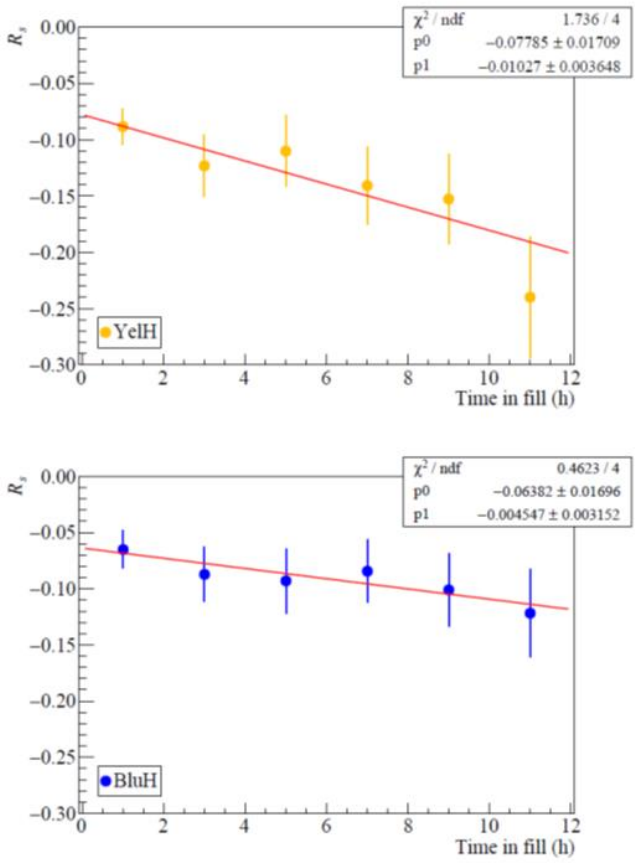
Asymmetries in JHET



Bunch asymmetry in pCarbon



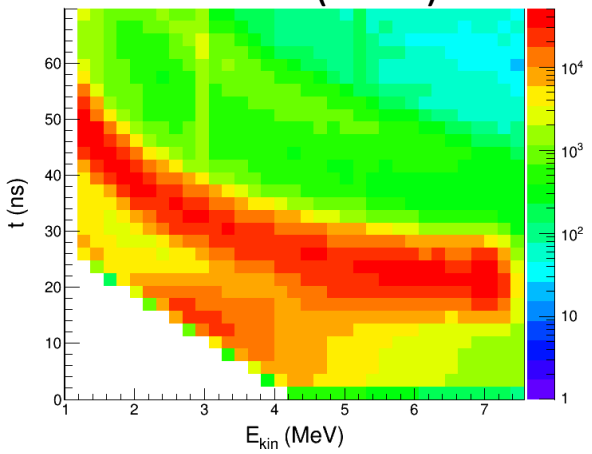
Time dependence



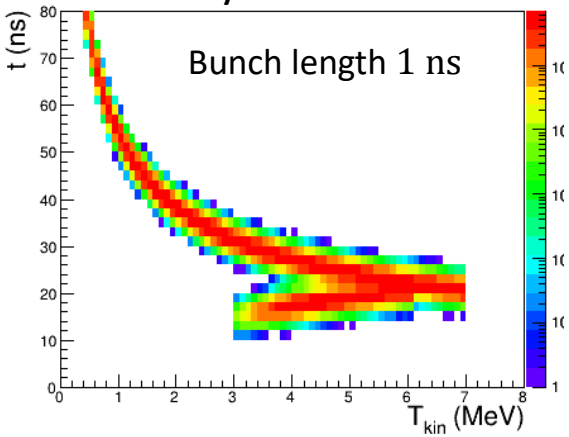
Significant and time dependent longitudinal bunch polarization profiles have been observed in 2017 data.

Elastic Recoil and Background

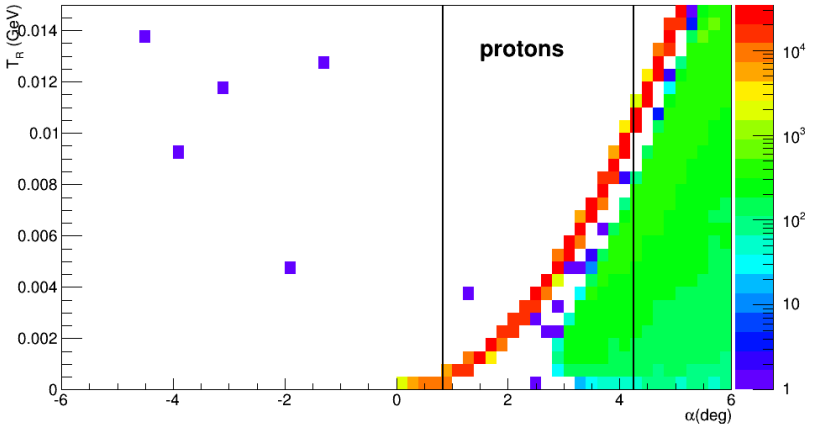
Data (2017)

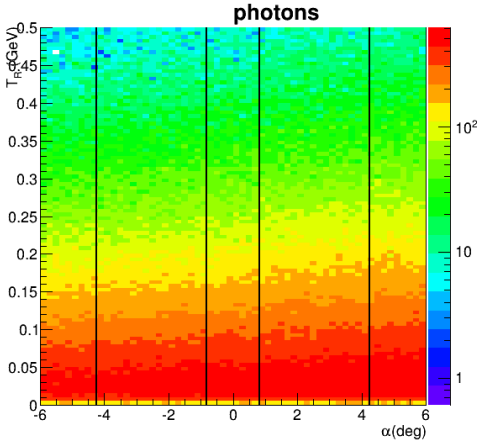


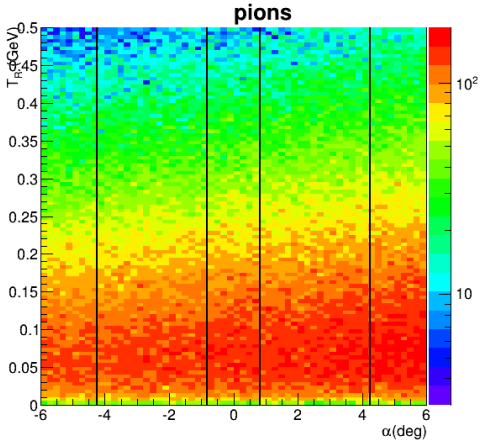
Toy simulation



- $p+p$ at $\sqrt{s} = 21.6$ GeV
- PYTHIA 6.4.28, Tune 320
  - QCD $2 \rightarrow 2$
  - Elastic
  - Diffractive
- Prompt background
  - pions / photons up to a few GeV
  - Kinematic correlation lost

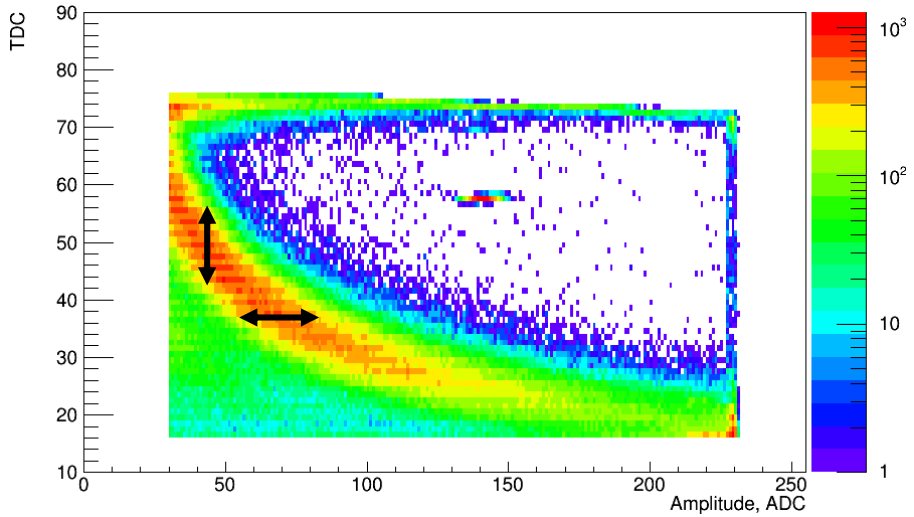






- Planned test with veto detector for charged pions
- Significant background also at low energies
- Problematic for much reduced bunch spacing

EIC Luminosity and Bunch Spacing

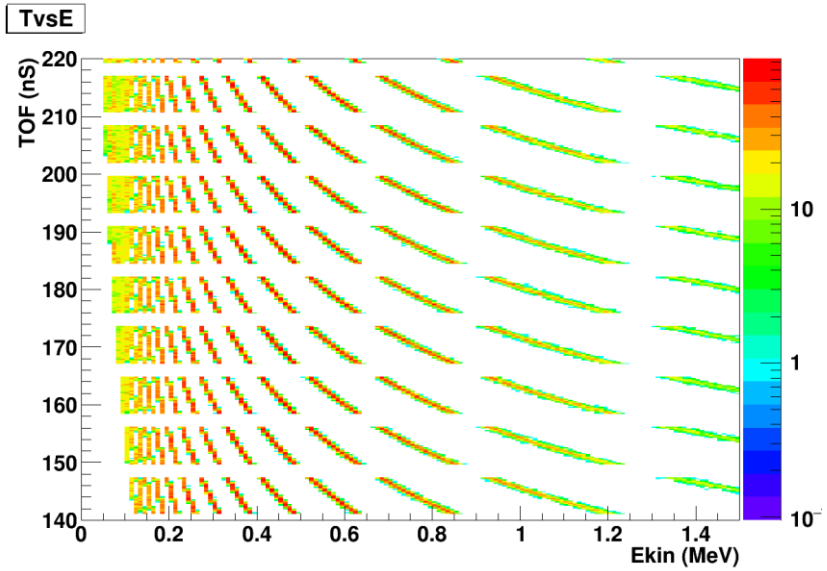


Bunch length

Detector resolution

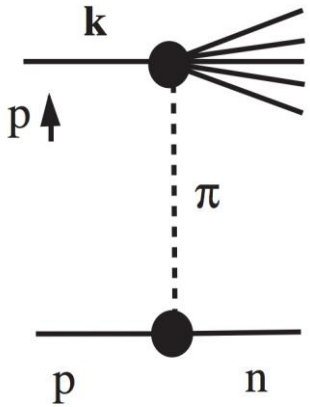
120 bunches → 1320 bunches

106 ns → 8.9 ns

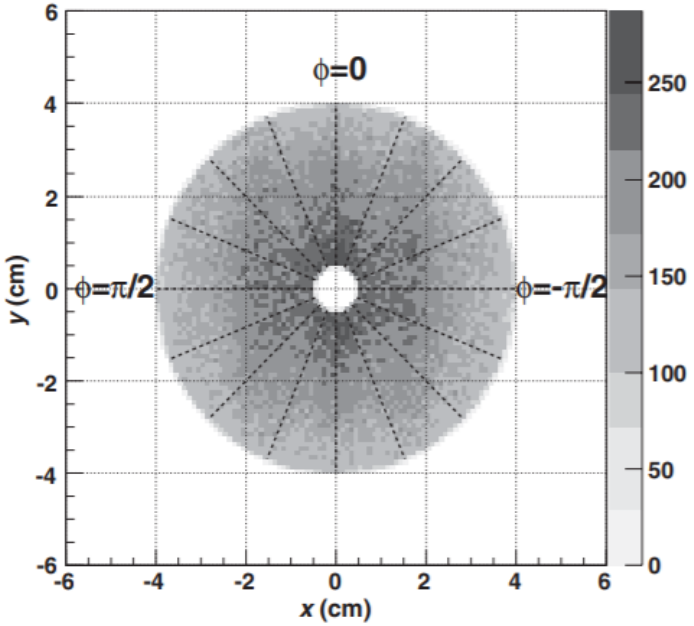


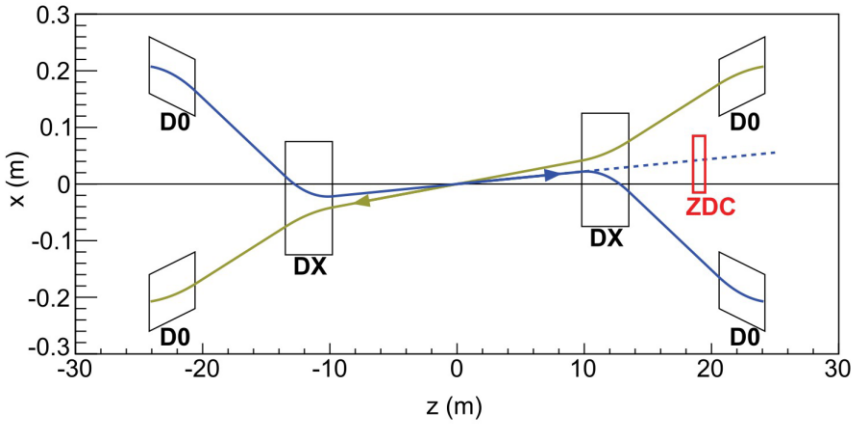
- Carbon polarimeters (high rate)
- Reduced bunch spacing requires rejection and understanding of background
- Potential background asymmetry or dilution
- Loss of increased asymmetry at lower energies, $A_N(-t)$

Polarimetry with Forward Neutrons

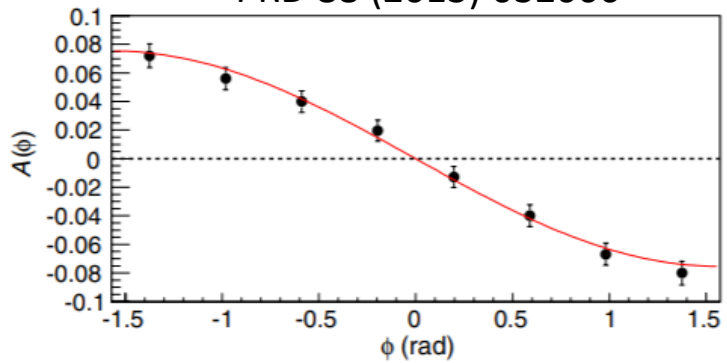


- Early RHIC measurement $p^{\uparrow} + p \rightarrow n + X$
  - Forward neutrons in Zero Degree Calorimeter (ZDC)
- Significant asymmetry, $A_N \approx 8\%$
  - Interference of π^+ (spin-flip) and a_1^+ (spin-nonflip) exchanges (Kopeliovich et al.)
- Now a tool for local polarimetry in experiments
  - Tune spin rotators for azimuthal asymmetry → 0



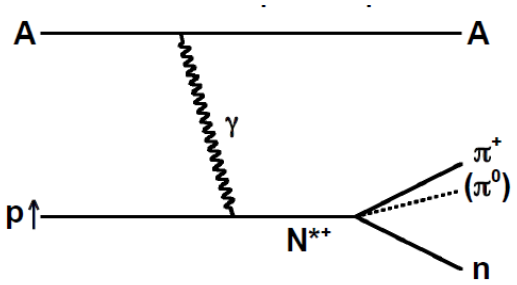


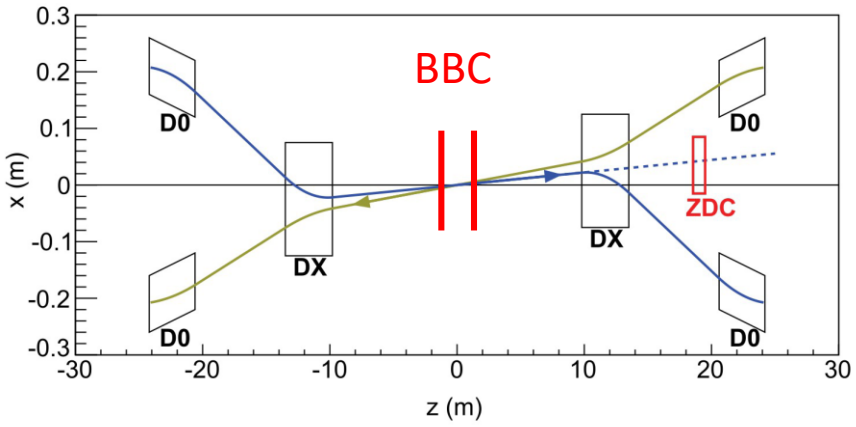
PRD 88 (2013) 032006



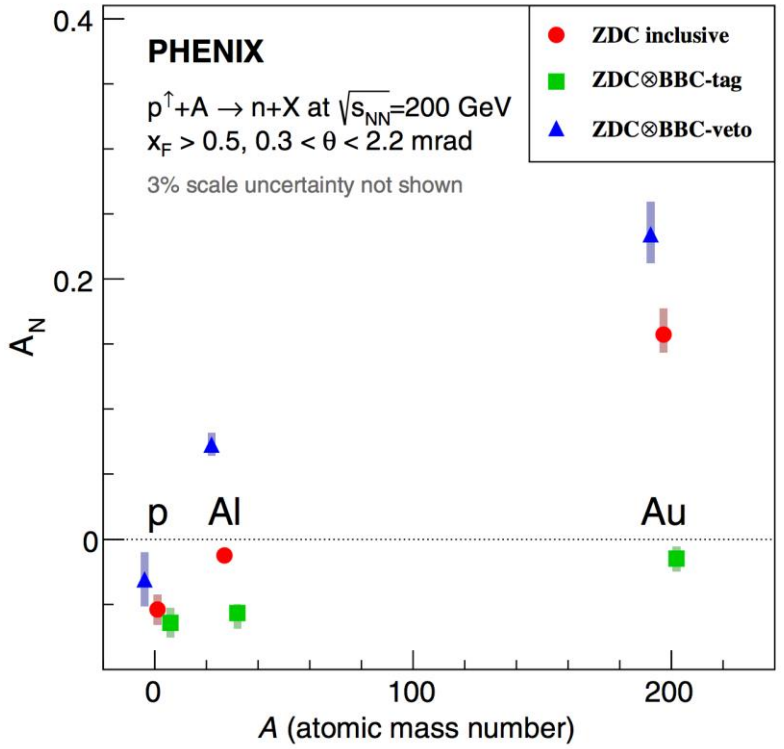
Nuclear Dependence of Forward Neutrons

- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra-peripheral collision extension to π/a_1 model





PHENIX, PRL 120, 022001 (2018)



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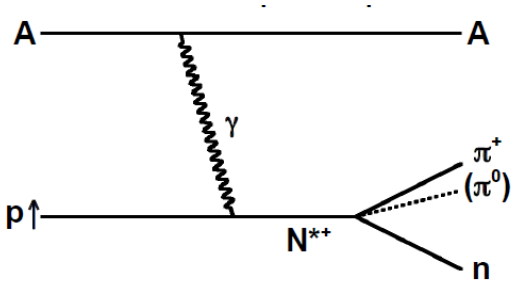
- Photon flux from STARlight
  Klein et al., Comput. Phys. Comm. 212 (2017) 258
- $\gamma + p^{\uparrow} \rightarrow n + \pi^{+}$ from MAID
  Drechsel et al., Eur. Phys. J. A 34 (2007) 69



G. Mitsuka, PRC 95 (2017) 044908

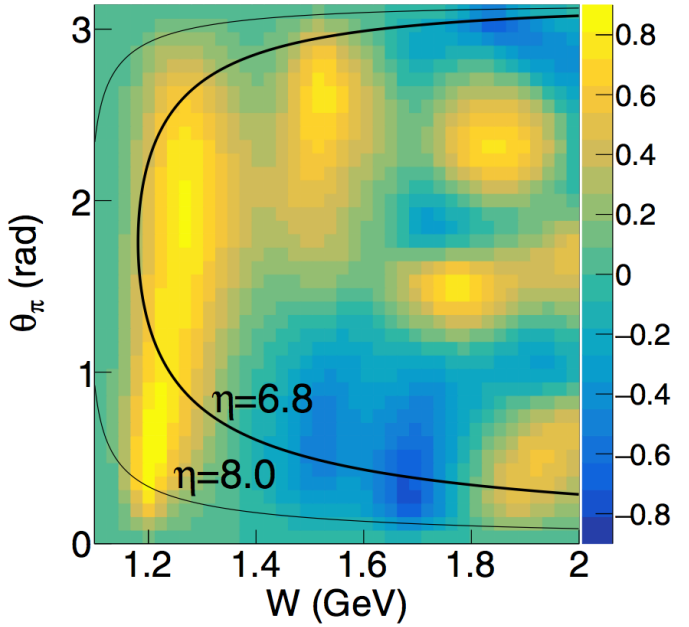


FIG. 2. Target asymmetry $T(\theta_\pi)$ of the $\gamma^* p^{\uparrow} \rightarrow \pi^+ n$ interaction as function of W. In the detector reference frame, the curves correspond to the rapidity of produced neutrons $\eta = 6.8$ and 8.0.

Nuclear Dependence of Forward Neutrons

- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra-peripheral collision extension to π/a_1 model
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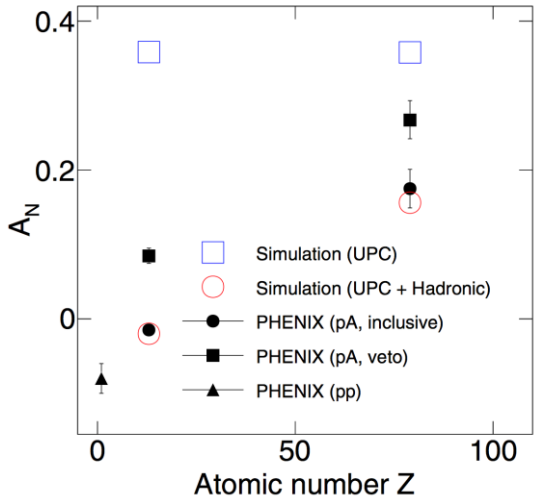
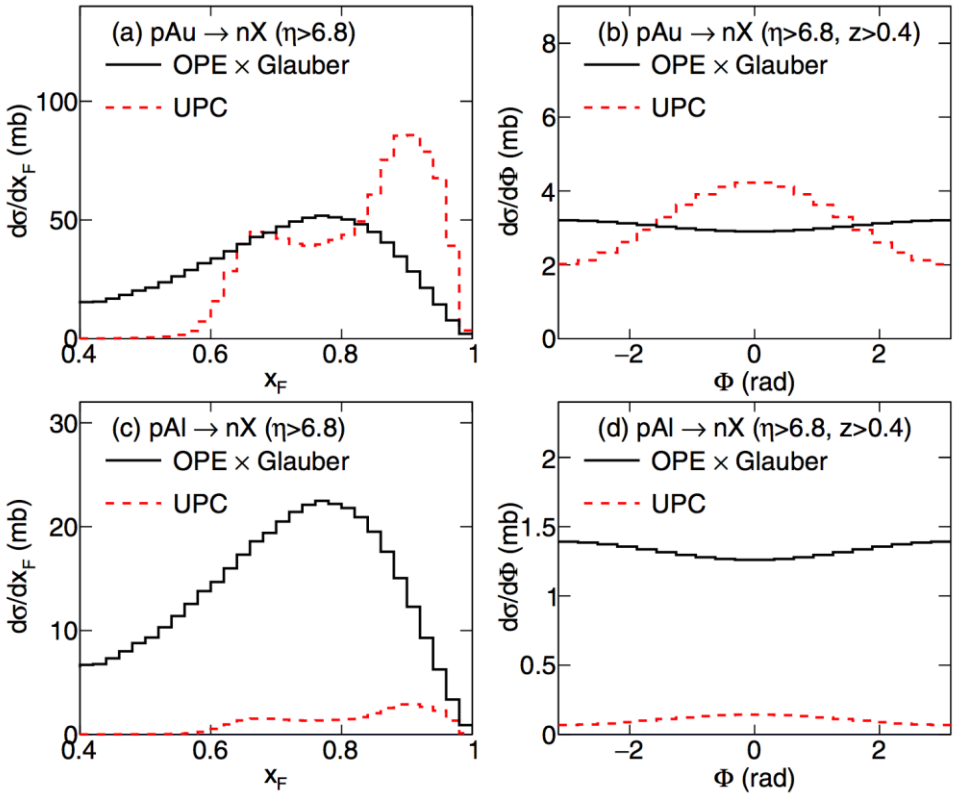
- $\gamma + p^{\uparrow} \rightarrow n + \pi^{+}$ from MAID
  Drechsel et al., Eur. Phys. J. A 34 (2007) 69
- Excellent agreement with data



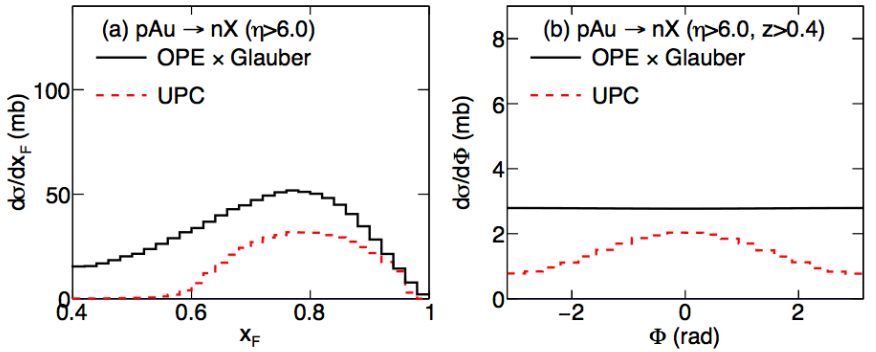
G. Mitsuka, PRC 95 (2017) 044908



Nuclear Dependence of Forward Neutrons

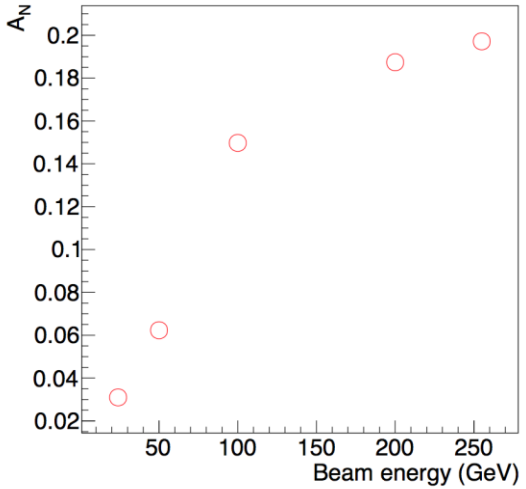
- Surprise in $p + Al$ and $p + Au$ collisions
- Very large asymmetry (with opposite sign)
- Select low multiplicity with beam-beam counters
- Ultra-peripheral collision extension to π/a_1 model
- Photon flux from STARlight
  Klein et al., Comput. Phys. Comm. 212 (2017) 258
- $\gamma + p^{\uparrow} \rightarrow n + \pi^{+}$ from MAID
  Drechsel et al., Eur. Phys. J. A 34 (2007) 69
- Potential candidate for fast polarimetry with fixed target (Au)
- Neutron mulitplicity for azimuthal asymmetry
- Target effect on beam

G. Mitsuka, PRC 95 (2017) 044908

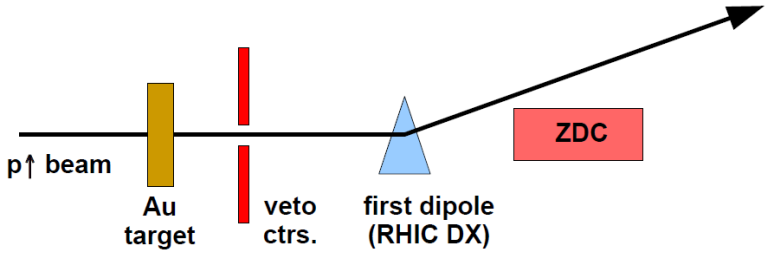


$E_{beam} = 100$ GeV

$\sigma_{UPC} = 17.3\,\mathrm{mb}$



Private communication (G. Mitsuka → W. Schmidke) for fixed target kinematics



Outlook

- Proton polarimetry at RHIC is well established
- Combination of absolute normalization with fast measurements
  - Time dependent polarization decay
  - Transverse and longitudinal bunch profiles
- High luminosity (short bunch spacing) is challenging
  - Bunch by bunch polarization measurement
  - Improvements in detector performance and read-out needed
- Potential new concept for fast polarimeters (high energy neutrons)
- Also required
  - Local polarimetry at IP
  - Light ion beam polarimetry
- Be prepared for surprises!

https://groups.google.com/a/eicug.org/forum/#!forum/eicug-polarimetry