中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Beam Polarimetry for Future Hadron Facilities at IMP

Boxing Gou
Institute of Modern Physics, CAS

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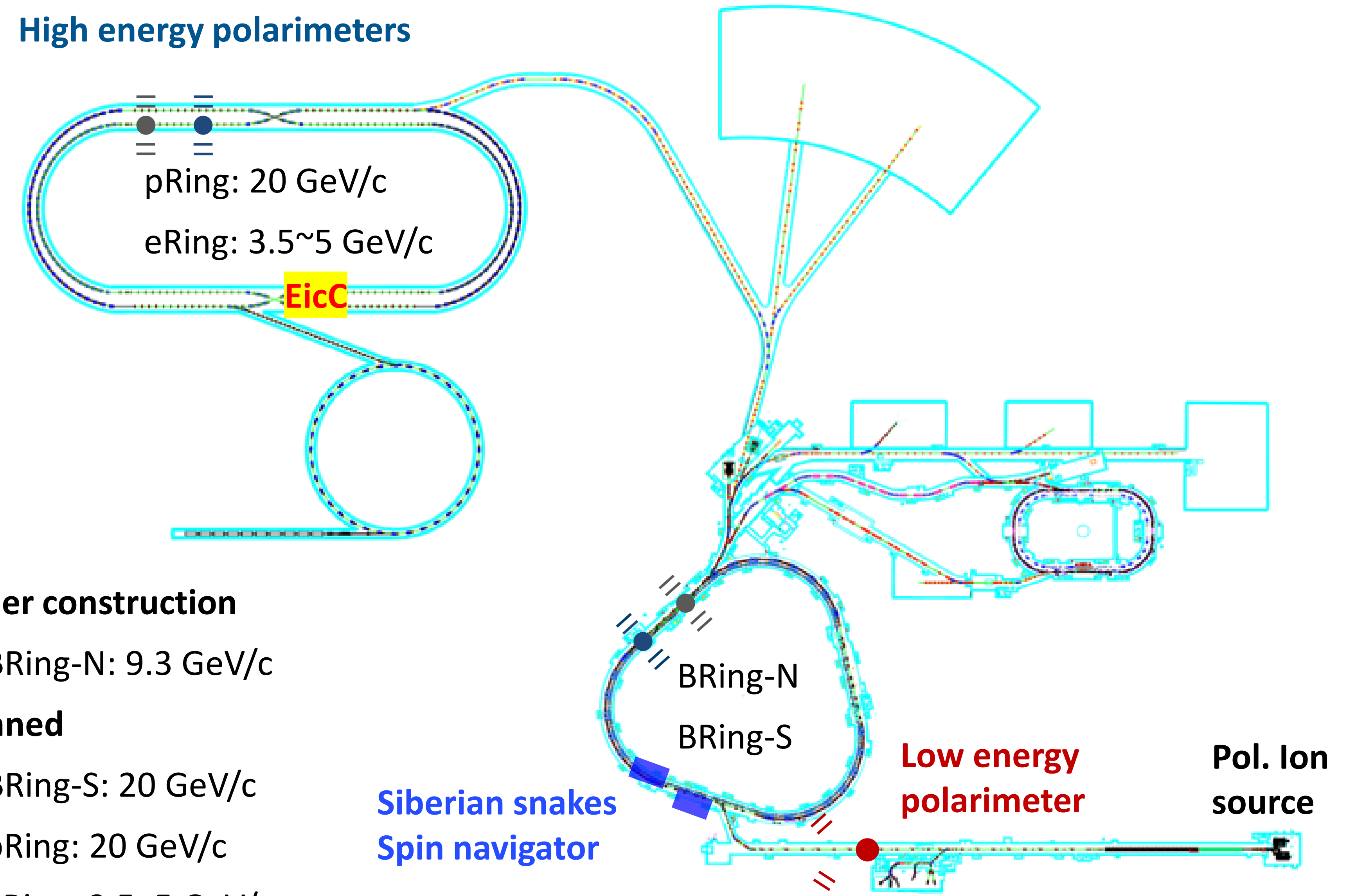
Content

- Future hadron accelerators at IMP
- General consideration & reference reaction selection
- Polarimeters based on elastic scattering in CNI region
  - Heavily adopted from RHIC experiences
  - pp-CNI absolute polarimeter
  - pC-CNI fast polarimeter
- Polarimeter based on pe elastic scattering
  - new method
- Possible physics program with polarimetric apparatus
  - Physics program with CNI-pp polarimeter
  - Physics program with pe polarimeter
- Current activities

Future accelerators at IMP



Under construction

- BRing-N: 9.3 GeV/c

Planned

- BRing-S: 20 GeV/c
- pRing: 20 GeV/c
- eRing: 3.5~5 GeV/c

General principle

- A reference reaction $\vec{p}X \rightarrow Y$ is needed for beam polarimetry

$$\frac{d^2\sigma}{d\theta d\varphi} = \frac{1}{2\pi}\frac{d\sigma}{d\theta}\times[1+A_N \cdot P \cdot \cos\phi]$$ (transversely single polarized cross section)

- Analyzing power
  function of (E, θ)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

  - i.e. physical asymmetry, reflects and determined by the spin structure and dynamics
  - **should be a prior known (measured or calculable)/self-calibrated**

- Asymmetry
  function of (E, θ, ϕ)

$$\varepsilon = \frac{n^{\uparrow} - n^{\downarrow}}{n^{\uparrow} + n^{\downarrow}} = PA_N \cos\phi$$

n: # of detected particles

- Polarization
  constant

$$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = \frac{\varepsilon}{A_N \cos\phi}$$

N: # of beam particles

- Figure of merit $\mathrm{FOM} = \sigma \cdot (\mathrm{A_N})^2$
  - **larger FOM $\rightarrow$ higher statistical precision**

Reference reaction search

- **pp and pC elastic scatterings** have been widely used as polarimetric reactions
  - at almost all proton accelerators (PSI, TRIMUF, LAMPF, COSY, SATURNE, ZGS, KEK-PS, AGS, RHIC …)
  - in a broad energy range from ~20 MeV to 250 GeV

5 helicity amplitudes for $\mathrm{pp} \rightarrow \mathrm{pp}$

$\phi_1(s,t) = \langle + + | M | + + \rangle$, u

$\phi_2(s,t) = \langle + + | M | - - \rangle$, d

$\phi_3(s,t) = \langle + - | M | + - \rangle$, u

$\phi_4(s,t) = \langle + - | M | - + \rangle$, d

$\phi_5(s,t) = \langle + + | M | + - \rangle$, s

spin-nonflip

double spin-flip

single spin-flip

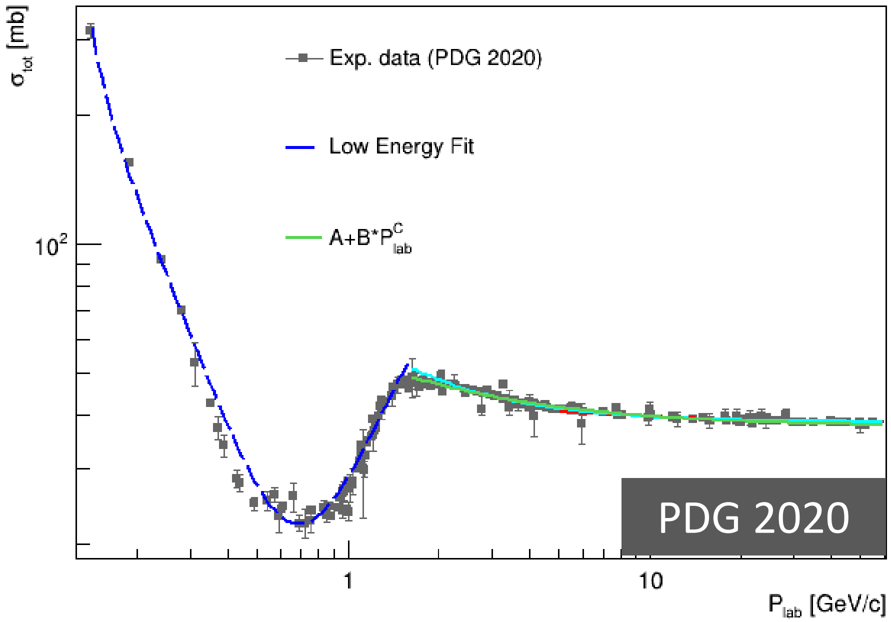
Reduce to 2 amplitudes for $\mathrm{pC} \rightarrow \mathrm{pC}$

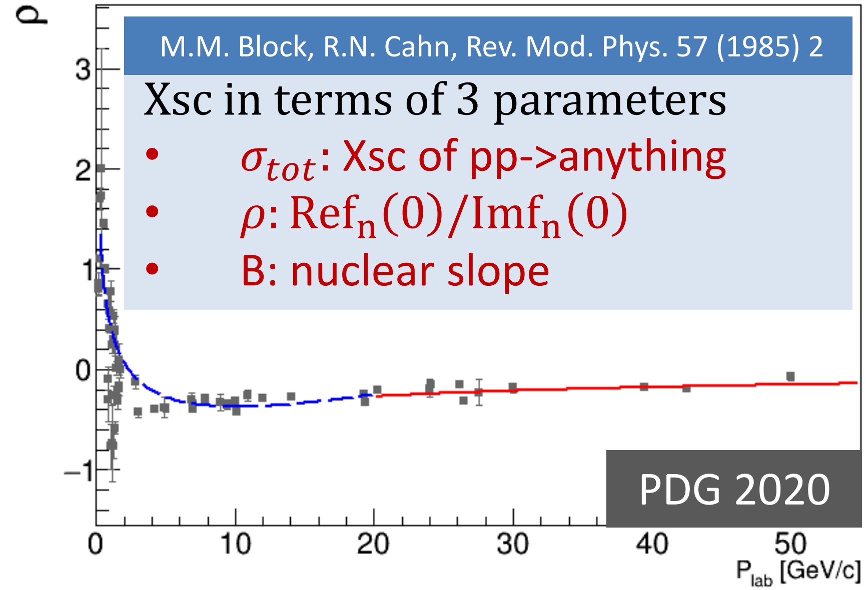
- Spin-non flip amplitude
- Spin-flip amplitude

Each amplitude can be decomposed into hadronic (nuclear) and electromagnetic parts

$$\phi_i = \phi_i^h + \phi_i^{em} e^{i\delta_c}$$

pp elastic scattering Xsc

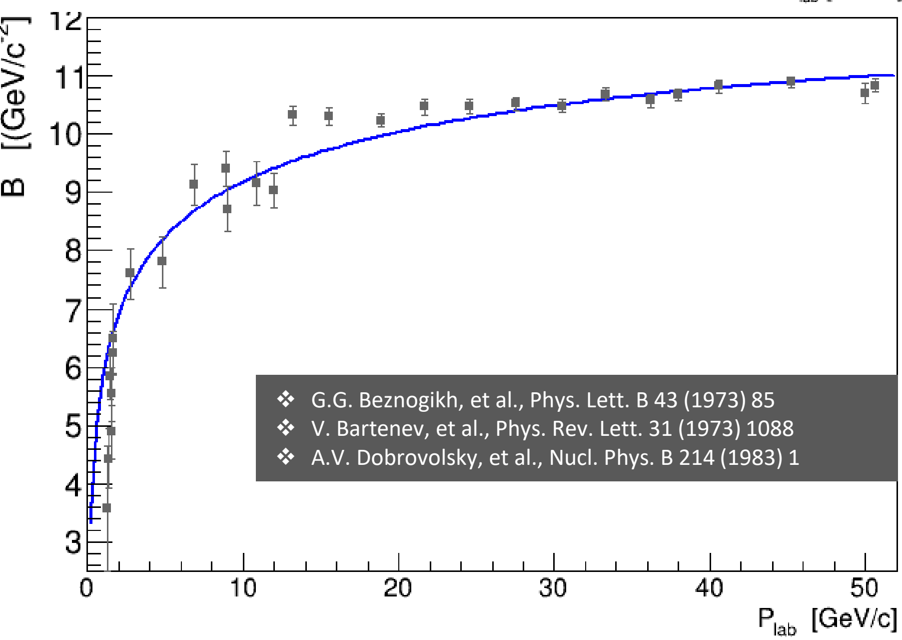


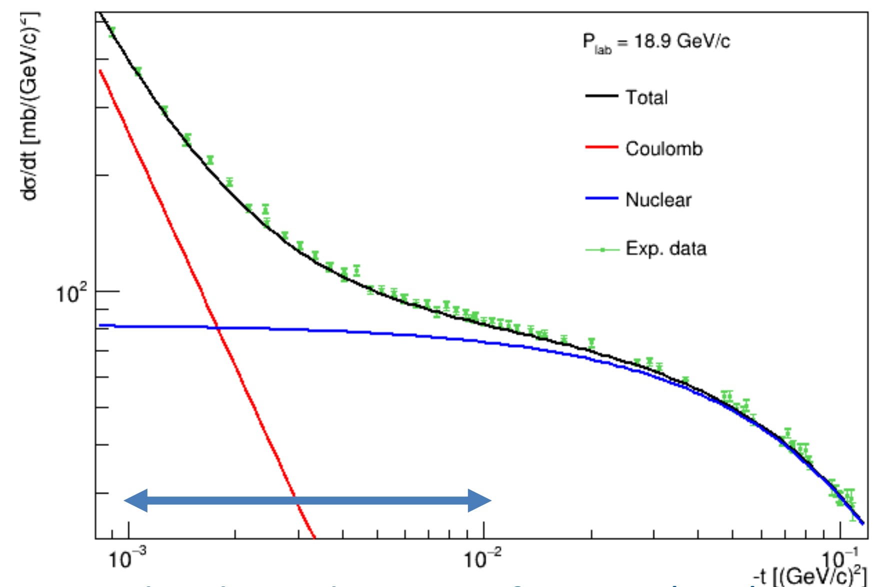


M.M. Block, R.N. Cahn, Rev. Mod. Phys. 57 (1985) 2

Xsc in terms of 3 parameters

- σ_{tot}: Xsc of pp->anything
- ρ: $\mathrm{Re}f_n(0)/\mathrm{Im}f_n(0)$
- B: nuclear slope

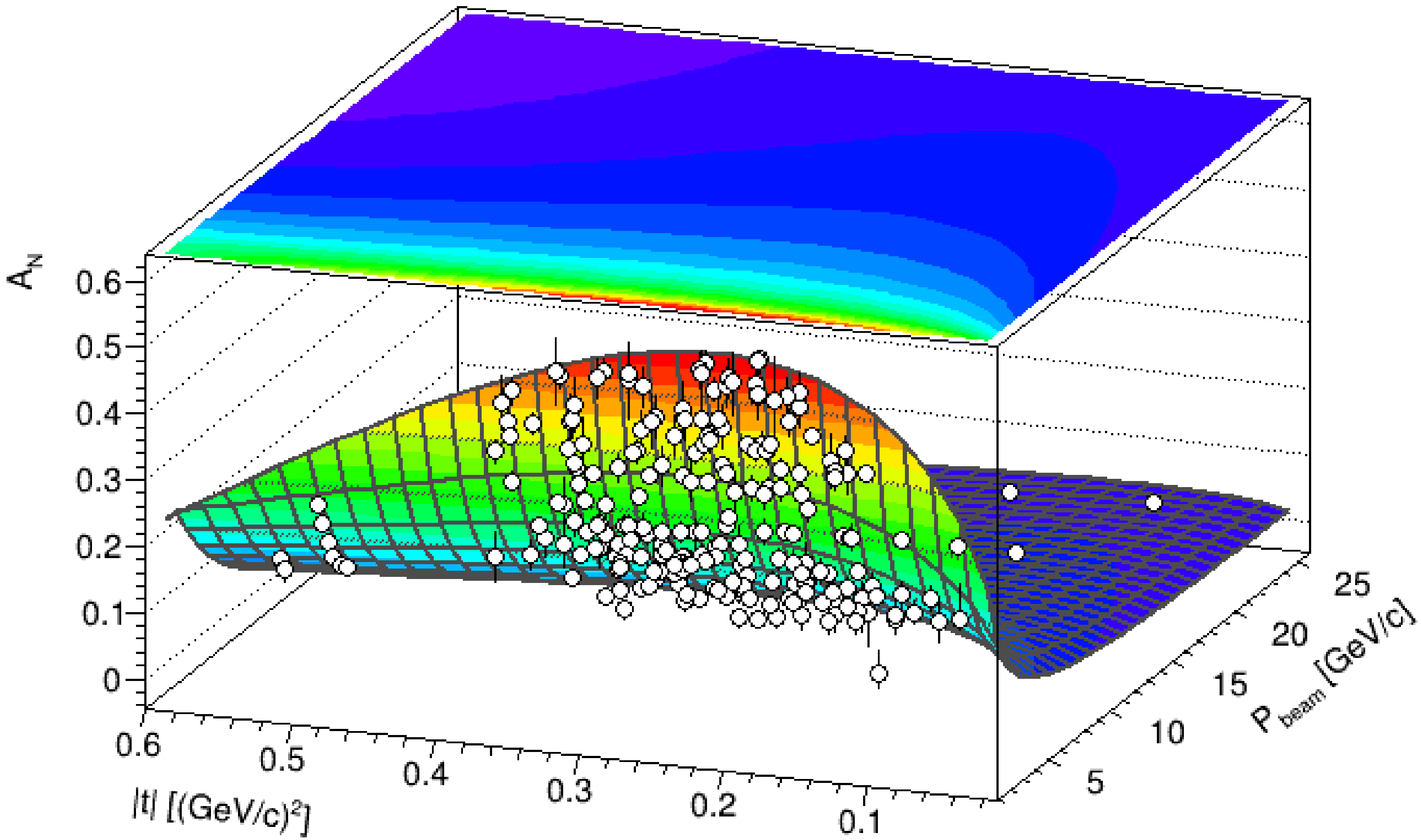




Coulomb-nuclear interference (CNI)

pp elastic scattering A_N at large |t|

A_N gets maximum in the range of $0.15 \lesssim |t| \lesssim 0.30\ (\mathrm{GeV/c})^2$



A_N at CNI region (very-small |t|)

$\mathbf{A_N}$ arises from interference between single-spin flip (ϕ_5) and **spin-non flip (ϕ_+)** amplitudes

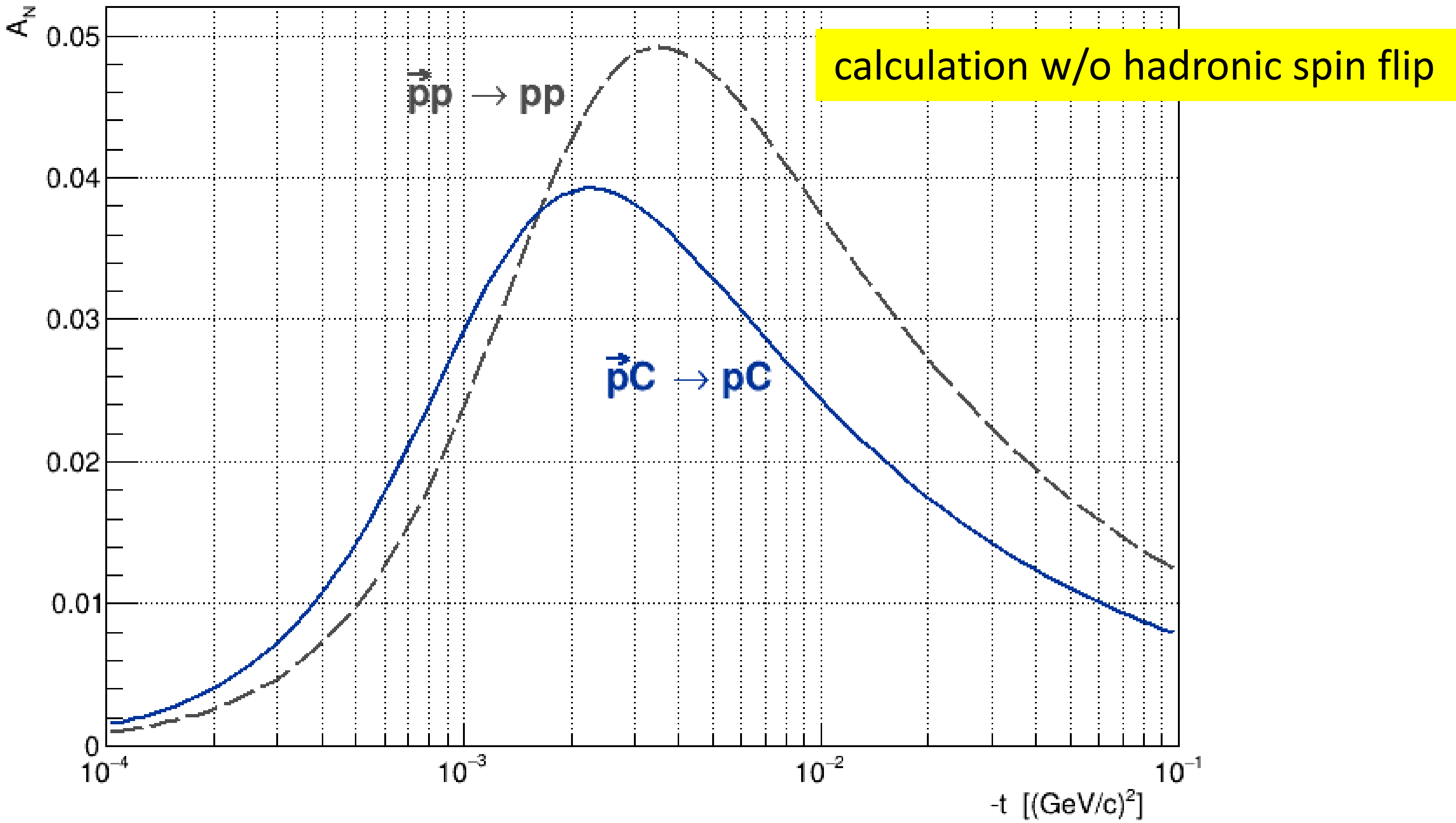
$$A_N \frac{d\sigma}{dt} \cong -\frac{4\pi}{s^2} Im\{\phi_5^{em*}\phi_+^h + \phi_5^{h*}\phi_+^{em}\}$$

Major contribution, easy to calculate

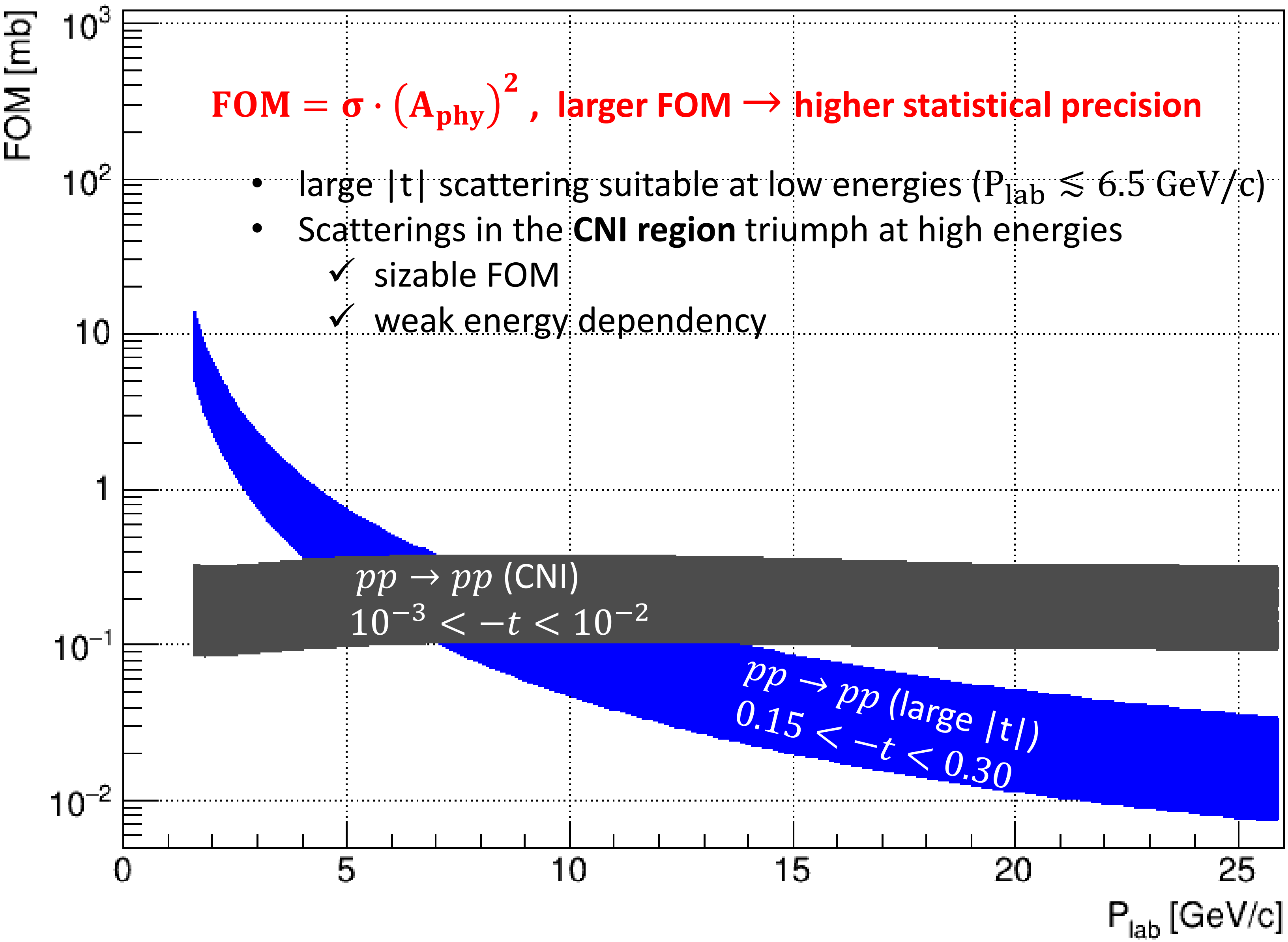
$$A_N(t) = \frac{\kappa t_0 t\sqrt{-t}}{m_p(t^2+t_0^2)} \qquad t_0 = \frac{8\pi\alpha Z}{\sigma_{tot}}$$

N.H. Buttimore et al., Phys. Rev. D 18, 694(1978)

Small, incalculable, to be measured



Reference reaction selection



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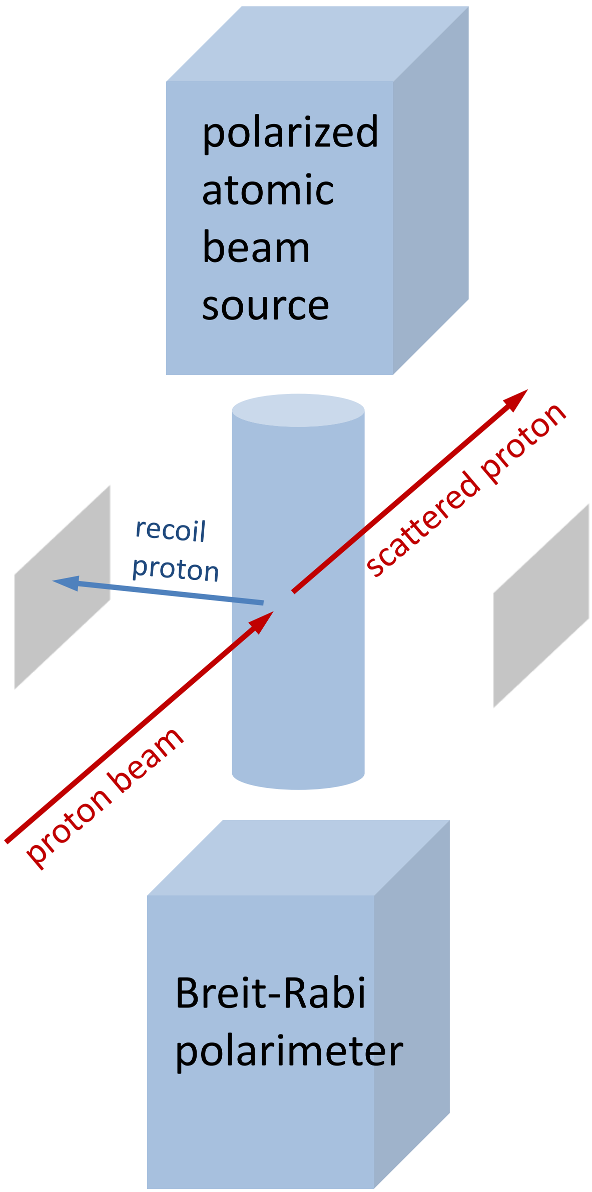
Pol. H-Jet polarimeter



A_N can be self-calibrated with a pol. H target

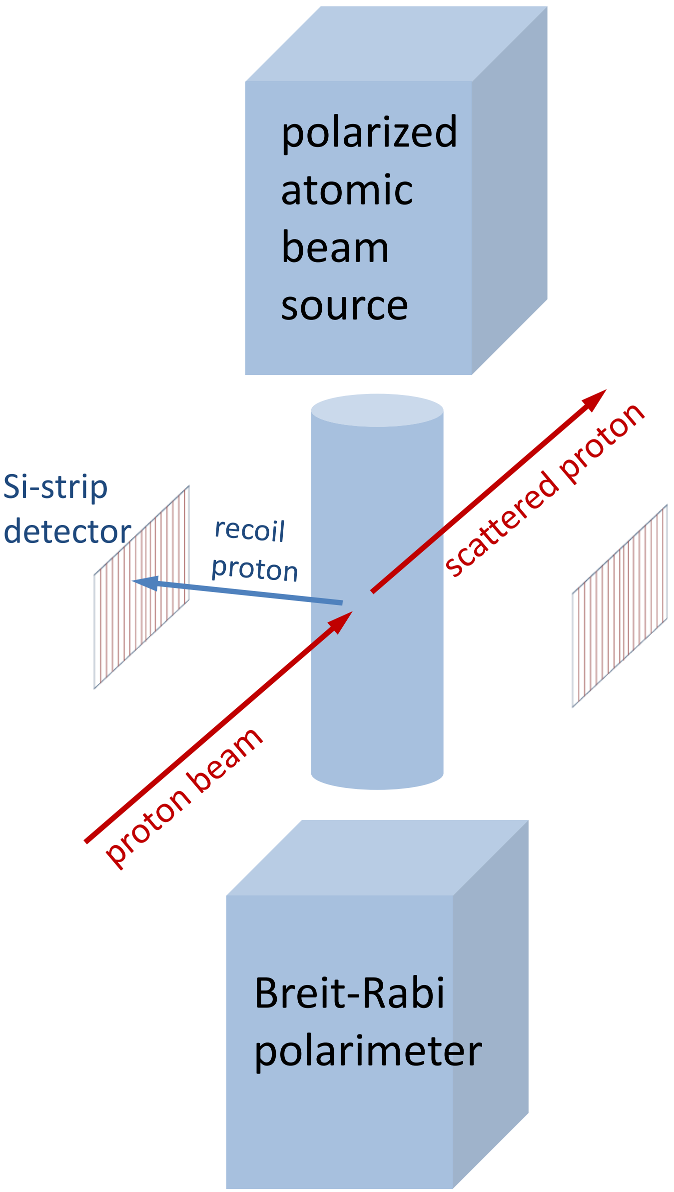
	①	②	③	④
Beam	↑	↓	↑	↓
Target	↑	↑	↓	↓

- Identical beam & target particles

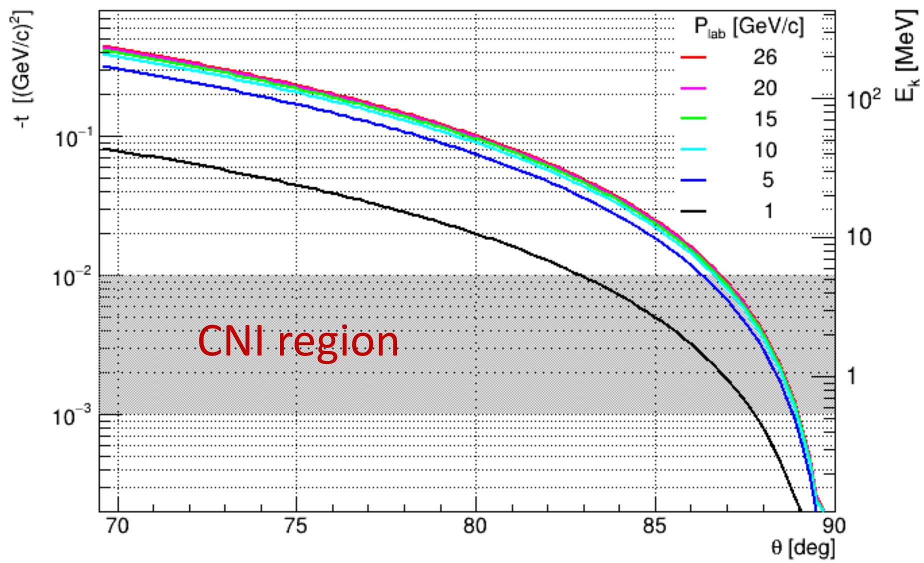
Same A_N for $\begin{cases} \vec{p}p \to pp \text{ ① + ③ and ② + ④} \\ p\vec{p} \to pp \text{ ① + ② and ③ + ④} \end{cases}$

- $\mathrm{P_{beam}} = \frac{\varepsilon_{\mathrm{beam}}}{A_N} = -\frac{\varepsilon_{\mathrm{beam}}}{\varepsilon_{\mathrm{target}}} \mathrm{P_{target}}$
- $\mathrm{P_{target}}$ measured with Breit-Rabi polarimeter
- Left-right asymmetry: $\varepsilon = \frac{N_L - N_R}{N_L + N_R}$ measured with **symmetrically placed detectors**

Pol. H-Jet polarimeter in CNI Region

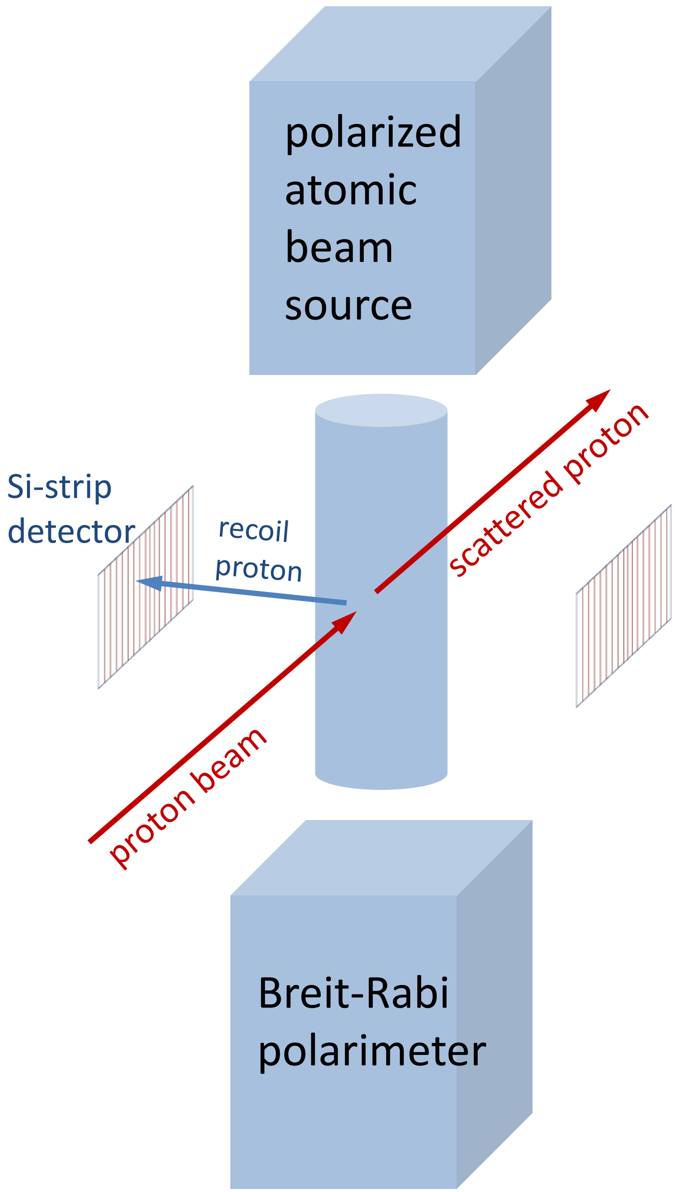


The polarimeter is energy independent in the CNI region



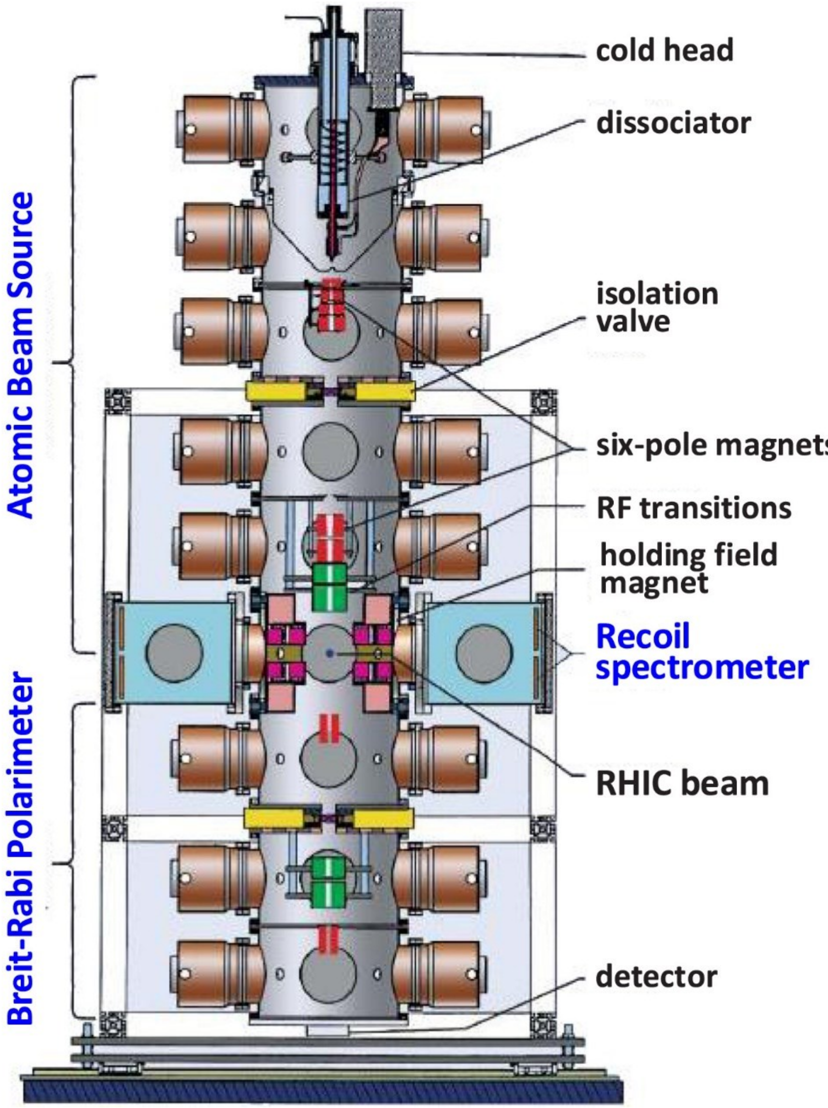
- CNI region: $-t$: $10^{-3} - 10^{-2}$ $(\mathrm{GeV/c})^2$
- Only detect recoil protons (E_{K}): $0.6 - 5.3$ MeV
- Two si-strip detectors covering $\theta \lesssim 90^{\circ}$
- No need to change the hardware with energy

Pol. H-Jet polarimeter in CNI region at RHIC



The H-Jet polarimeter at RHIC

Precision: 5% in 1 hour



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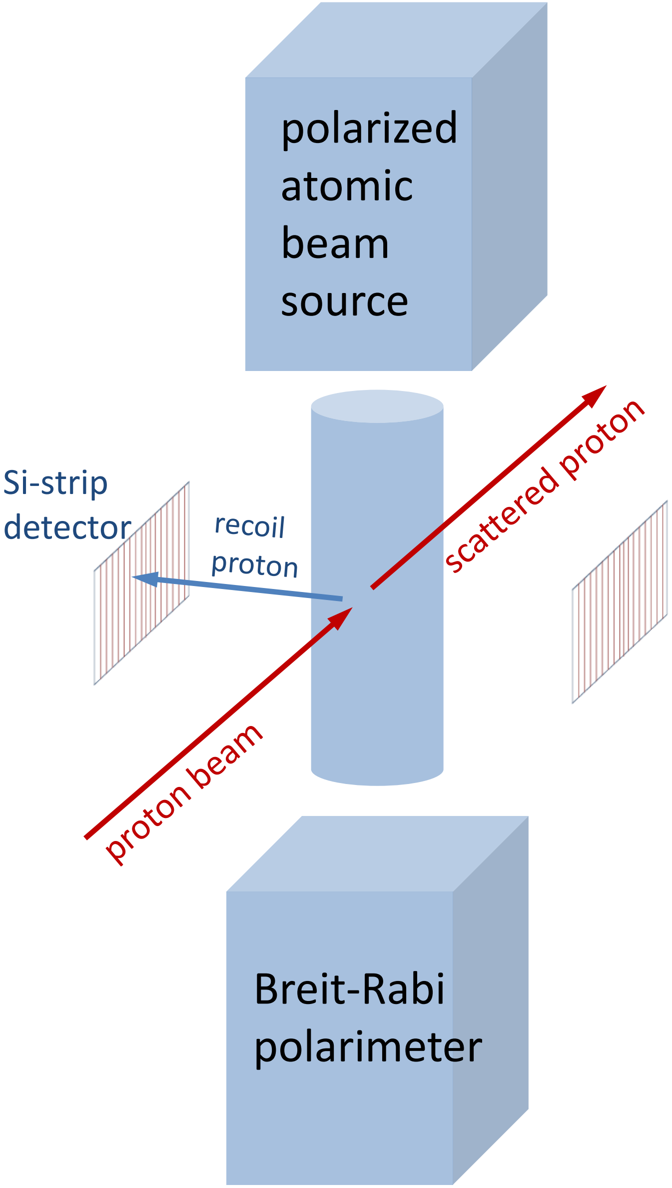

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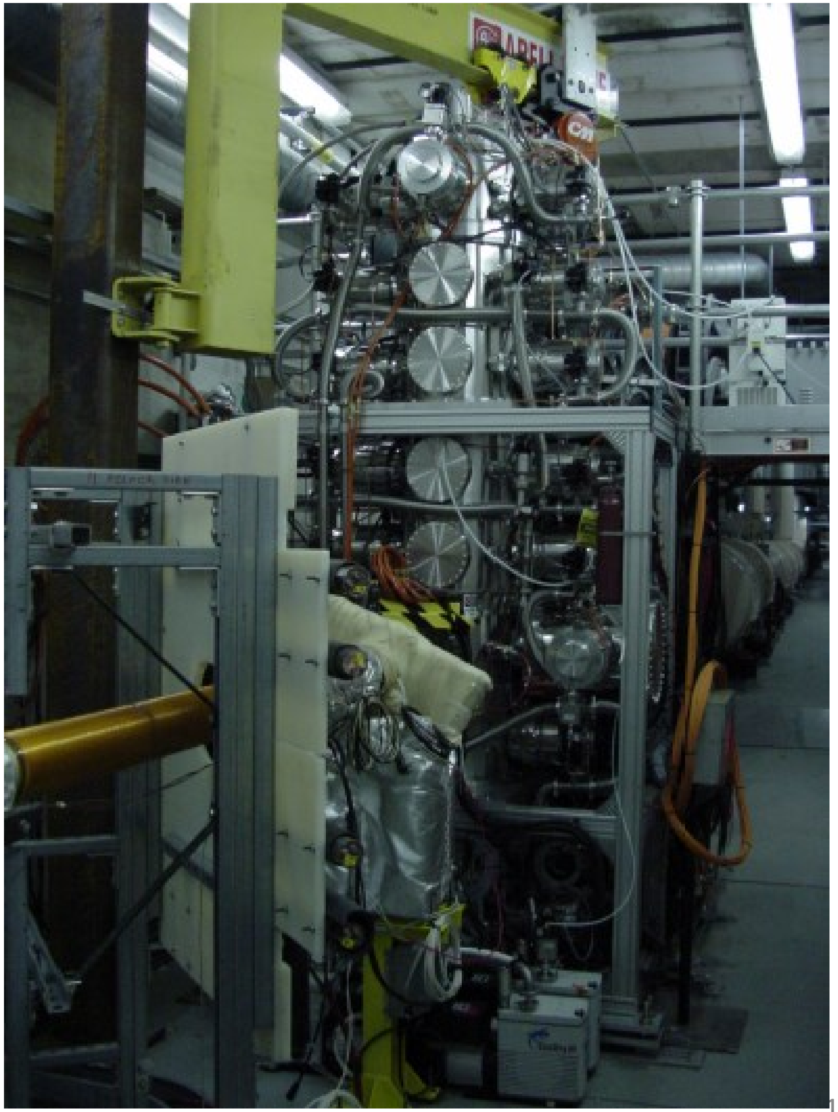
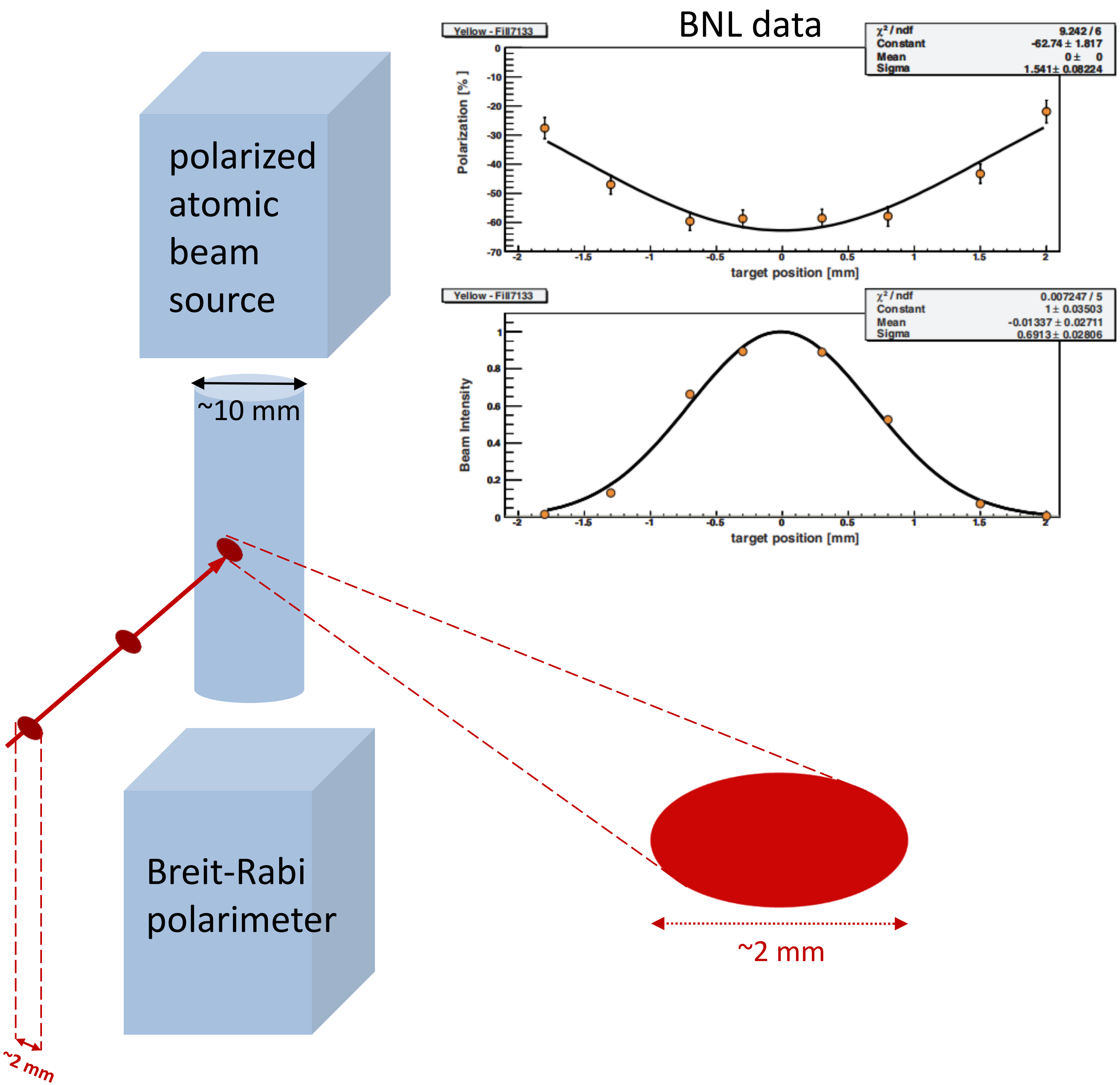
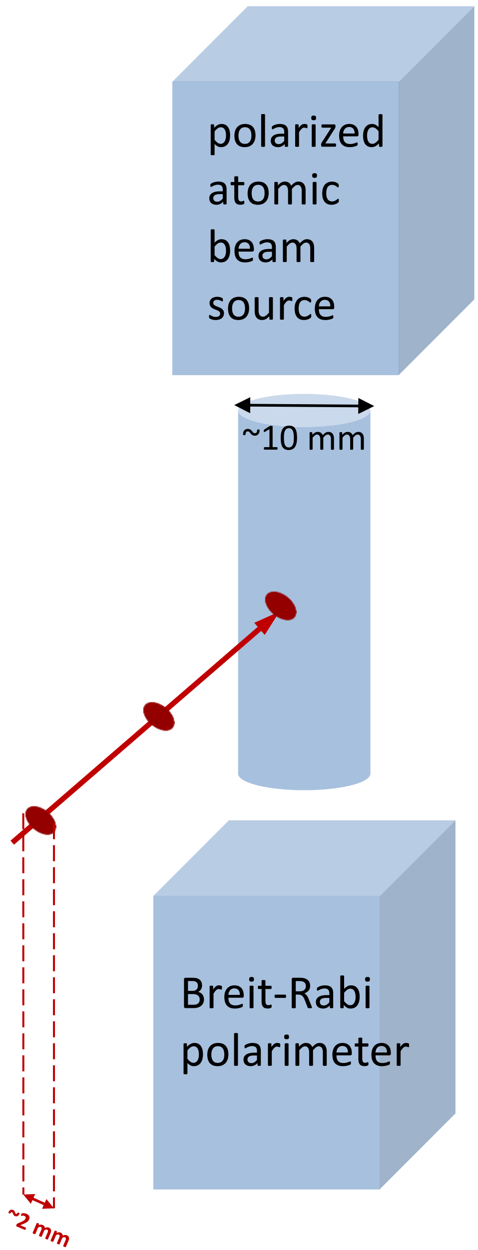


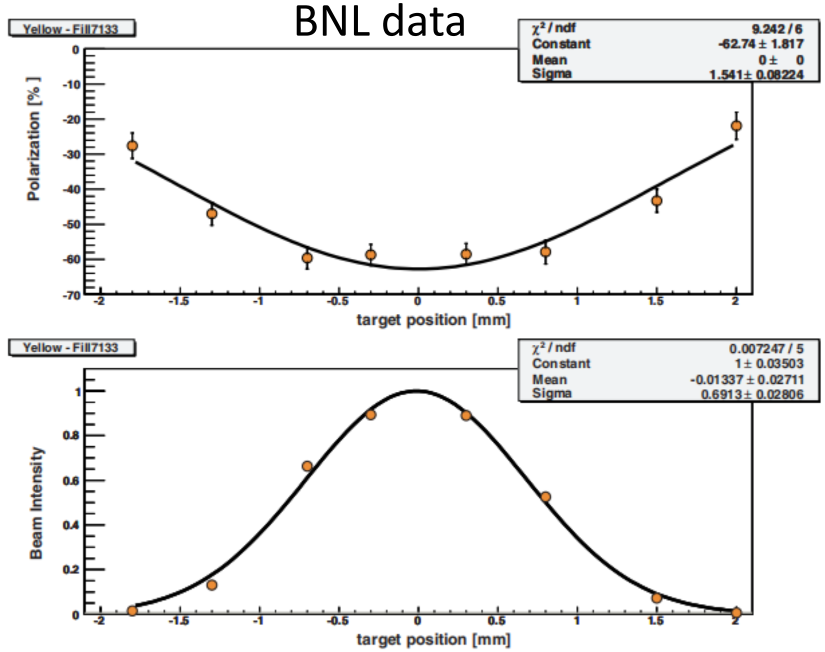
Polarization profile



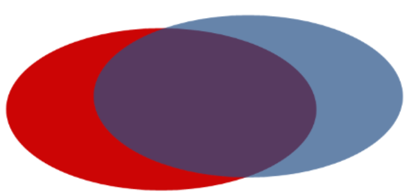
Polarization profile



BNL data

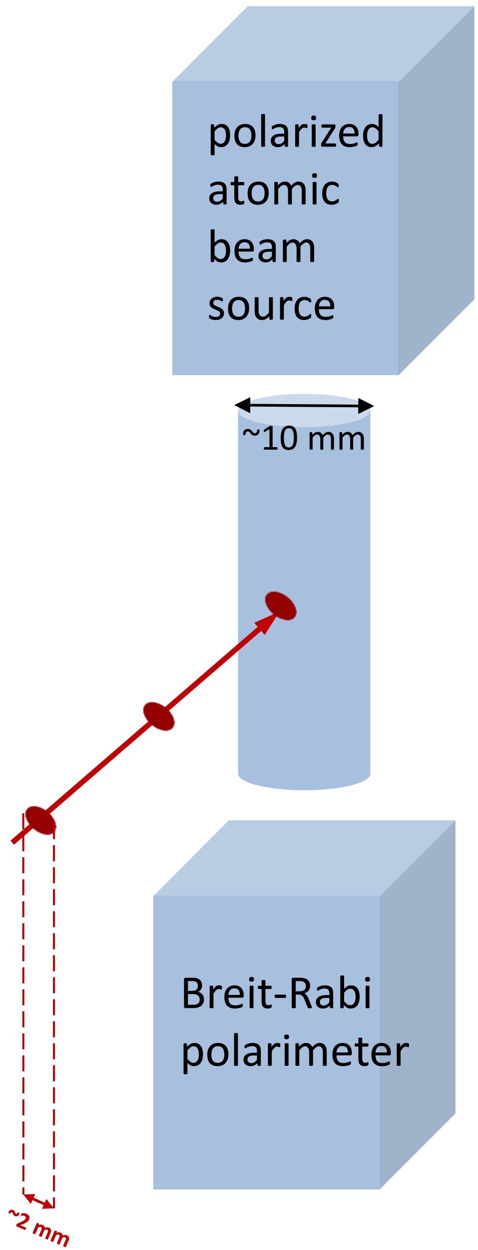


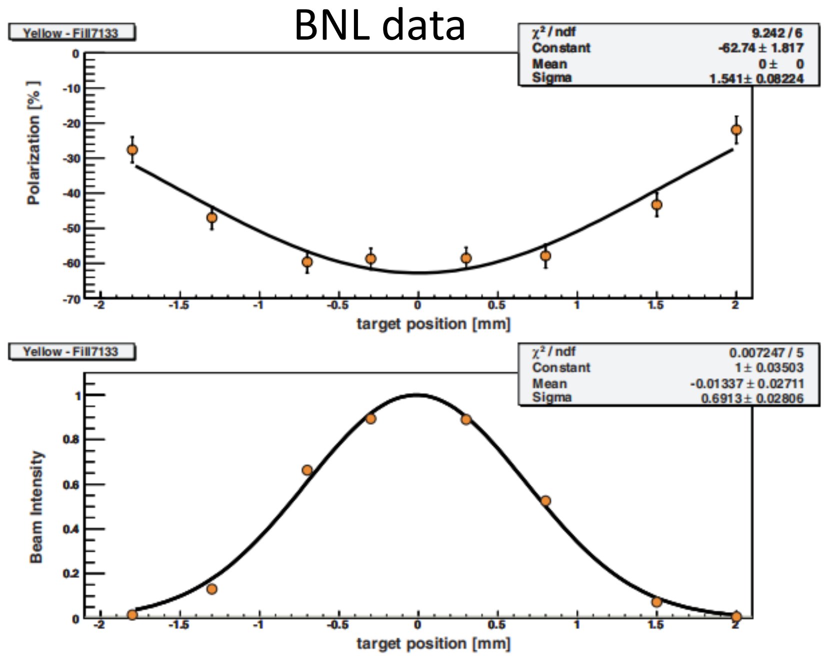
Beam-beam overlap at collider

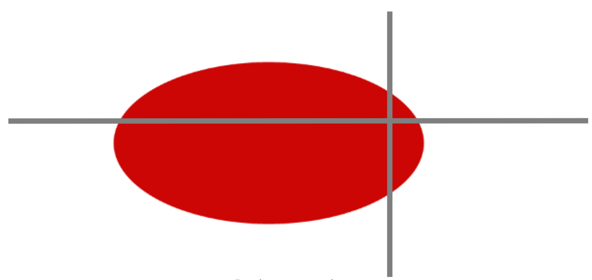


$$\langle P_p \rangle = P_p(x,y) \otimes I_p(x,y) \otimes I_e(x,y)$$

Polarization profile

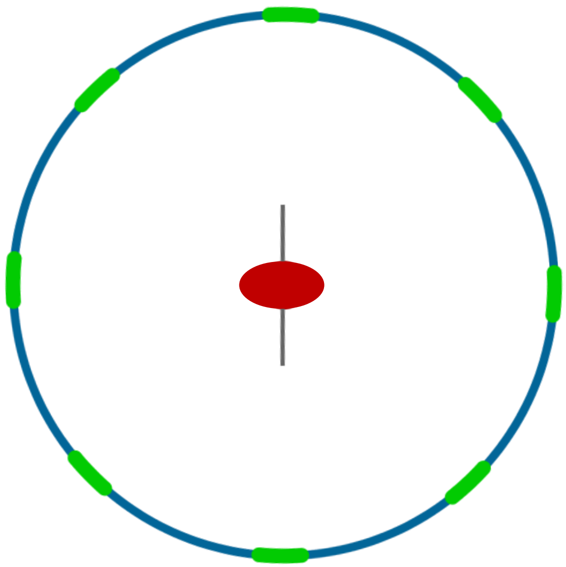




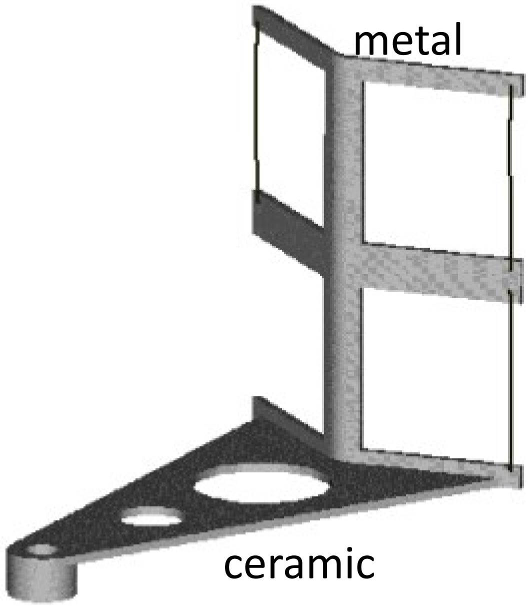


Measure $P_p'(x, y)$ with fiber targets

p-C polarimeter

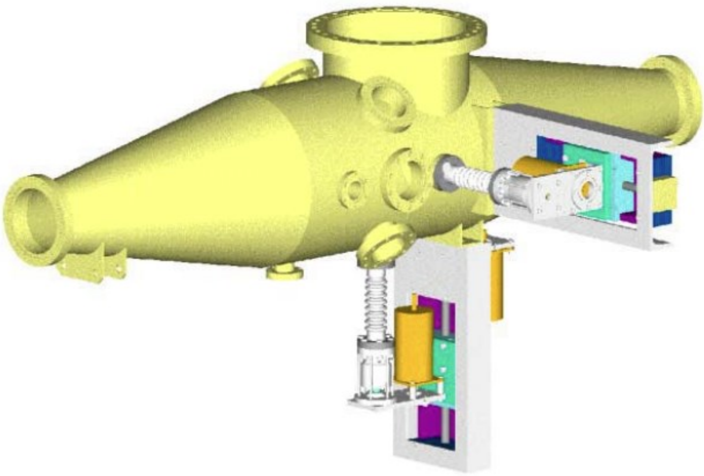


The RHIC/AGS p-C polarimeter 2001 design

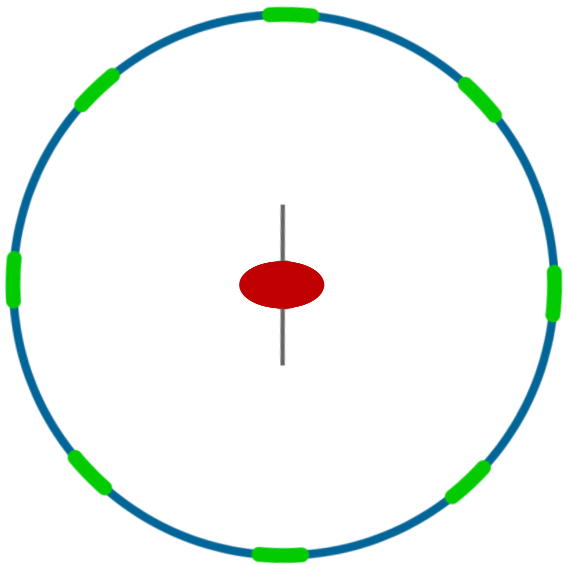


Target box
- Radius: 16 cm

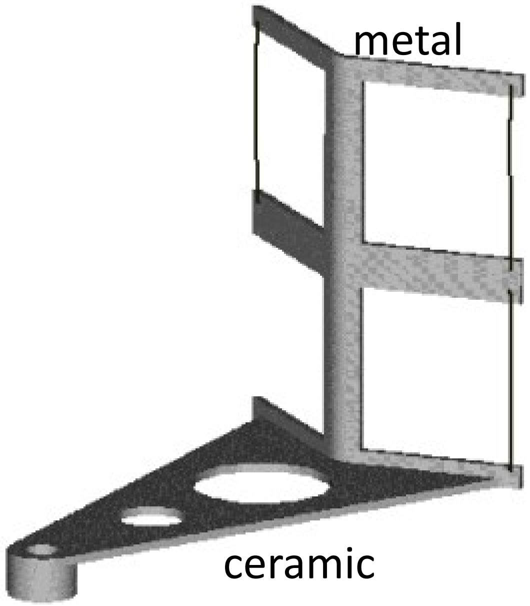
Target frame
- ceramic v plate
- metal holders
- 4 holders (3 carbon + 1 empty)
- 1 left empty for background check



p-C polarimeter



The RHIC/AGS p-C polarimeter



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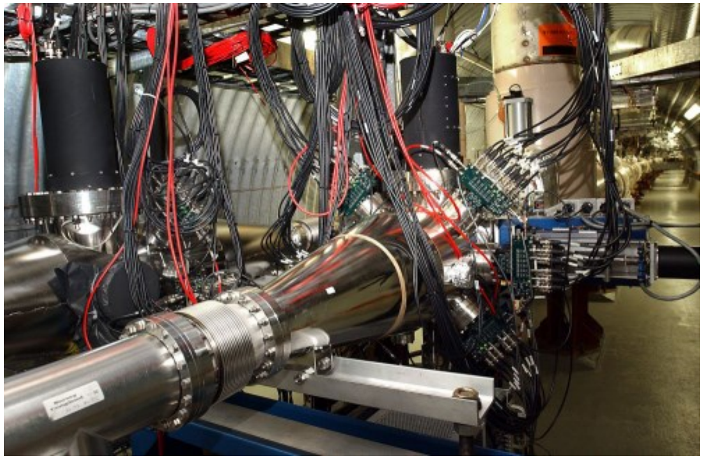
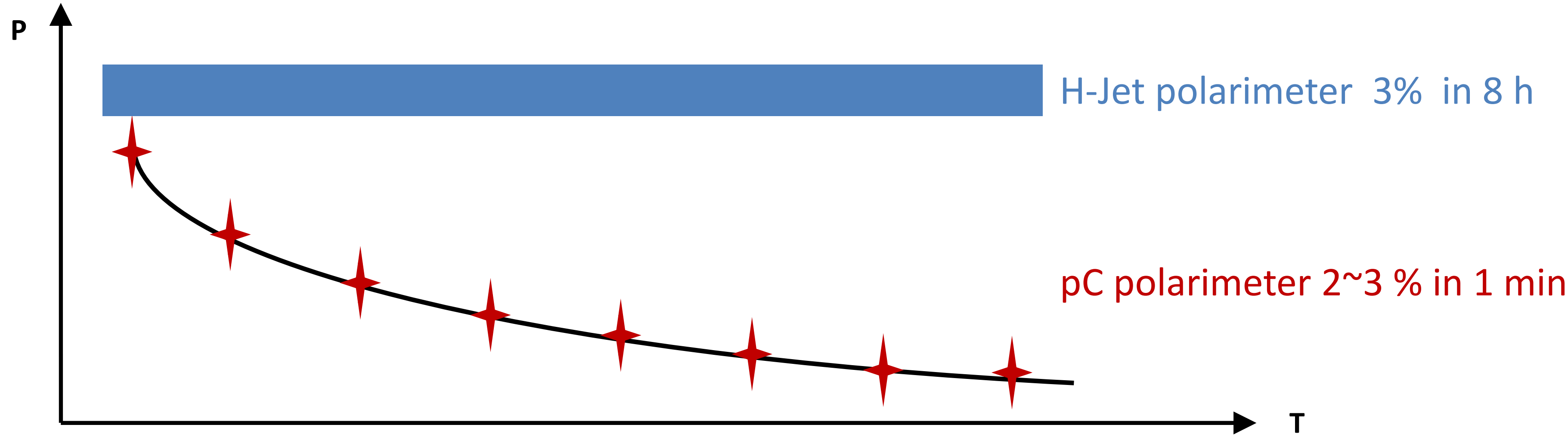


Polarimetry at RHIC

The RHIC experience will be adopted for EicC



	H-Jet polarimeter	**pC polarimeter**
Target	Polarized H gas jet	Carbon fiber
Target thickness	~ $10^{12} atoms/cm^2$	~ $10^{16}\ atoms/cm^2$
Event rate	~ 60 Hz	~ 2 MHz
Operation	continuously	~ 1 min/h
Analyzing power	self-calibrated	unknown
Role	Absolute, slow Noninvasive	Fast, relative Polarization profile Feedback for machine tuning

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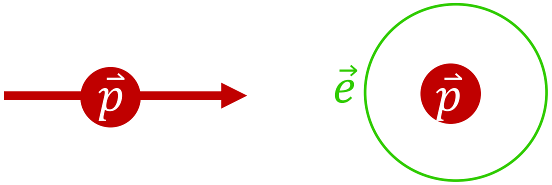
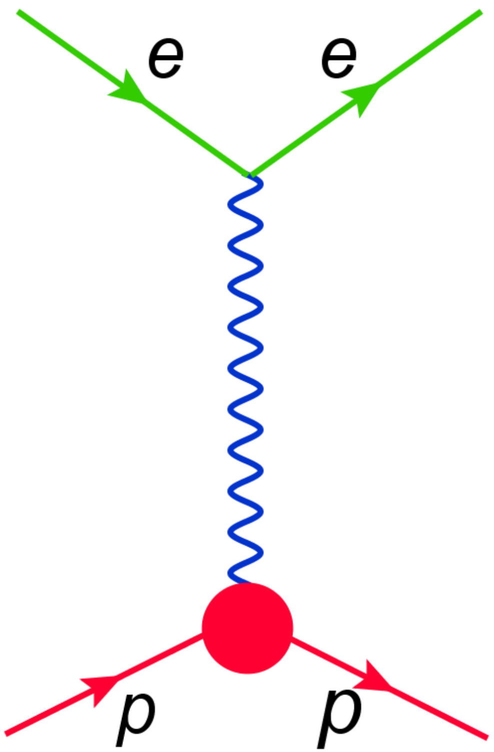
$\vec{\mathrm{p}}\,\vec{\mathrm{e}} \to \mathrm{p}e$ with polarized H target

Polarized hydrogen target is also a polarized electron target !!!



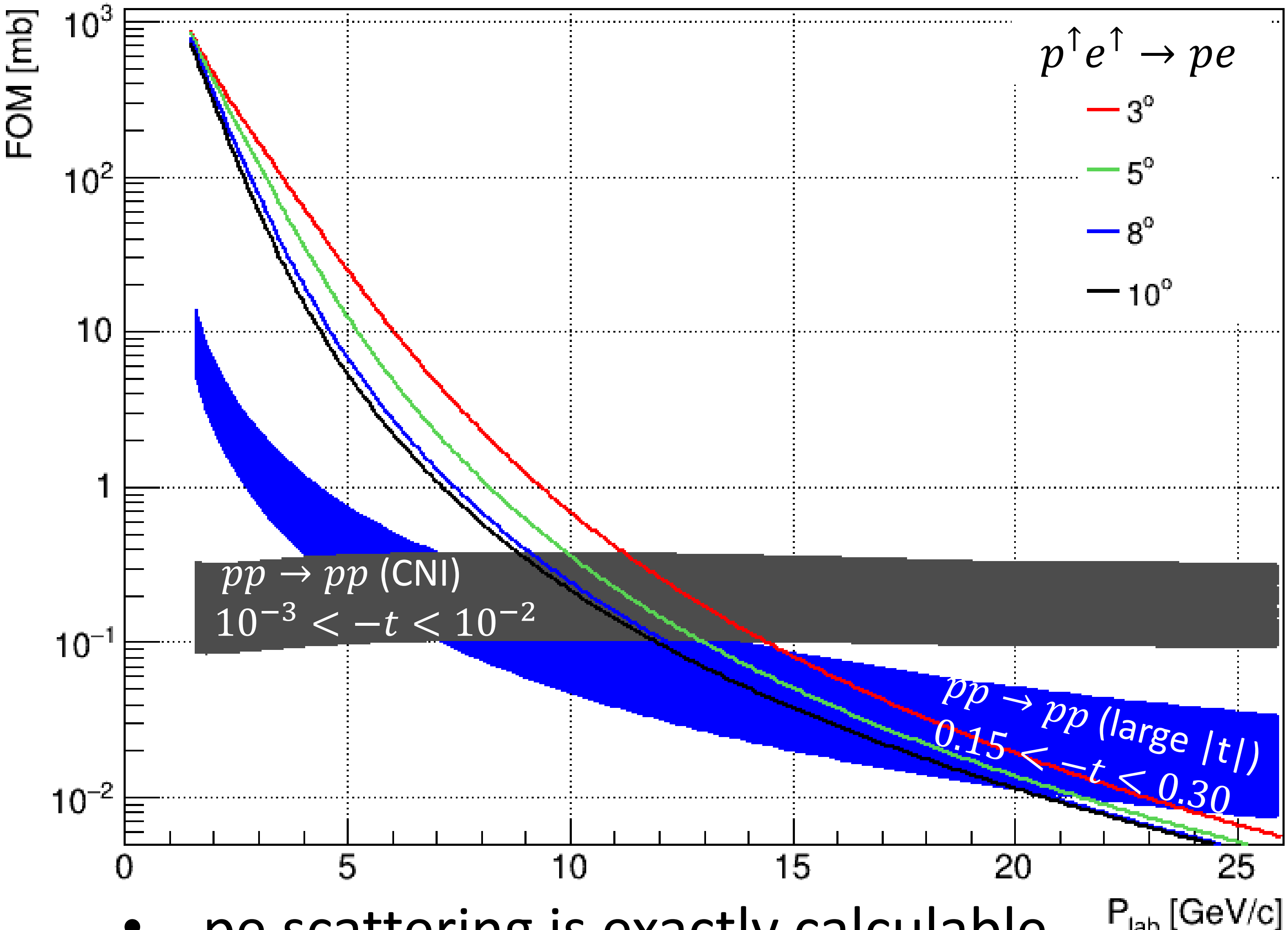
beam

target



- Very small Q^2 in inverse kinematics
- Proton form factors well measured
- All observables are exactly calculable
  Phys. Rev. C **84**, 015212(2011)

FOM: pe vs pp



- pe scattering is exactly calculable
- more suitable at HIAF energy range

Recoil electron detection — general idea

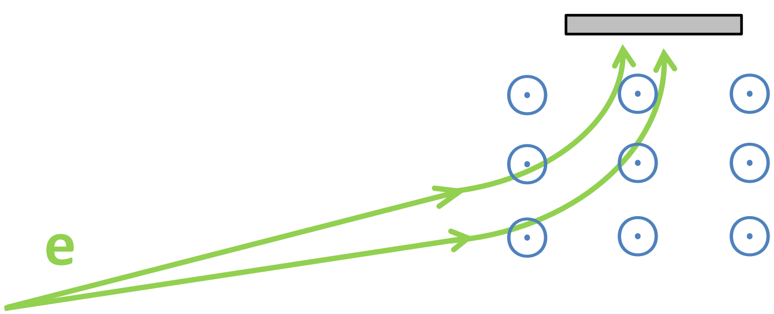
- Only detect recoil electron
  - θ: $3^{\circ} \sim 8^{\circ}$
  - E: $10 \sim 200$ MeV

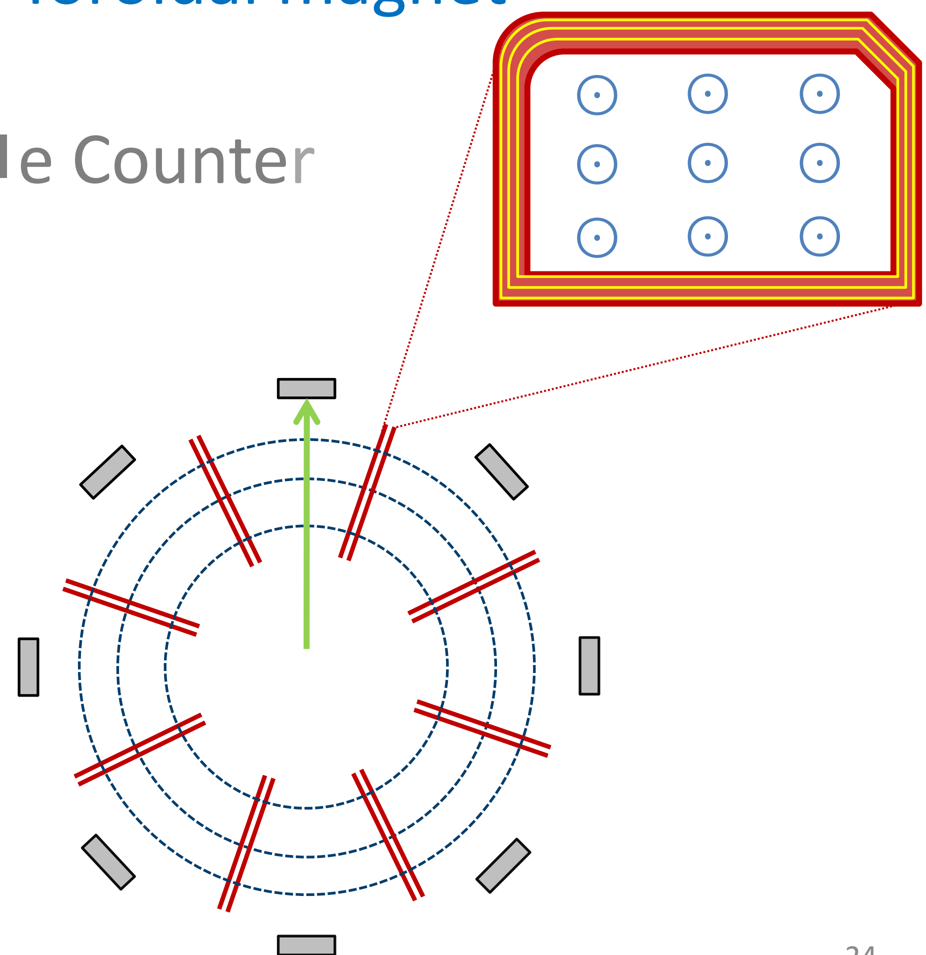
- Reject background with toroidal magnet

■ Electric coil

■ Toroidal magnet

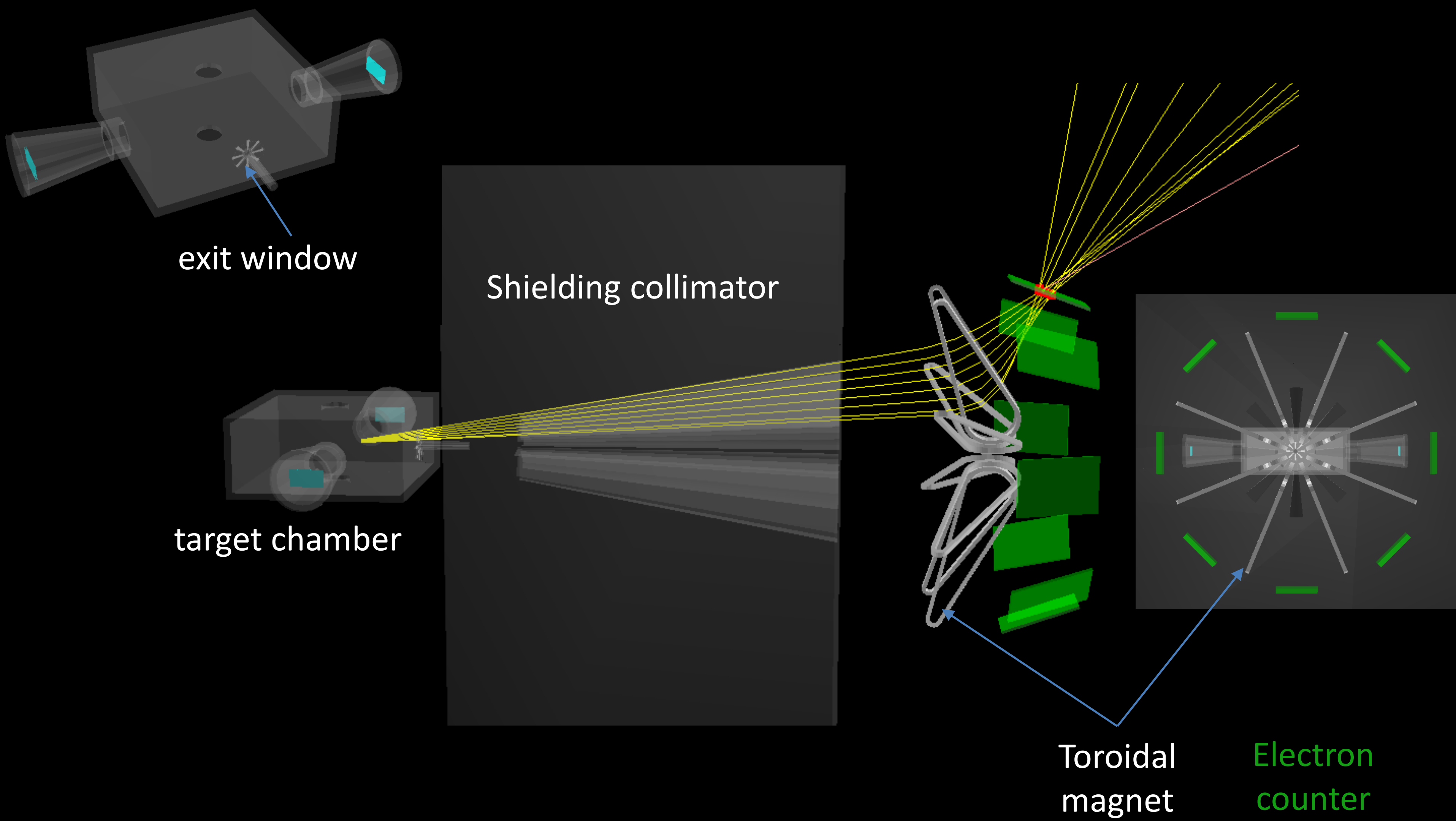
■ e Counter





$$\boxed{pe \rightarrow pe}$$

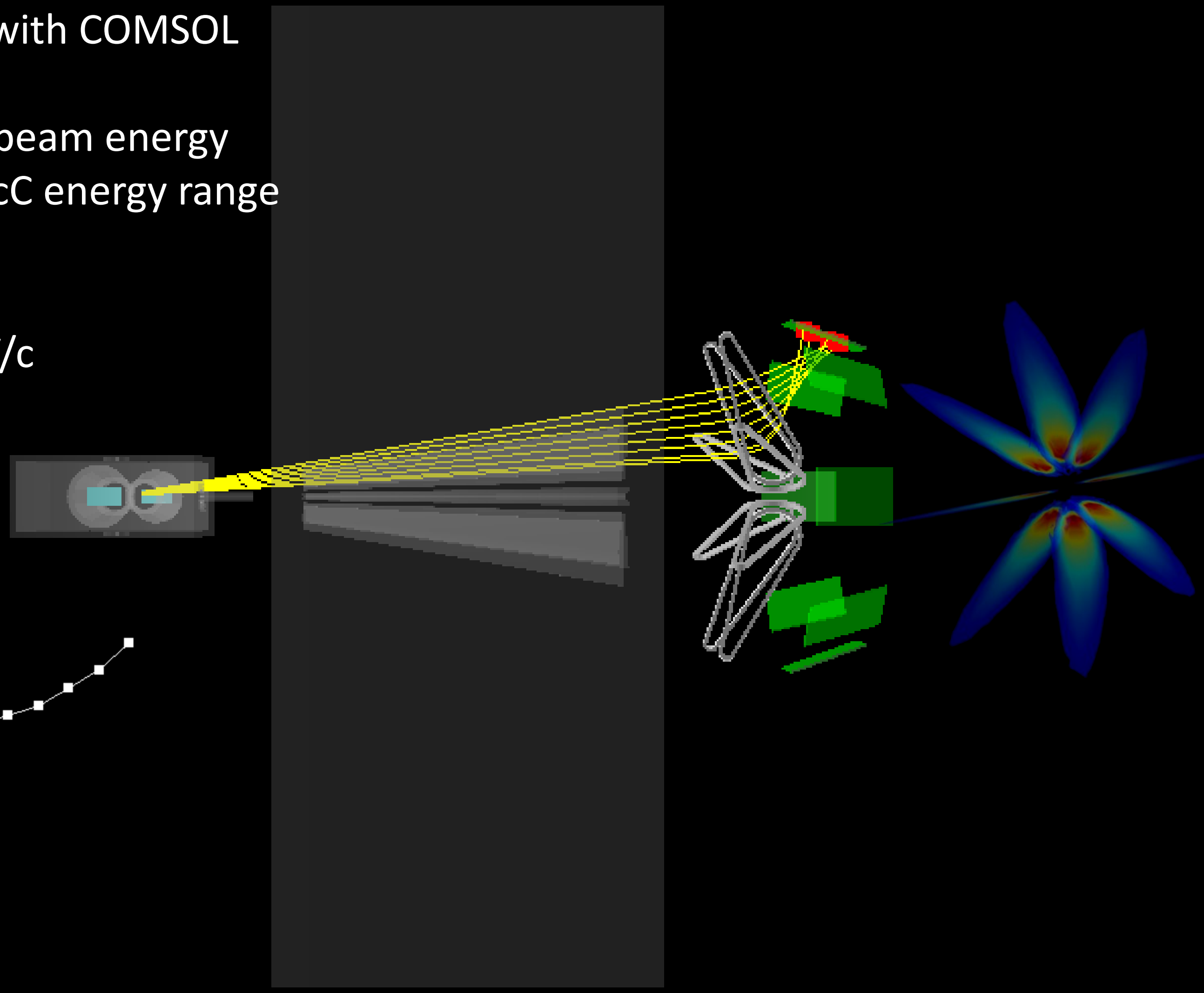
Recoil electron detection — apparatus

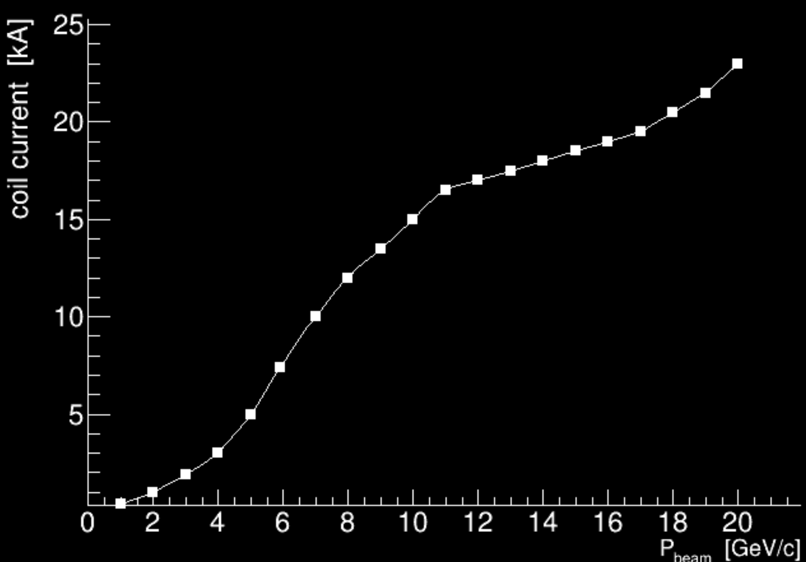


Toroidal magnet design

- Toroidal magnet emulated with COMSOL
- Asymmetric racetrack coil
- Coil current increases with beam energy
- Electron focused at HIAF-EicC energy range

Beam momentum： 1 GeV/c





Toroidal magnet design

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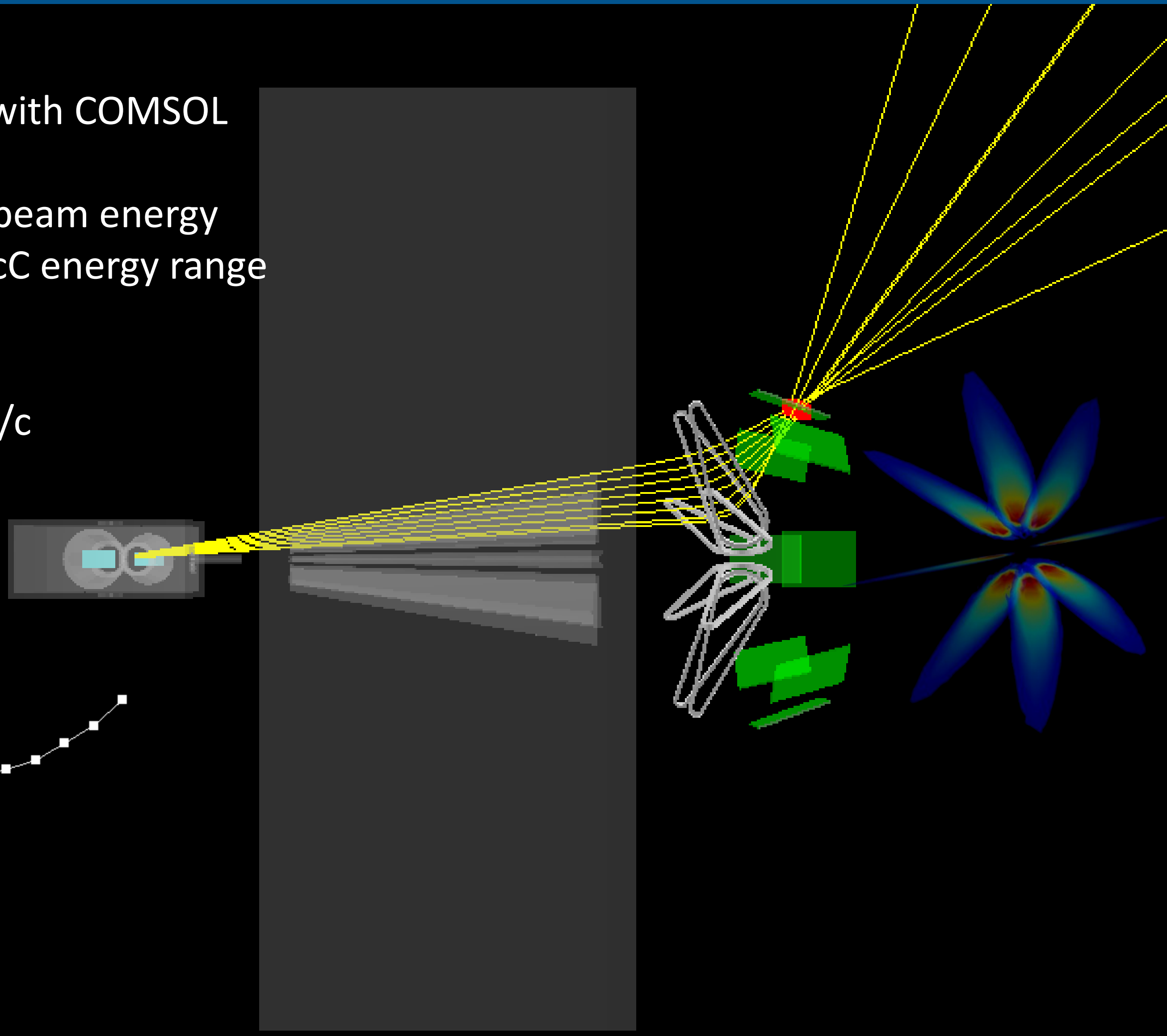
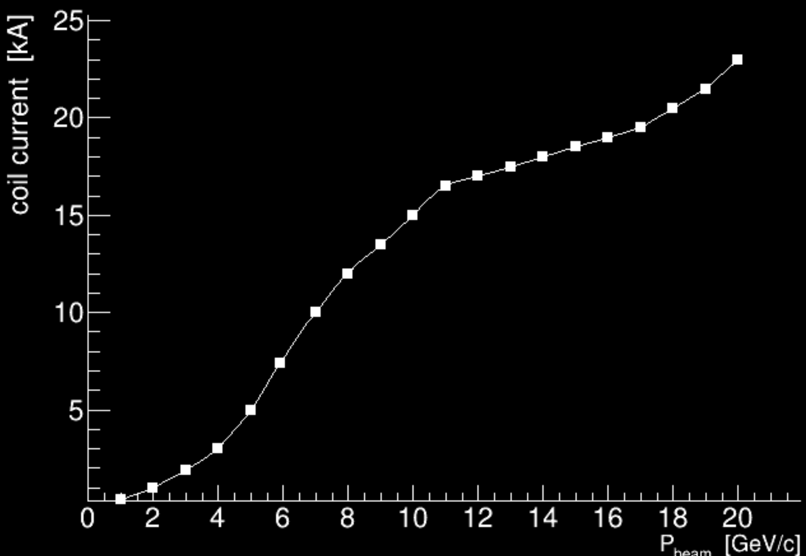
- Electron focused at HIAF-EicC energy range

Beam momentum： 5 GeV/c





Toroidal magnet design

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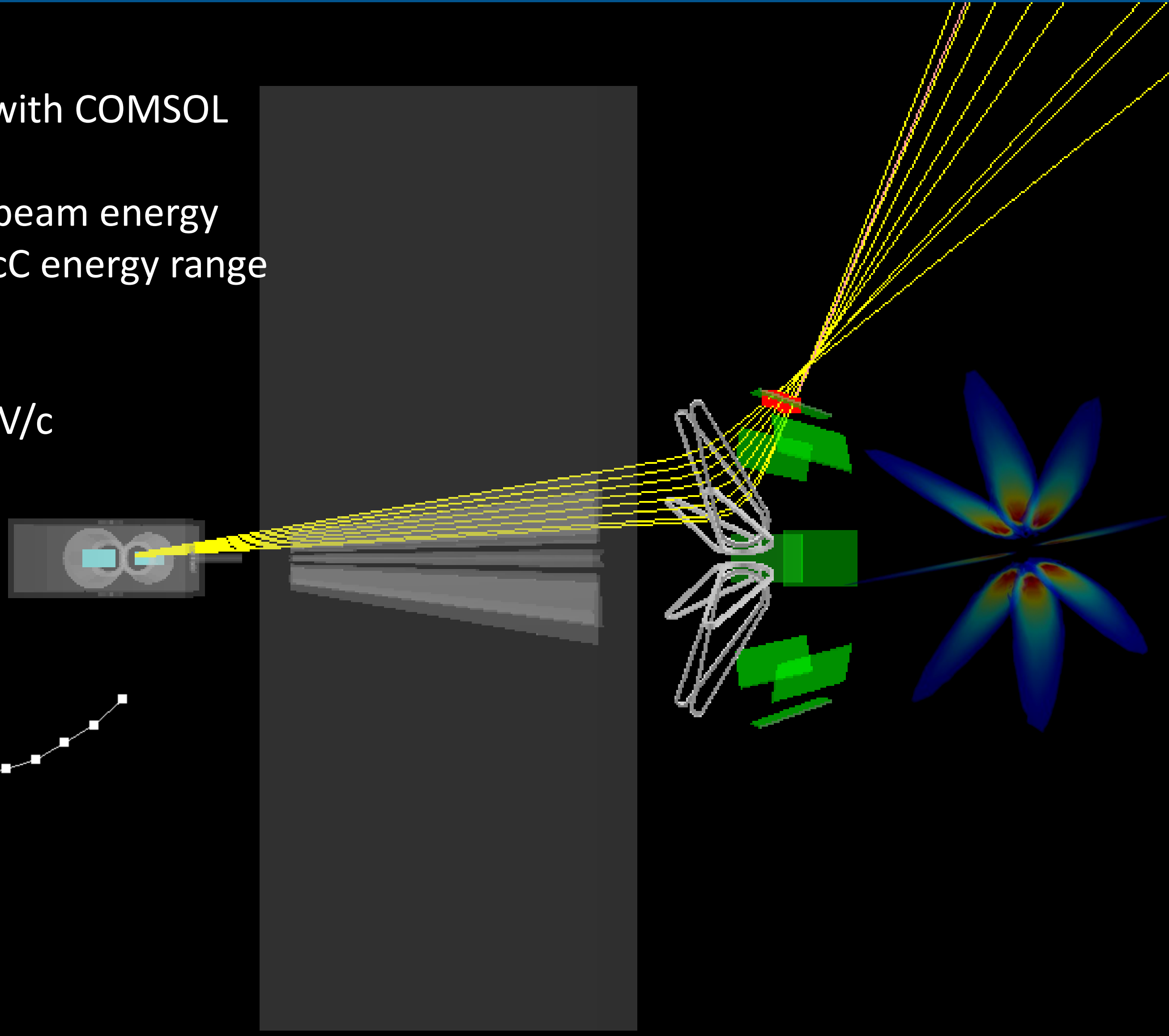
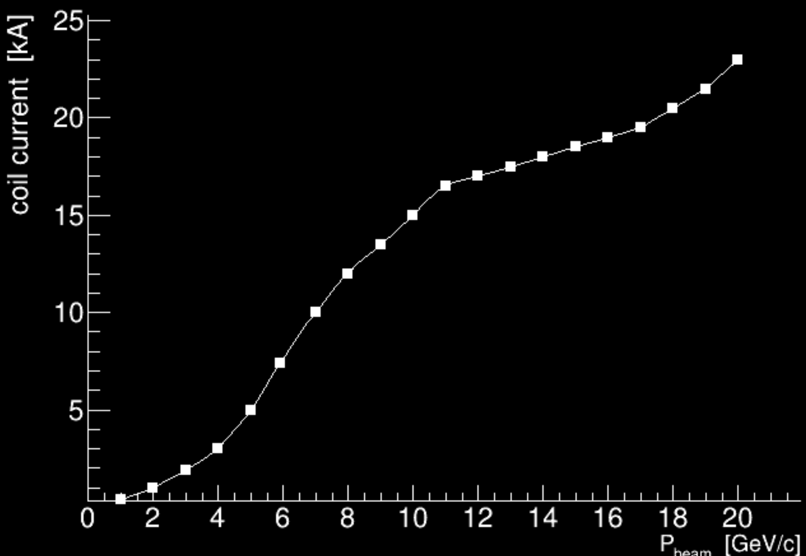
- Asymmetric racetrack coil
- Coil current increases with beam energy
- Electron focused at HIAF-EicC energy range

Beam momentum： 10 GeV/c





Toroidal magnet design

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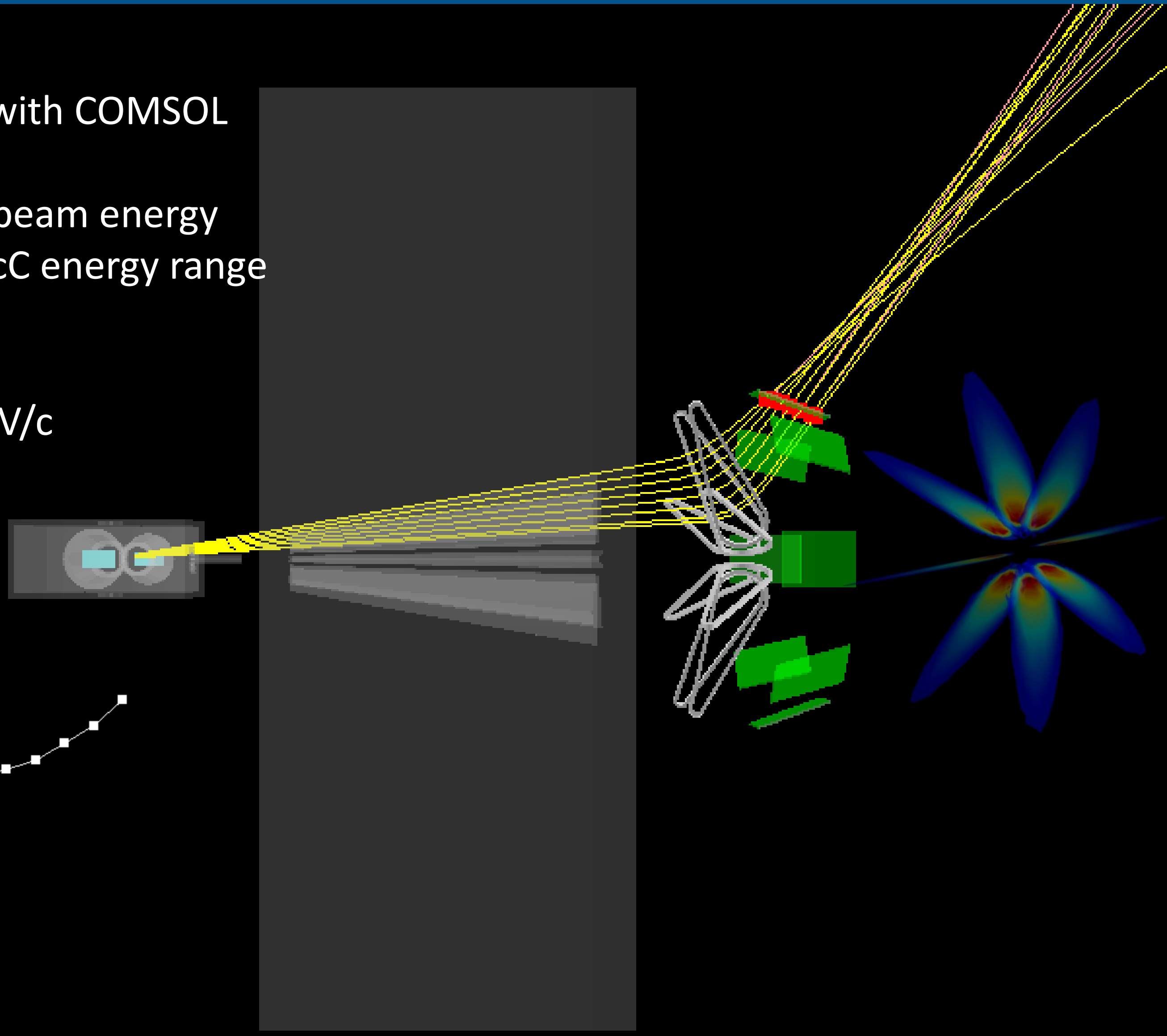
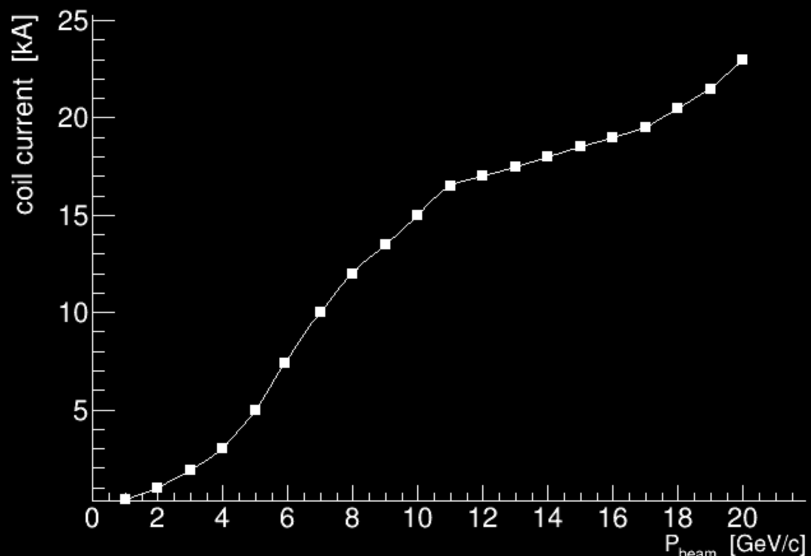
- Electron focused at HIAF-EicC energy range

Beam momentum： 15 GeV/c





Toroidal magnet design

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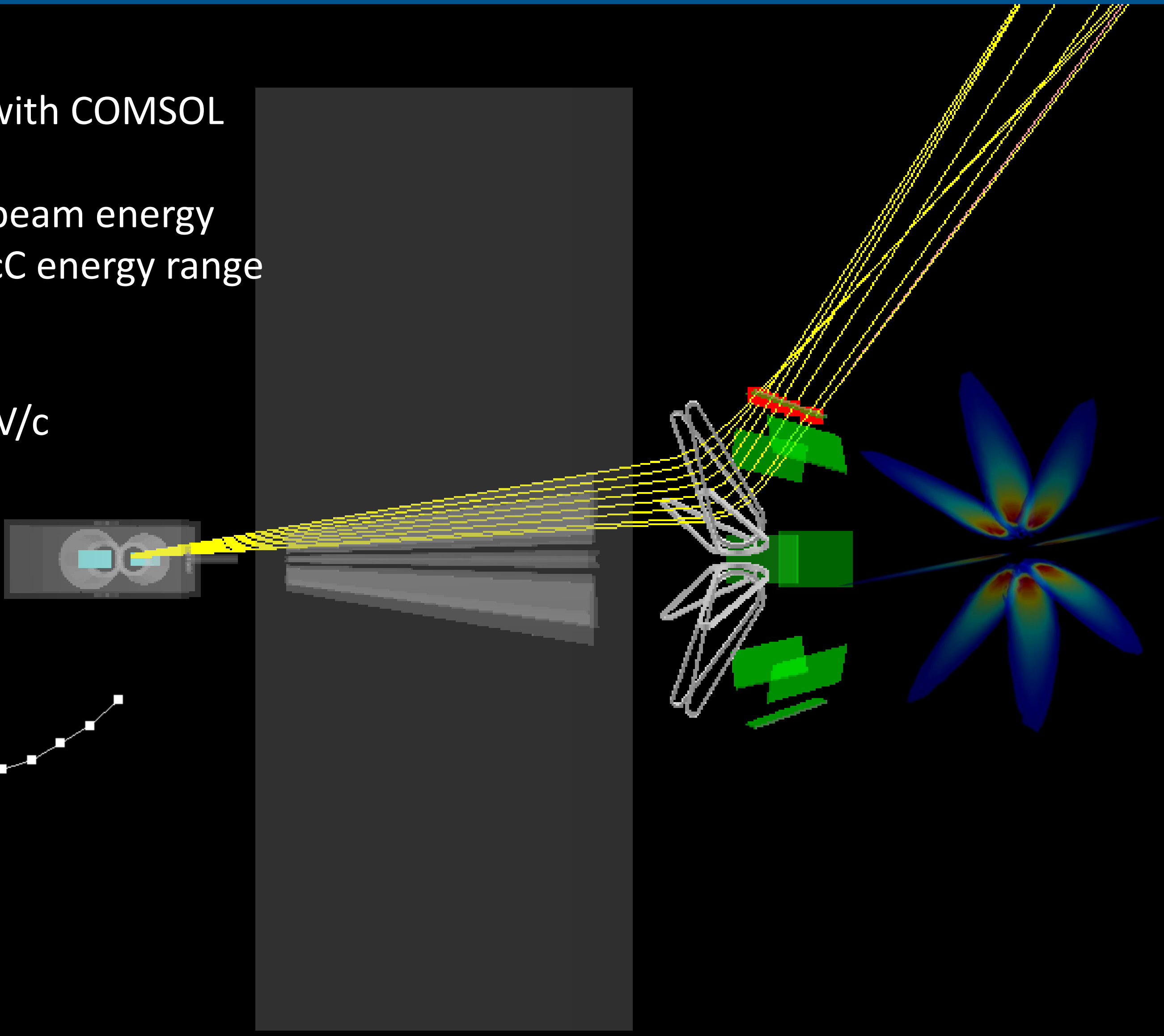
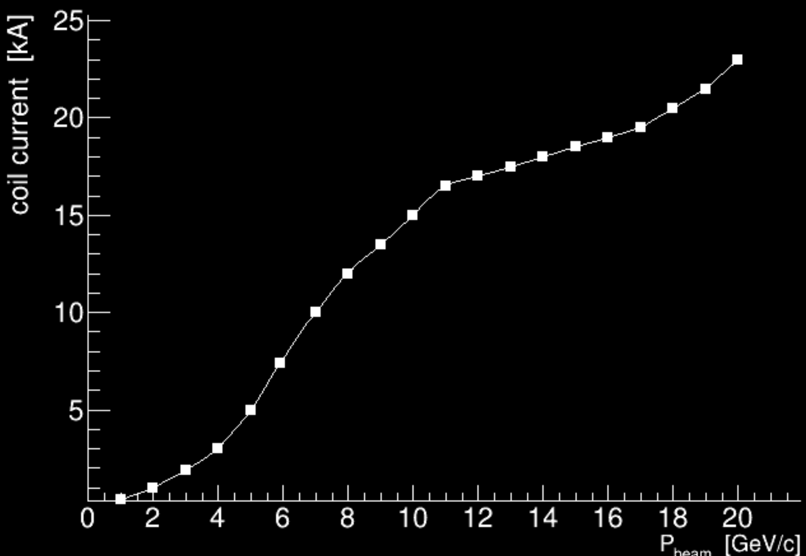
Beam momentum： 20 GeV/c





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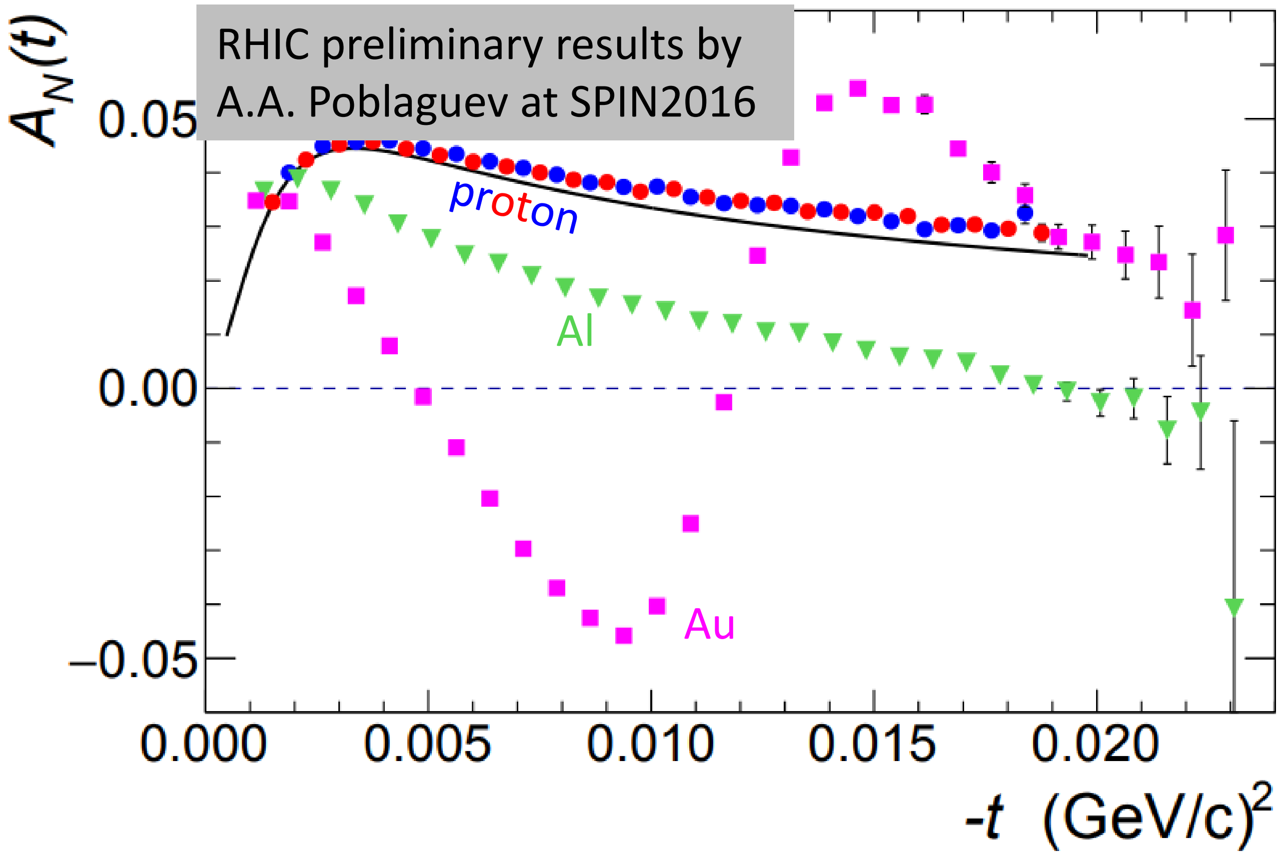
Physics with pp-CNI polarimeter

Ap polarized observable (A_N)

- Reaction: $\mathrm{A}\vec{\mathrm{p}} \to \mathrm{Ap}$
- Ap spin dynamics
- Nuclear many-body structure

Nuclear physics with spin-polarized experiments



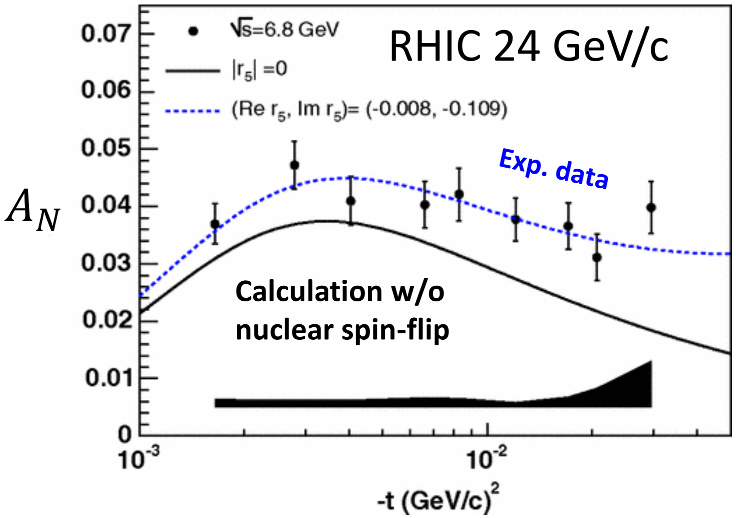
Foreseeable apparatus

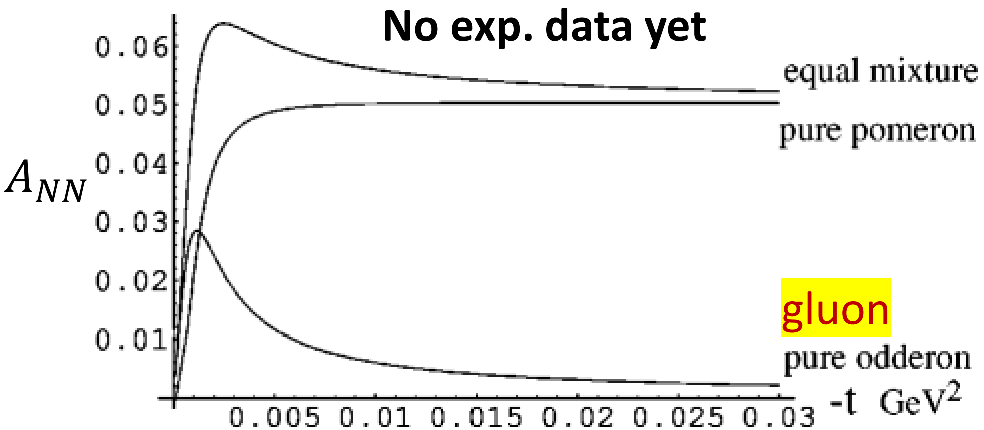
- unpolarized heavy-ion beams
- polarized gas hydrogen target
- silicon strip detectors

Physics with pp-CNI polarimeter

pp polarized observables (A_N, A_{NN})

- Reaction: $p\vec{p} \rightarrow pp, \quad \vec{p}\vec{p} \rightarrow pp$
- A_N : single spin-flip amplitude (mechanism)
- A_{NN}: double spin-flip amplitude 、 gluon search in t channel



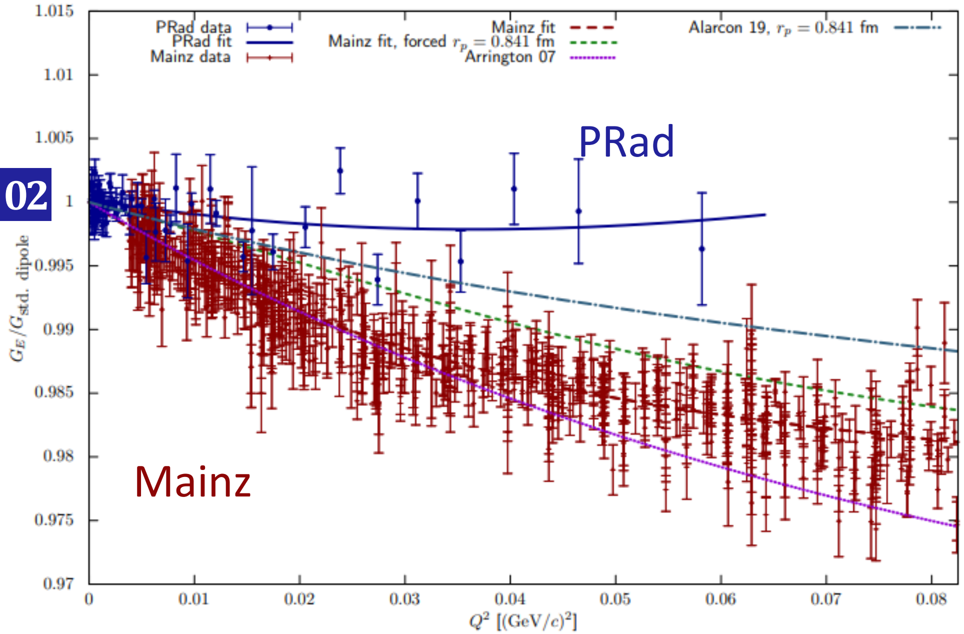


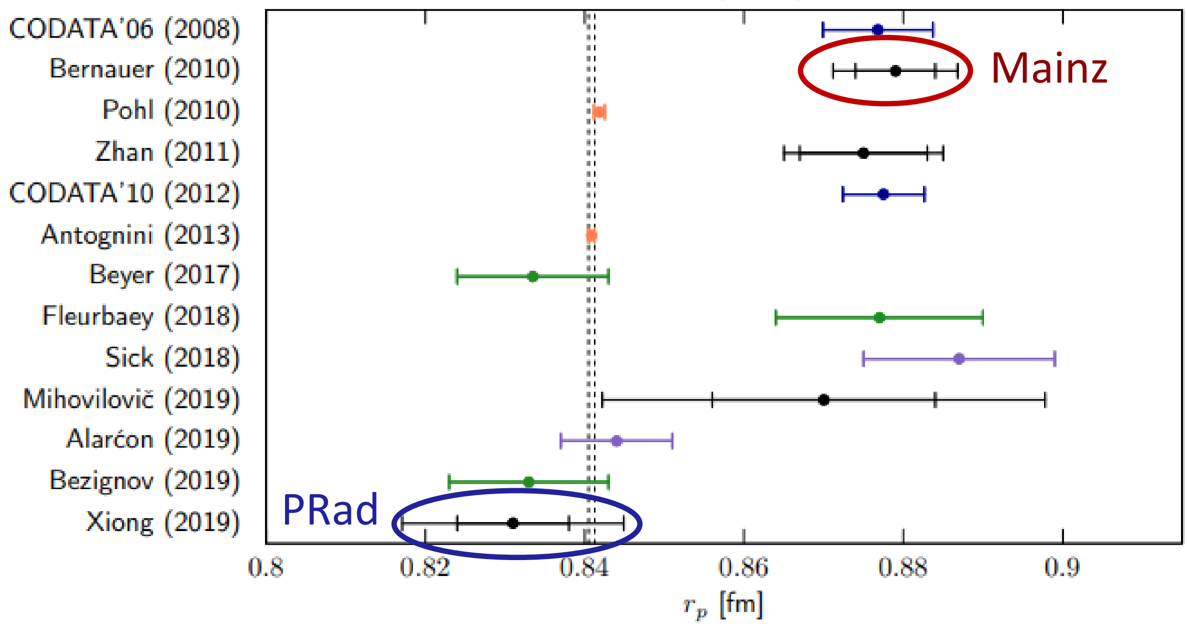
[1] Odderon and spin dependence of high energy proton-proton scattering
E. Leader and T. L. Trueman, Phys. Rev. D 61, 077504 (2000)

[2] Spin-dependent Pomeron and Odderon in elastic proton–proton scattering
Yoshikazu Hagiwara, …, and **Jian Zhou**, Eur. Phys. J. C 80 427 (2020)

Physics with pe polarimeter – proton radius puzzle

$Q_2: 2.5\times10^{-4} \sim 0.02$





- Proton electromatic form factors (G_E, G_M) measured in ep elastic scattering
- Proton charge radius (r_p) extracted from G_E

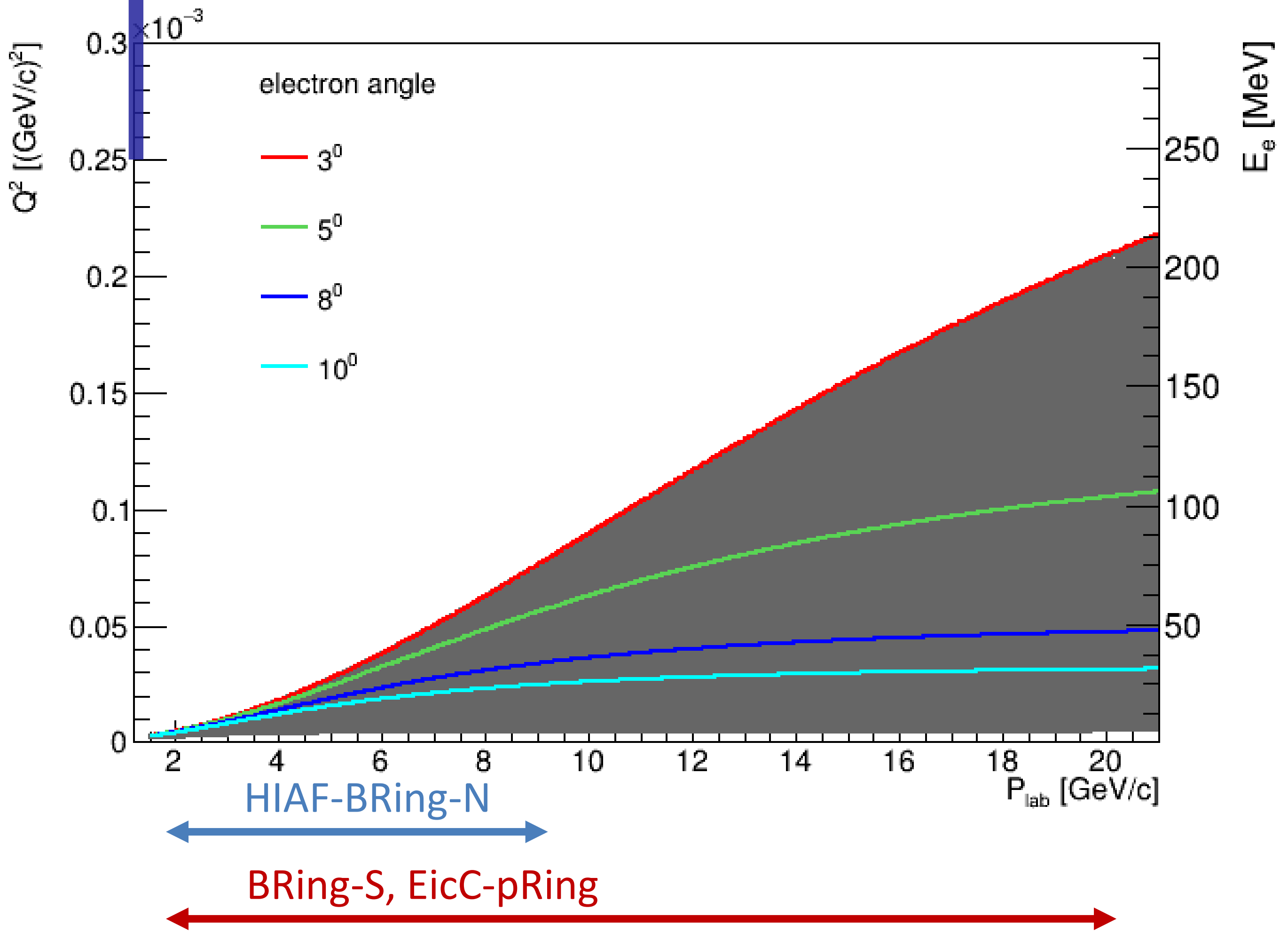
$$r_p = -6\frac{dG_E}{dQ^2}\bigg|_{Q^2\to0}$$

- **r_p (G_E) from PRad is different from previous measurements**

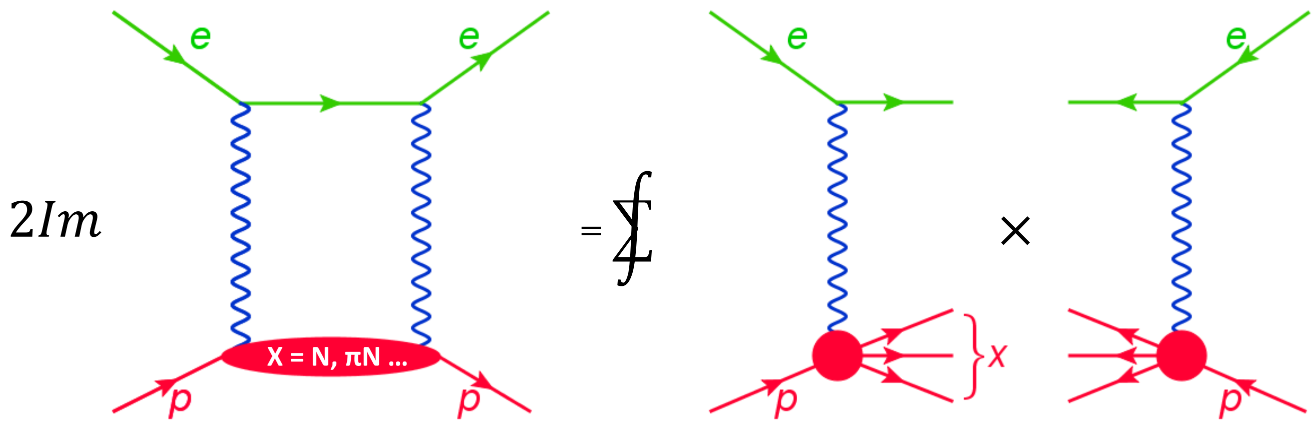
Physics with pe polarimeter – pe kinematics

PRad

With proton beam and electron target at HIAF/EicC-pRing, ultra low $Q_2 (< 2 \times 10^{-4})$ can be accessed in pe scattering



Physics with pe polarimeter – $p\vec{e}$ vs $\vec{e}p$



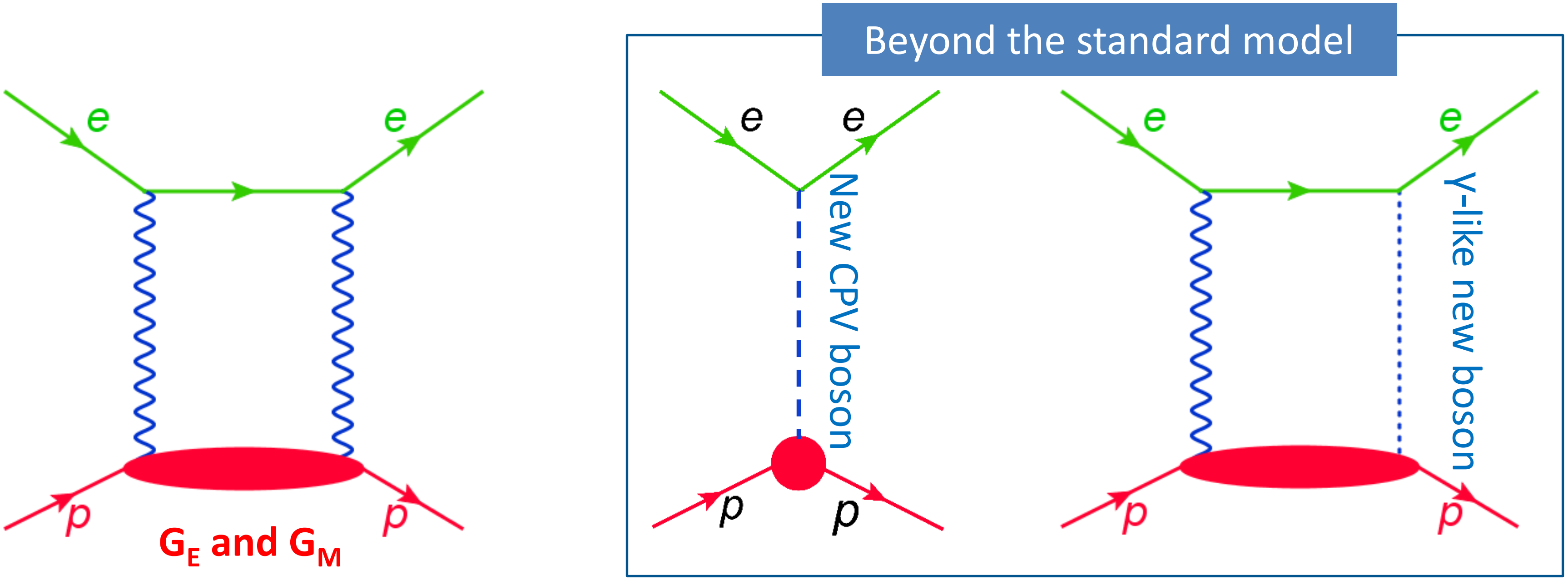
- Transverse asymmetry $A_\perp = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$ in $\vec{e}$p scattering arises from two-photon exchange (imaginary amplitude: $\mathrm{Im}\mathcal{M}_{2\gamma}$)

- Unitarity → $A_\perp$ calculated from intermediate states X

- In $\vec{e}\mathrm{p} \to \mathrm{ep}$
  - possible intermediates: X = N, πN … → Non-pQCD uncertainty
  - Lorentz effect with $\vec{e}$ beam → $A_\perp \propto \frac{m_e}{E} \sim 10^{-6}$ (tiny signal)

- In $\mathrm{p}\vec{\mathrm{e}} \to \mathrm{pe}$ (very-low $\mathbf{Q_2}$)
  - X = N → $A_\perp$ calculated with **G_E and G_M (no theoretical uncertainty)**
  - No Lorentz effect → $A_\perp$ increases by 3 orders

New approach for r_p study and new physics search



- $A_\perp$ only sensitive to **G_E and G_M** → **New approach to study proton EM radius**
- Possible to distinguished PRad and Mainz measurements
- **New physics** if $A_\perp$ differs significantly from the SM calculation

Content

- Future hadron accelerators at IMP

- General consideration & reference reaction selection

- Polarimeters based on elastic scattering in CNI region
  - Heavily adopted from RHIC experiences
  - pp-CNI absolute polarimeter
  - pC-CNI fast polarimeter

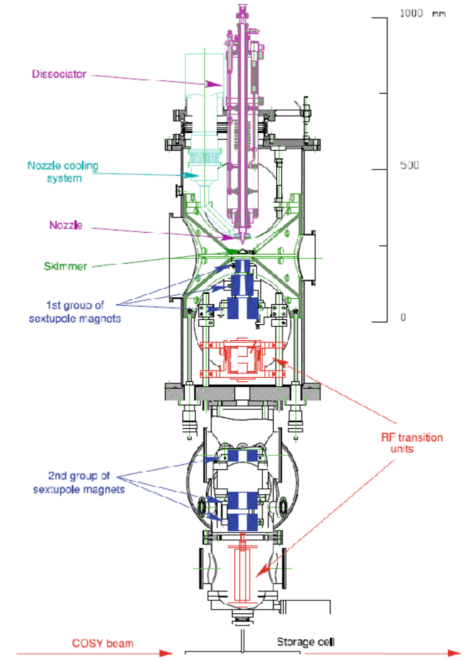
- Polarimeter based on pe elastic scattering
  - new method

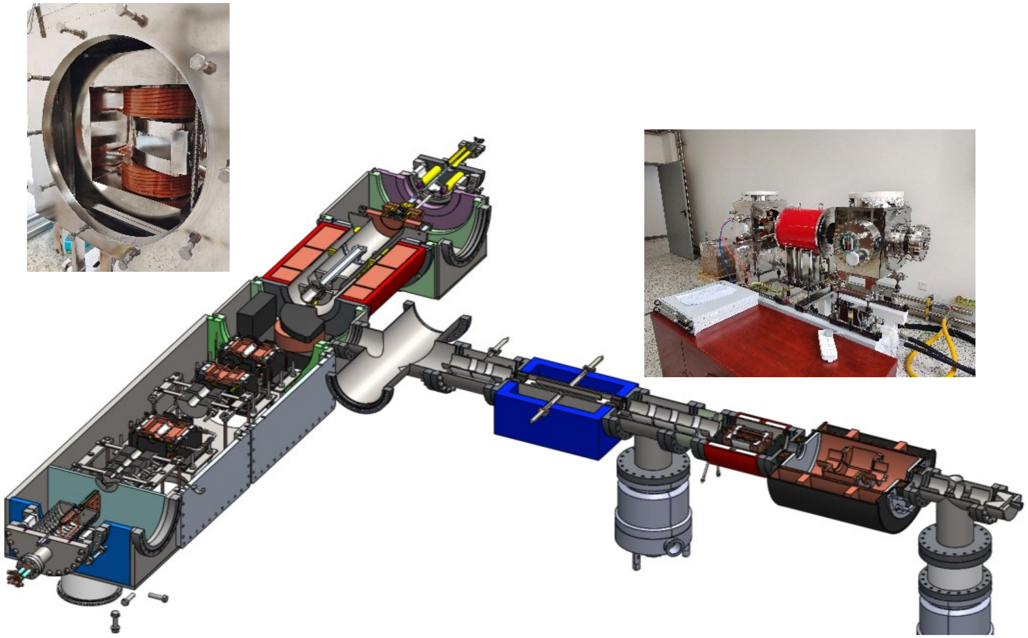
- Possible physics program with polarimetric apparatus
  - Physics program with CNI-pp polarimeter
  - Physics program with pe polarimeter

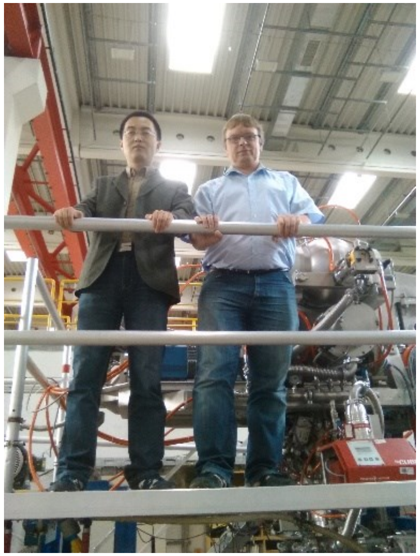
- Current activities

Current activities

- A joint polarized-physics team established at IMP
  - Polarized ion source
  - Polarized beam acceleration
  - Polarimetry (hydrogen target)
- National Key R&D program fund received from MOST
- An ion source at IMP is designed, key parts manufactured
- Collaboration with IKP on polarized target







Summary

- Proton beam polarimetry based on pp and pC CNI scatterings
  - Well established method
  - Applicable for deuteron and helion beams

- Proton polarimetry based on pe scattering

- Possible physics program with polarimeters
  - Nuclear spin dynamics/structure
  - NN spin dynamics
  - New approach for proton radius study/new physics search

- Spin physics at IMP launched

Thank you