中国科学院 CHINESE ACADEMY OF SCIENCES

HIAF

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

Efforts towards polarized beams and spin physics at HIAF

Boxing Gou

on behalf of the HIAF spin team

Joint seminar of High Energy Physics and Theoretical Physics Divisions
RC "Kurchatov Institute" - PNPI, Gatchina

ZOOM • September 17, 2026

Content

- Efforts towards polarized beams/targets for HIAF
  - Polarized ion sources
  - Acceleration of polarized beams
  - Beam polarimetry and polarized targets

- Spin physics at HIAF in the near future
  - Atomic, nuclear and hadron physics
  - New boson search
  - Test of time-reversal symmetry
  - Spin-rotating polarized target

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EDM, axion, dichroism etc.

Talk by N. N. Nikolaev (DSPIN26)

Natural Sci. Rev. 3200802 (2026)

Final-state polarization measurements not covered

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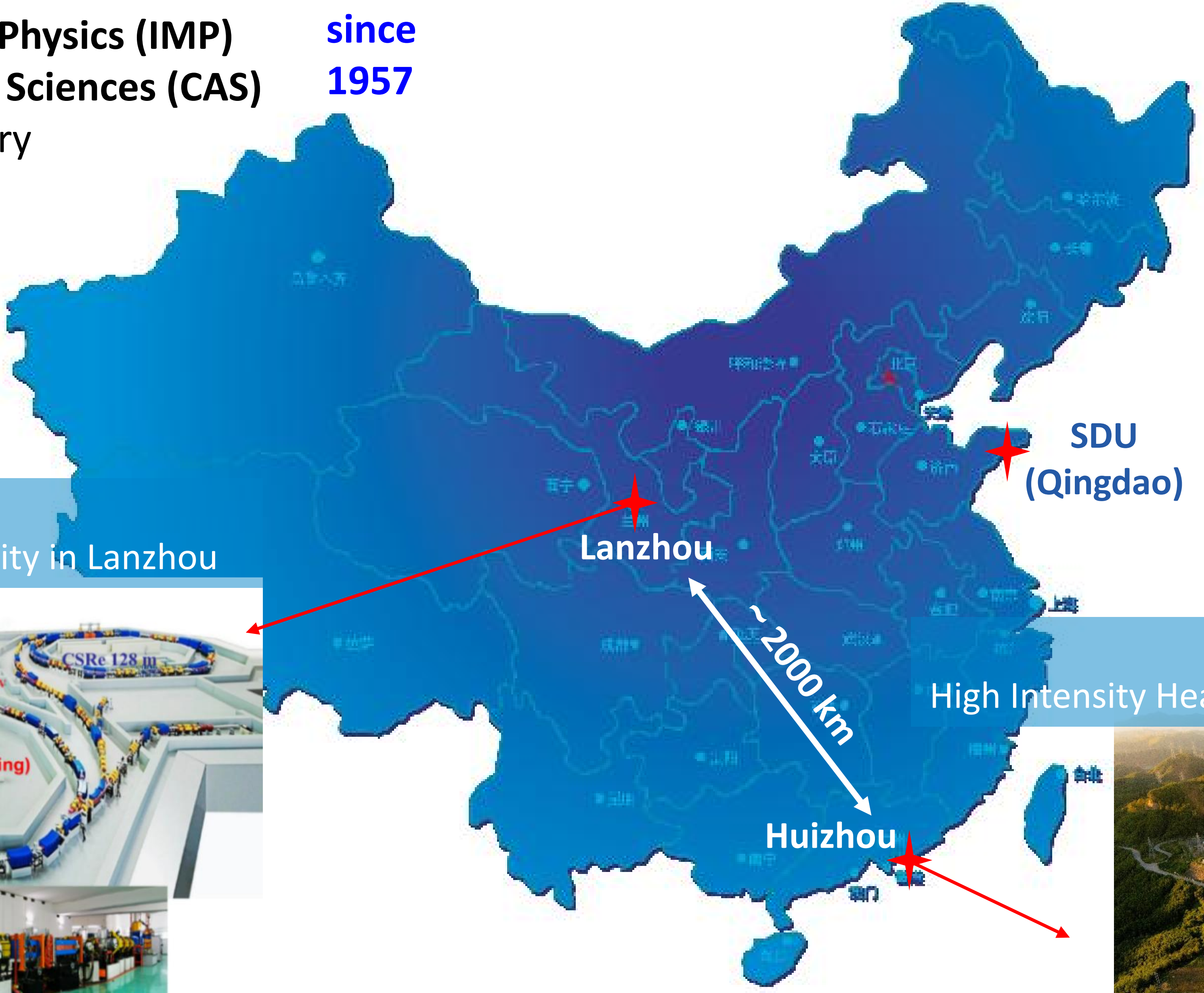
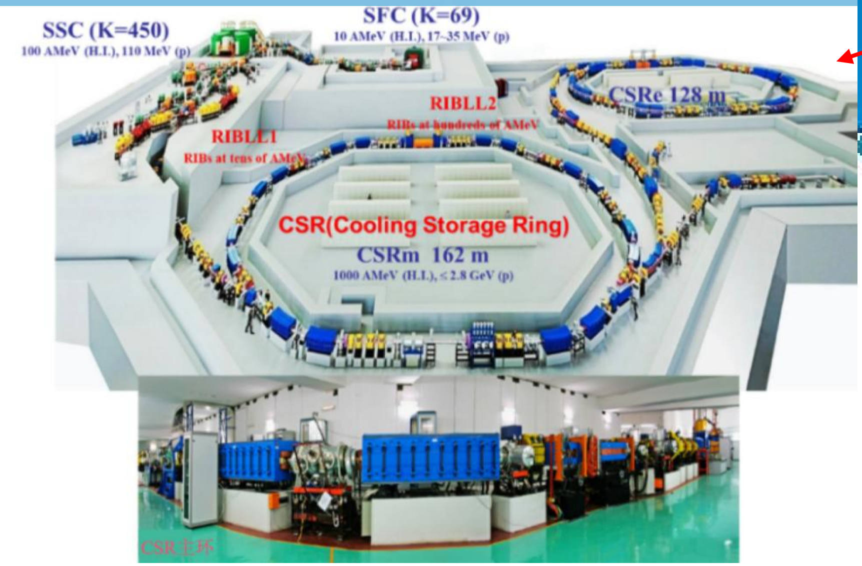
Introduction

Institute of Modern Physics (IMP)
Chinese Academy of Sciences (CAS) **since 1957**

- ➢ National Laboratory
- ➢ Two campuses
    - Lanzhou
    - Huizhou

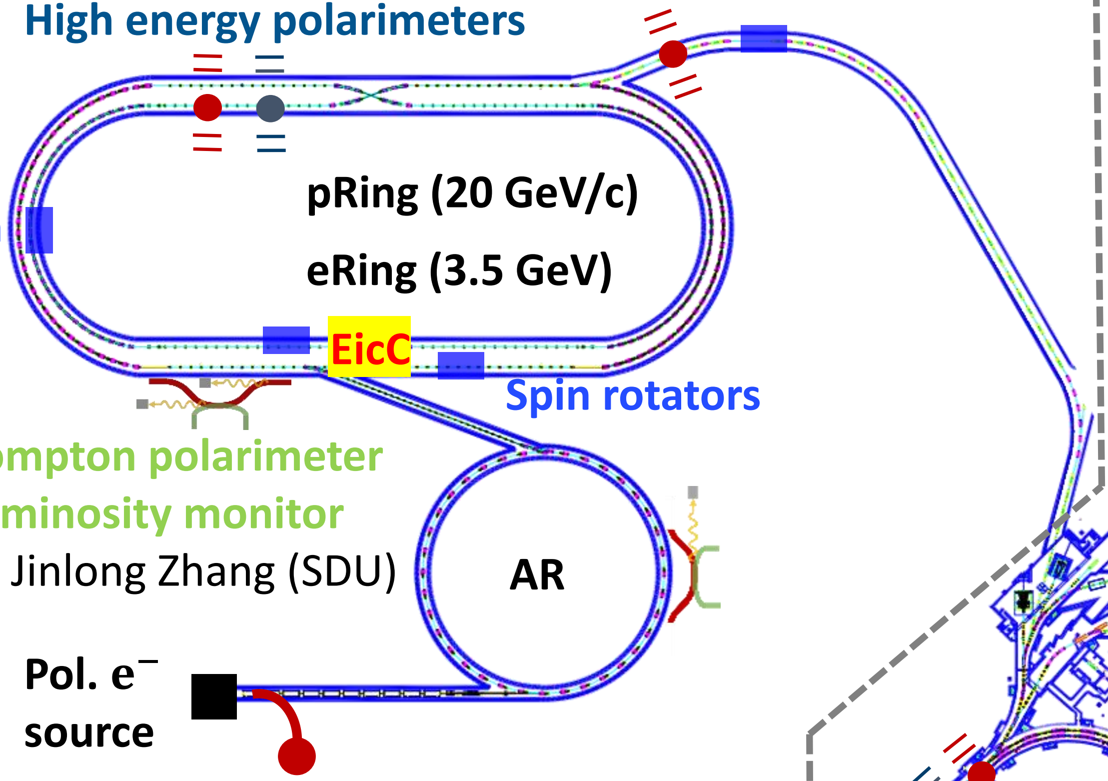


HIRFL
Heavy Ion Research Facility in Lanzhou



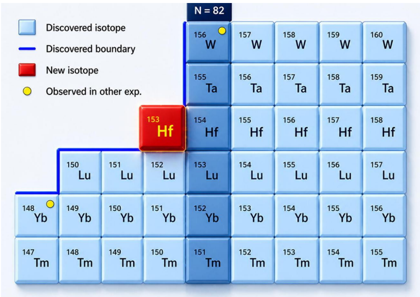
HIAF
High Intensity Heavy-ion Accelerator Facility

HIAF-EicC



High Intensity Heavy-ion Accelerator Facility (HIAF)

- ✓ first beam (October 28, 2025)
- ✓ first physics result (August 15, 2026)



talk by Jinlong Zhang (Tuesday, morning)

Electron ion collider in China (EicC)

- currently being proposed
- initial driving force of polarized beam development at IMP

Efforts towards polarized beams/targets at HIAF

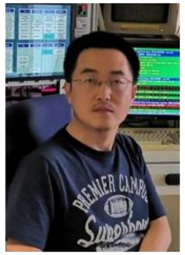
- A team for **polarized ion source**, **polarized beam acceleration** and **polarized target**
- International collaborations

team leader

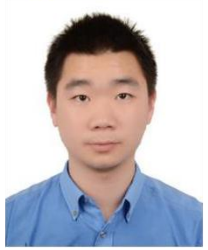
pol. 3He

engineering
vacuum

pol. H/D source

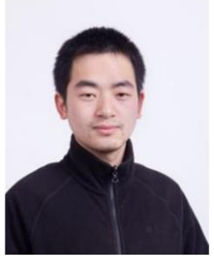


polarimeter
pol. H target



pol. ion source
pol. H target

magnet

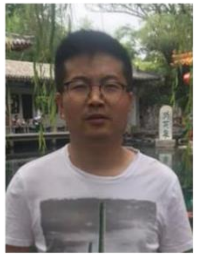


beam diagnostic

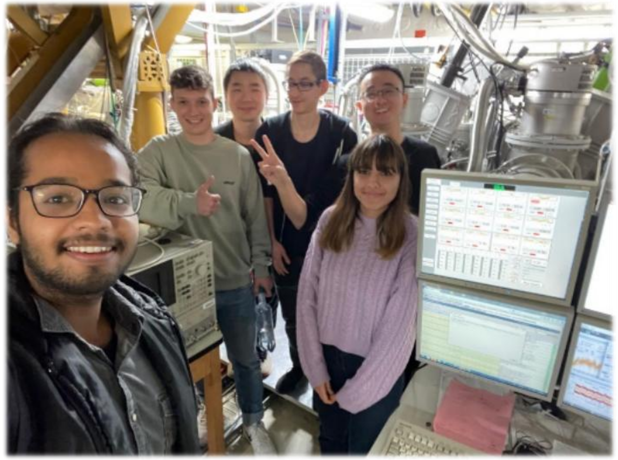
polarimeter
pol. H target

pol. beam acc.
spin manipulation

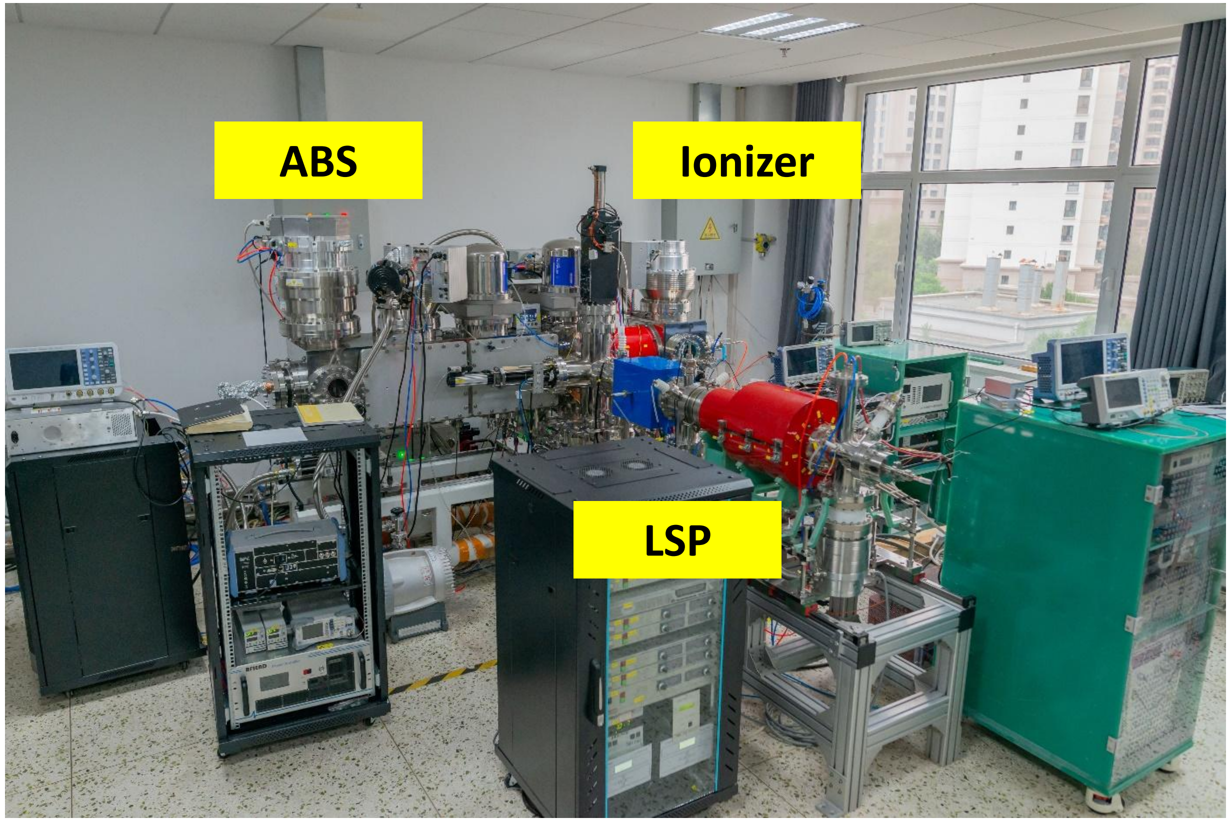
ionizer
Lamb-Shift
polarimeter



control system



Efforts towards polarized beams/targets at HIAF



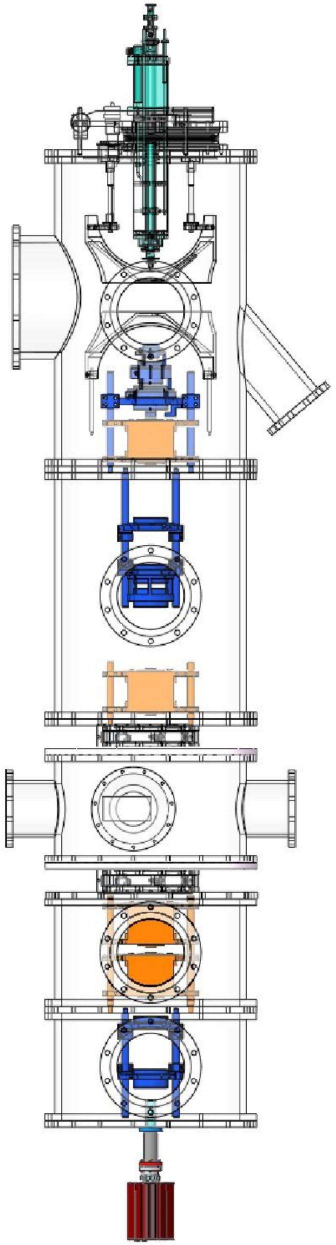
A polarized H^+/D^+ source already built at IMP

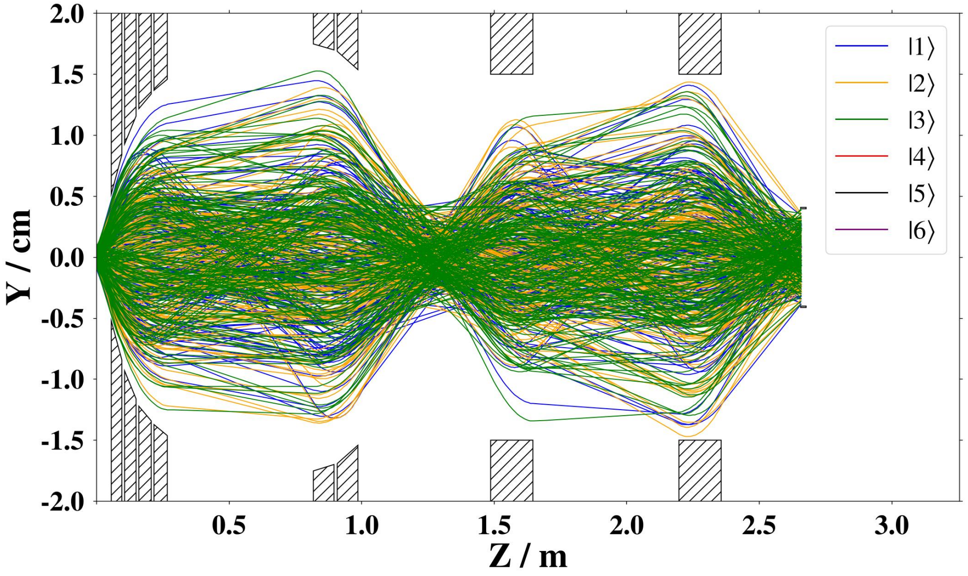
- **Intensity: > 1 mA**
- **Polarization: > 80%**
- **Repetition frequency: 2-5 Hz**
- **Pulse width: > 100 us**

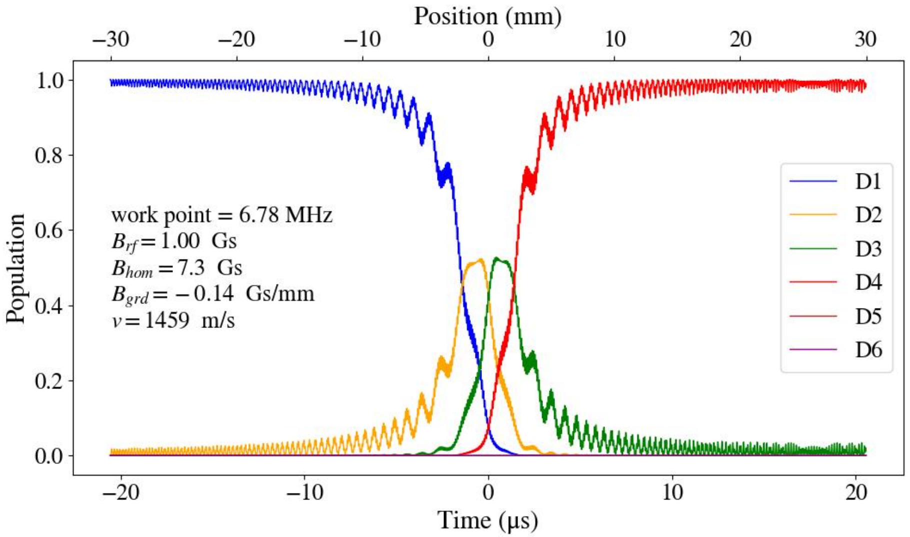
Polarized beam acceleration at HIAF investigated by Minxiang Li et al.

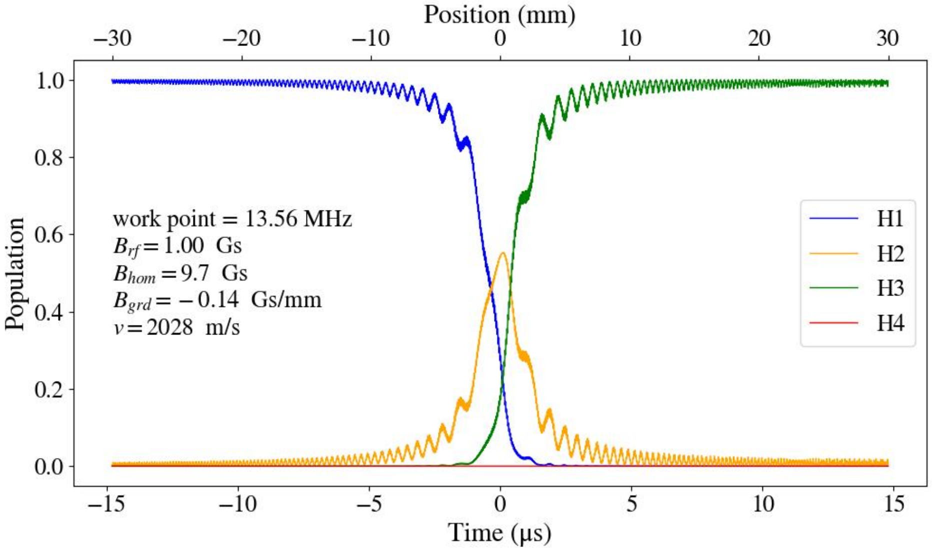
- constant field solenoid Siberian snake: NIMA 1031, 166405 (2022)
- tensor-polarized deuteron beam: Phys. Rev. Accel. Beams 28, 094002

PIT design in progress







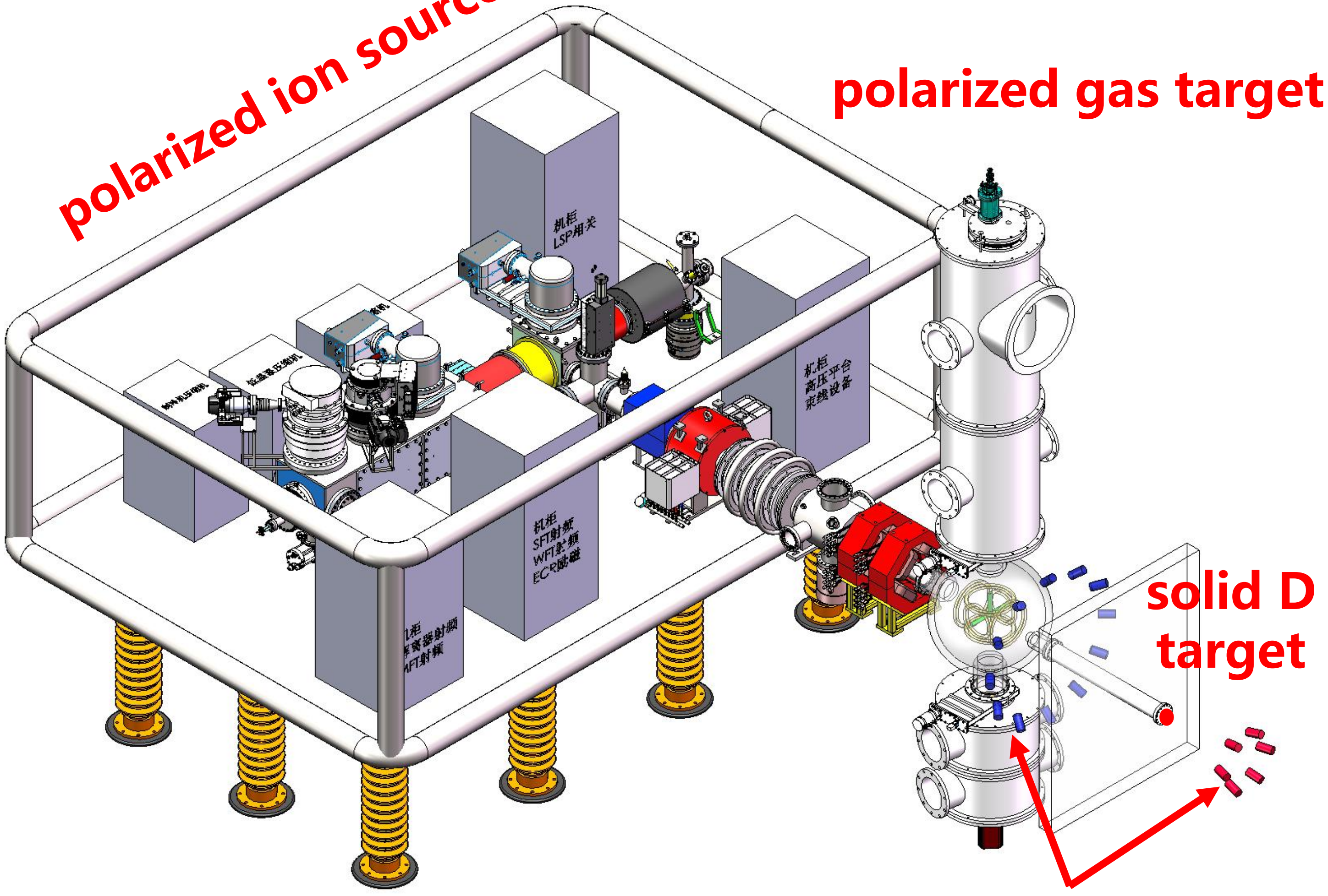


PIT design in progress

- ✓ Atomic tracking
- ✓ Zeeman transition
- ☐ Mechanical design being optimized

The DOPPLER project

Double Spin-polarized DD Fusion Research at IMP



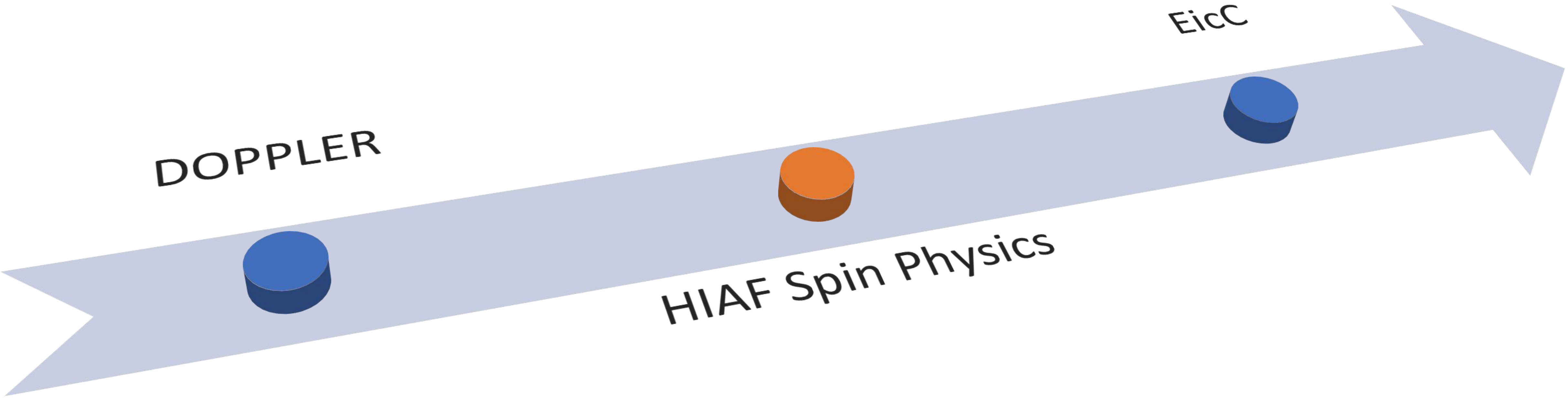
IMP, CAS
Pol. ion source: $\vec{D}^{+}$(10~225 keV)
Pol. gas target: $\vec{D}$ (~1500 m/s)

Lanzhou Uni.
Solid deuterium target
Neutron detector

Goal:
Data for DD polarized fusion
Oriented neutron source
Polarized neutron source

Funded by CAS

Roadmap



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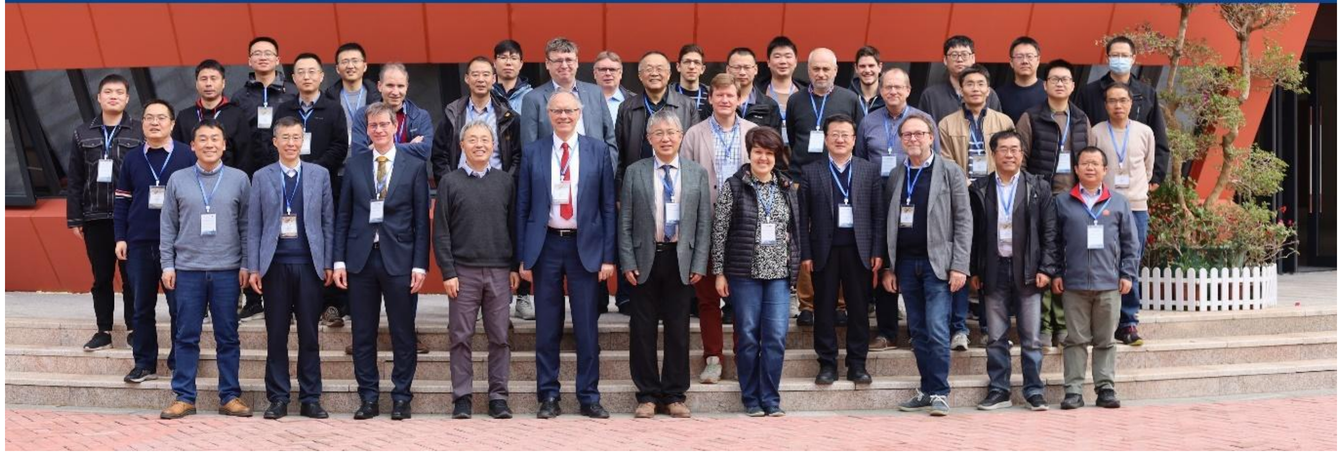
Spin physics at HIAF

- **PBT workshops (2024, 2026)**
- **Productive discussions about spin physics at HIAF**
- **Nice physics identified**
- **Welcome to the next PBT workshop**

The 1st Workshop on Polarized Beam and Target - Physics and Applications (PBT2024)

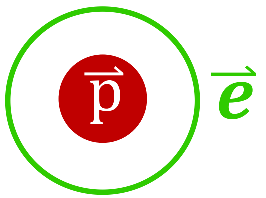


The 2nd Workshop on Polarized Beam and Target - Physics and Applications (PBT2026)

Spin physics at HIAF

Highlights

- Polarized gas target used as both proton target and electron target



- Spin degree of freedom in atomic/nuclear physics
- Beyond SM physics

target	beam	physics and observables
$\vec{e}$	charged ion beam	spin dependence of REC $Z^{Q+} + \vec{e}^- \rightarrow Z^{(Q-1)+} + \hbar\omega$
	p	$A_\perp$ in $p\vec{e} \rightarrow pe$ proton EM radii, new boson search
$\vec{p}$	p, d, A $\vec{p}$, $\vec{d}$	A_N, A_{NN} in $p\vec{p}$, $A\vec{p}$, $\vec{p}\vec{p}$, $\vec{n}\vec{p}$ ... NN interaction, NA spin dynamics
heavy-ion target (A)	$\vec{d}$	isovector force induced $\vec{d}$ rotation
$\vec{d}$	radioactive beams (A)	in $\vec{d}A \rightarrow pnA$ symmetry energy in EOS
	$\vec{p}$	$A_{y,xz}(0)$ in $\vec{p}\vec{d} \rightarrow pd$ time-reversal symmetry test

Atomic physics

New boson search

bread-and-butter physics

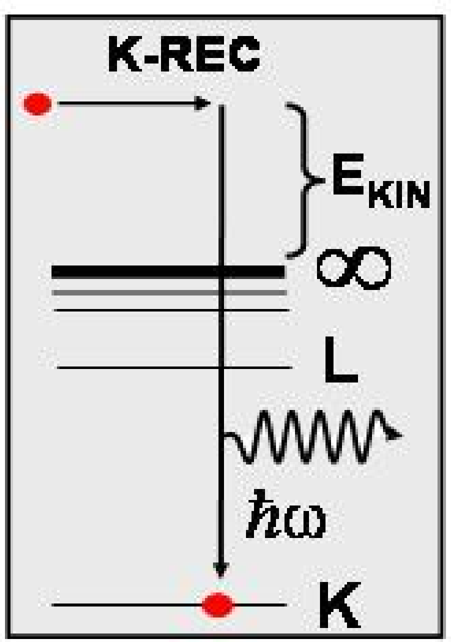
Nuclear physics

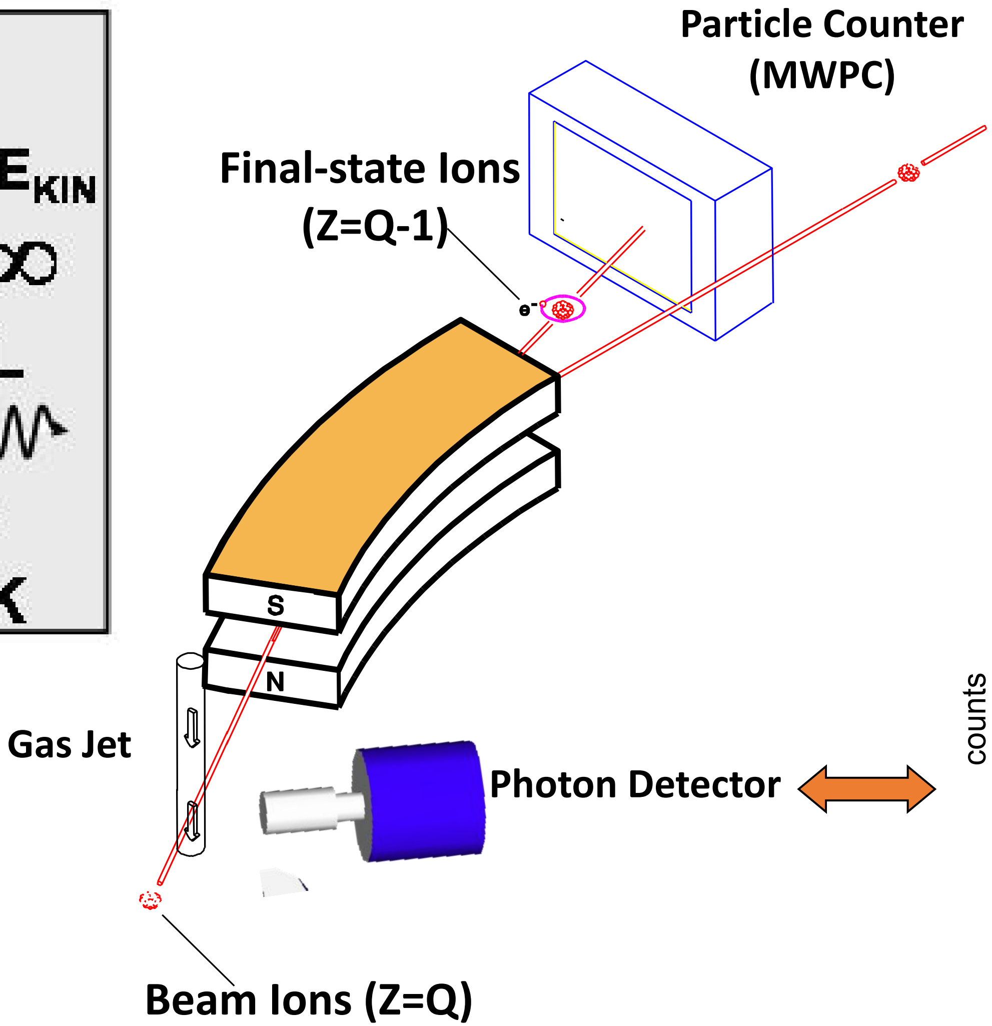
Fundamental symmetry

Polarized e^{-} capture

REC with pol. e target

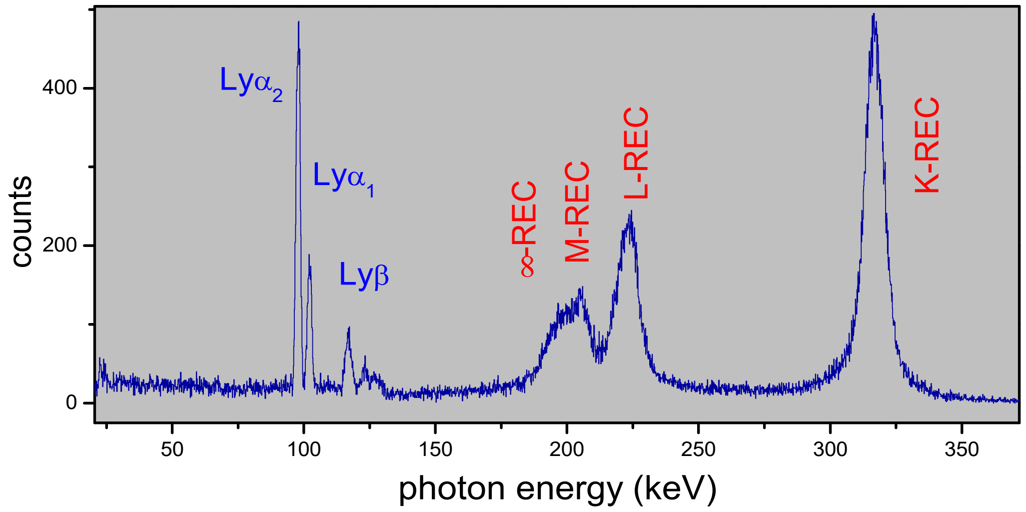
- Radiative electron capture (REC): $Z^{Q+} + e^- \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$





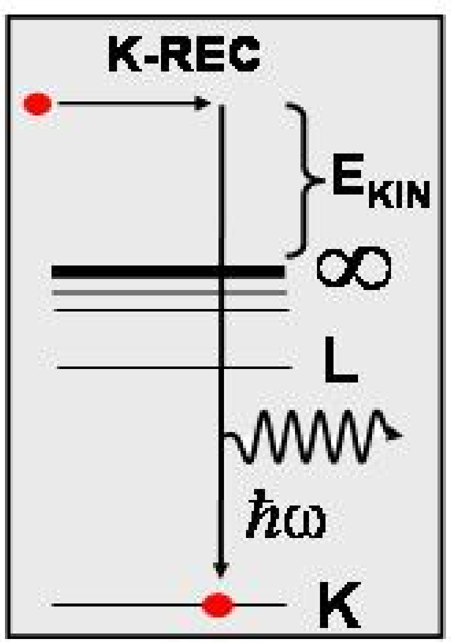
courtesy of Prof. Thomas Stöhlker and Dr. Anna Mayorova

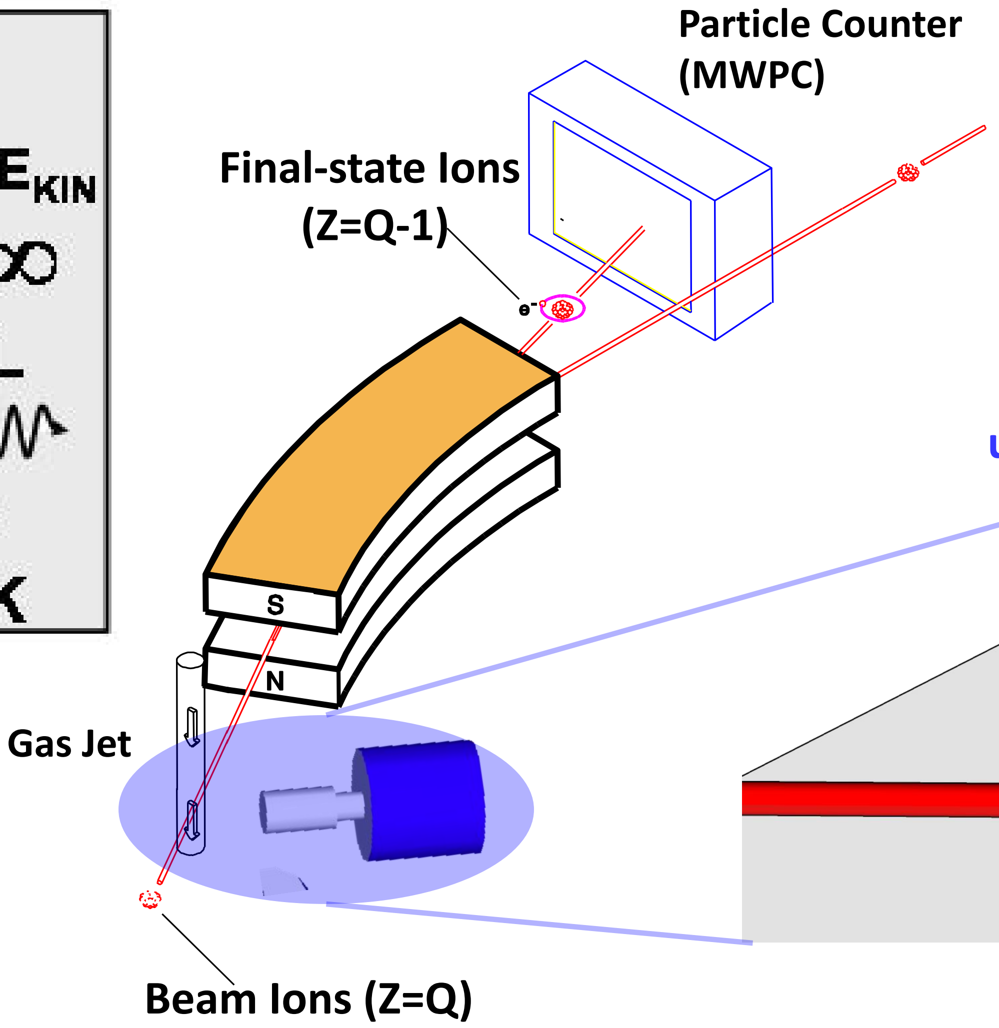
$U^{92+} + N_2$ @ 295 MeV/u

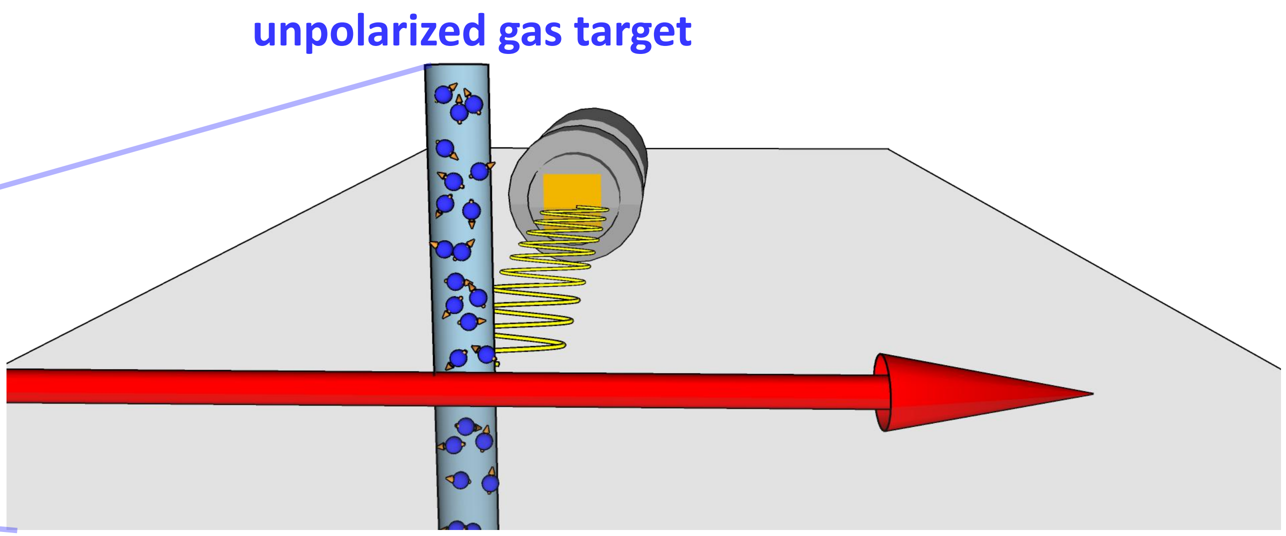


REC with pol. e target

- Radiative electron capture (REC): $Z^{Q+} + e^{-} \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$
- **Sensitive to ion and electron spin states**







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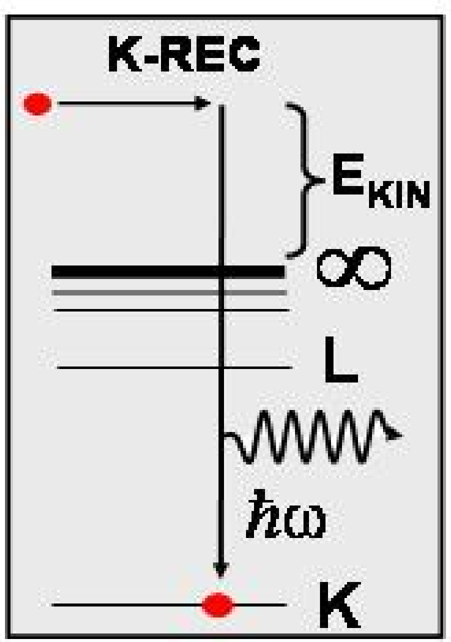

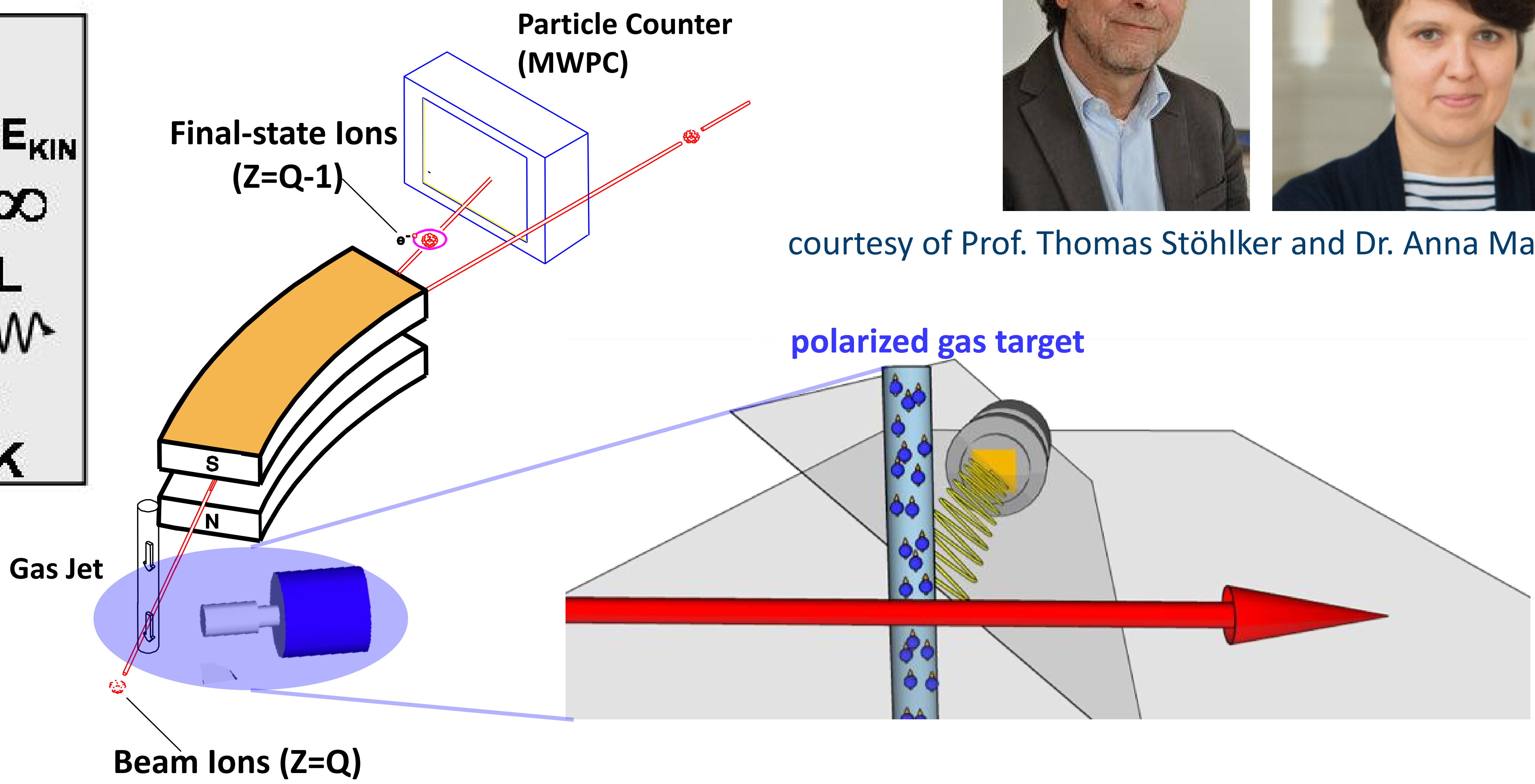

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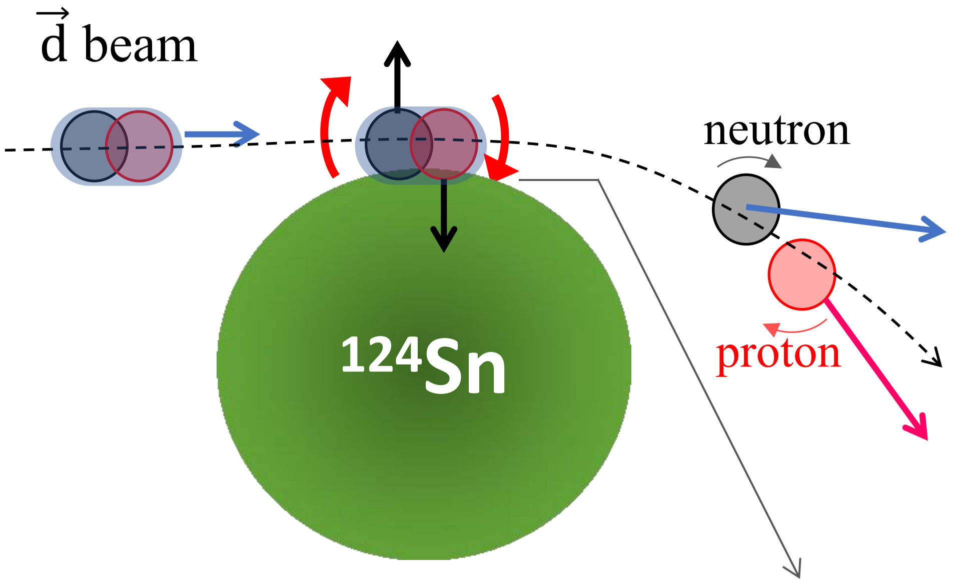
EoS and isovector force

EoS study with pol. d beam



Due to the difference of nuclear forces neutron and proton experiences, **extra rotation** occurs !

Isovector force

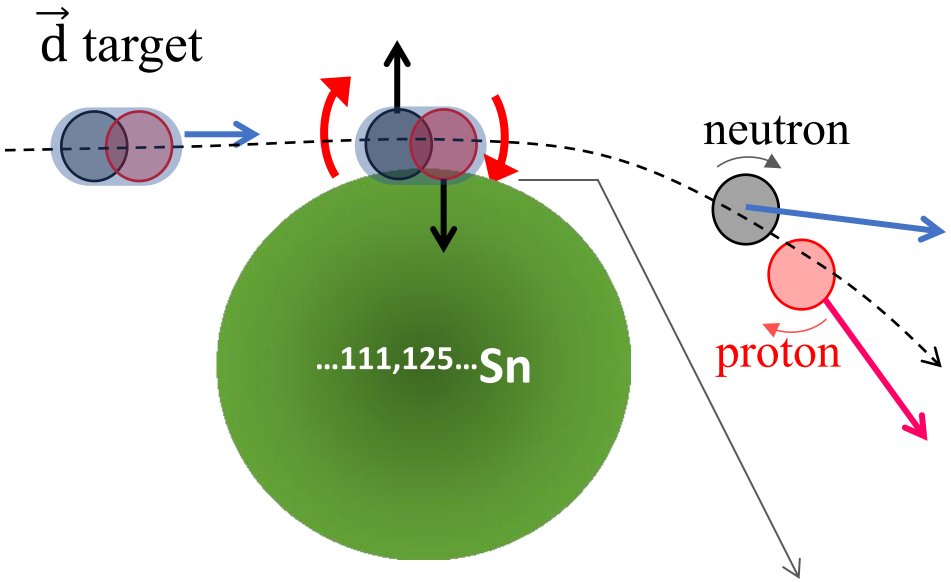
- $F_v \propto \delta^2 \frac{dE_{sym}}{d\rho} \frac{d\rho}{dr} \quad \left(\delta = \frac{\rho_n - \rho_p}{\rho}\right)$
- Attractive to p, repulsive to n
- Comparable with Coulomb force

courtesy of Prof. Zhigang Xiao

PRL 115, 212501 (2015); **PRC 101**, 024603 (2020)

- Coulomb force: leads to *Coulomb polarization* (Oppenheimer et al., 1935)
- Isovector force: leads to *isovector reorientation* **(IVR)**

EoS study with pol. d beam



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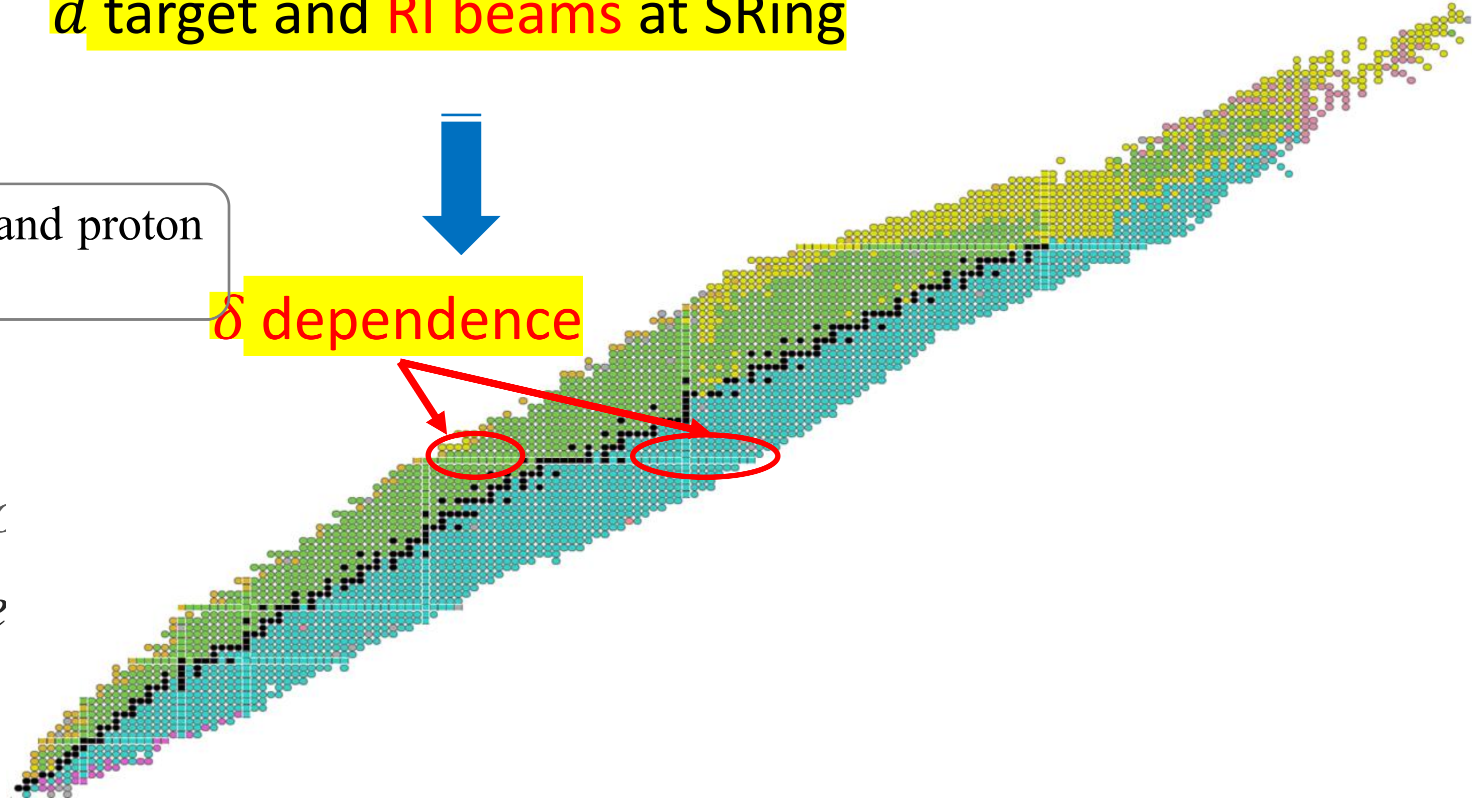
$\vec{d}$ target and RI beams at SRing



PRL **115**, 212501 (2015); **PRC 101**, 024603 (2020)

- Coulomb force: leads to *Coulomb pc*
- Isovector force: leads to *isovector re*

New boson search

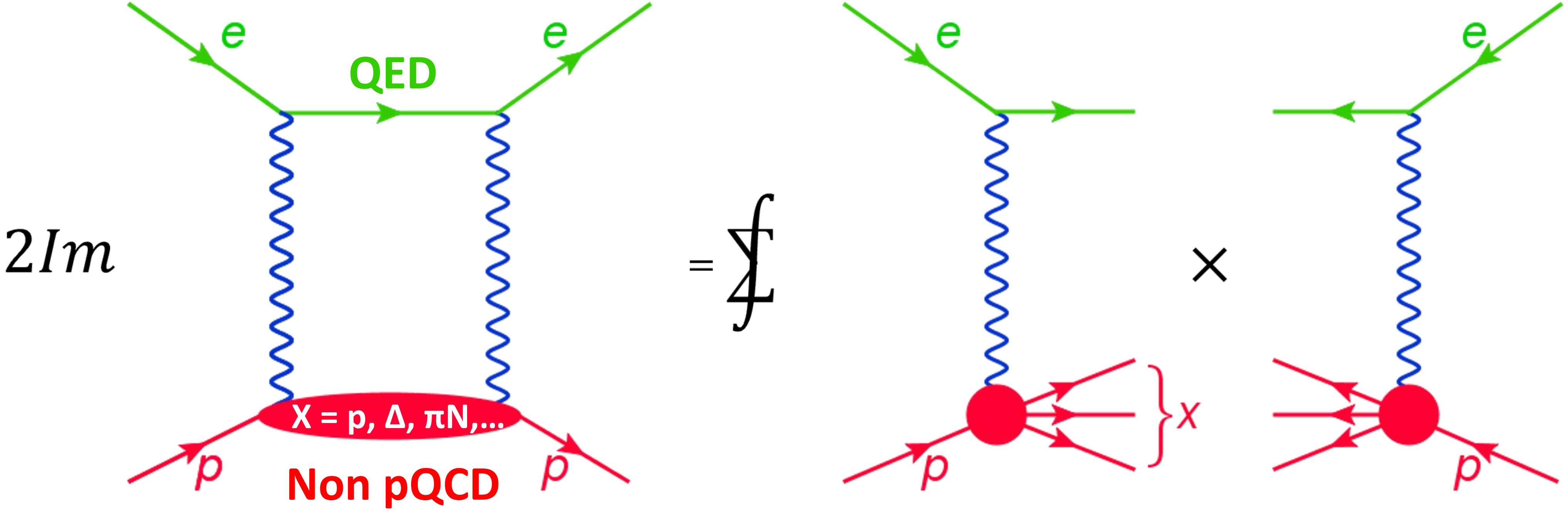
T-odd effects with transverse spin asymmetry

- transverse single spin asymmetry ($A_\perp$) is a T-odd observable

- arises from two-photon exchange in electron elastic scattering

$$A_\perp \propto \frac{Im\left(\mathcal{M}_\gamma^* \mathcal{M}_{2\gamma}\right)}{\left|\mathcal{M}_\gamma\right|^2} \sim \alpha_{EM} \sim 10^{-2}$$

Nucl. Phys. B 35 (1971) 365.



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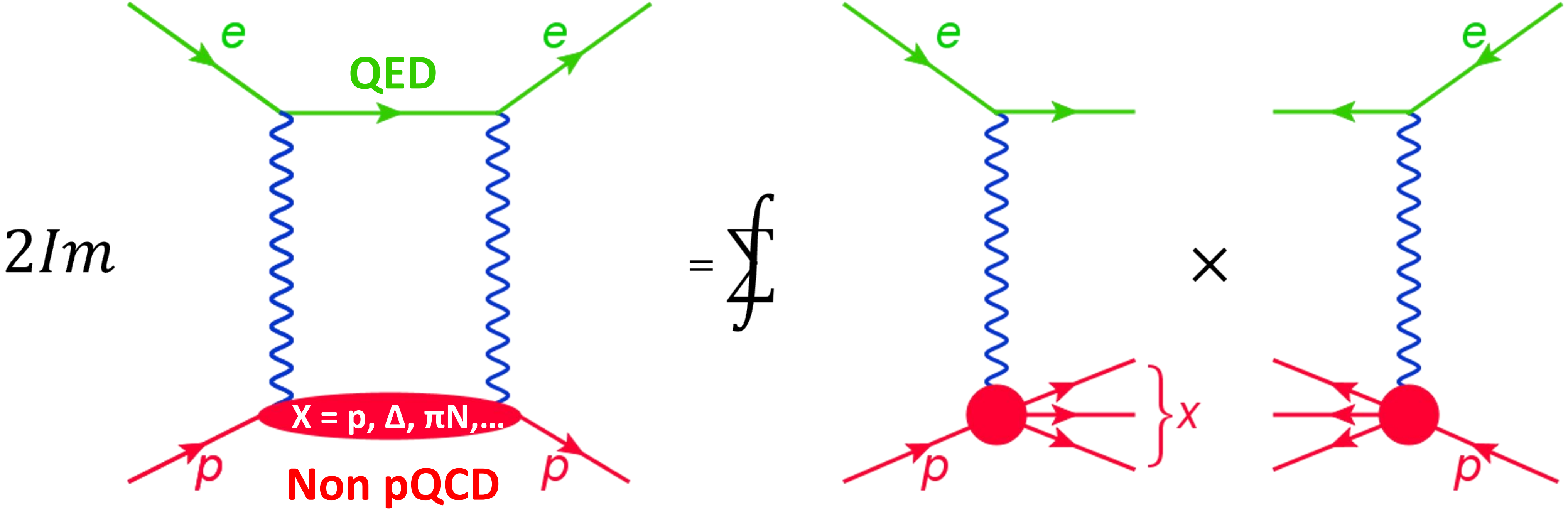
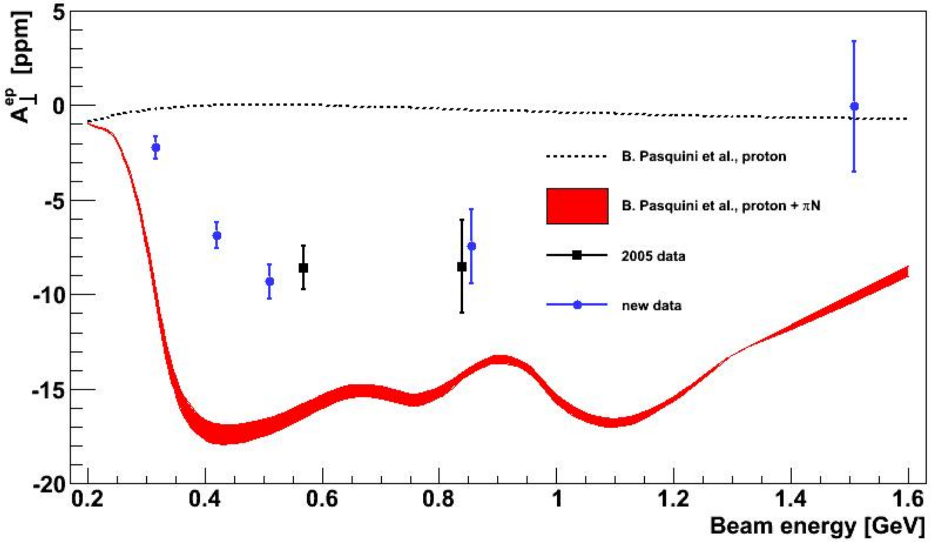
Nucl. Phys. B 35 (1971) 365.

Relativistic suppression ($1/\gamma$) for transversely pol. beam $\longrightarrow$ 10^{-6}

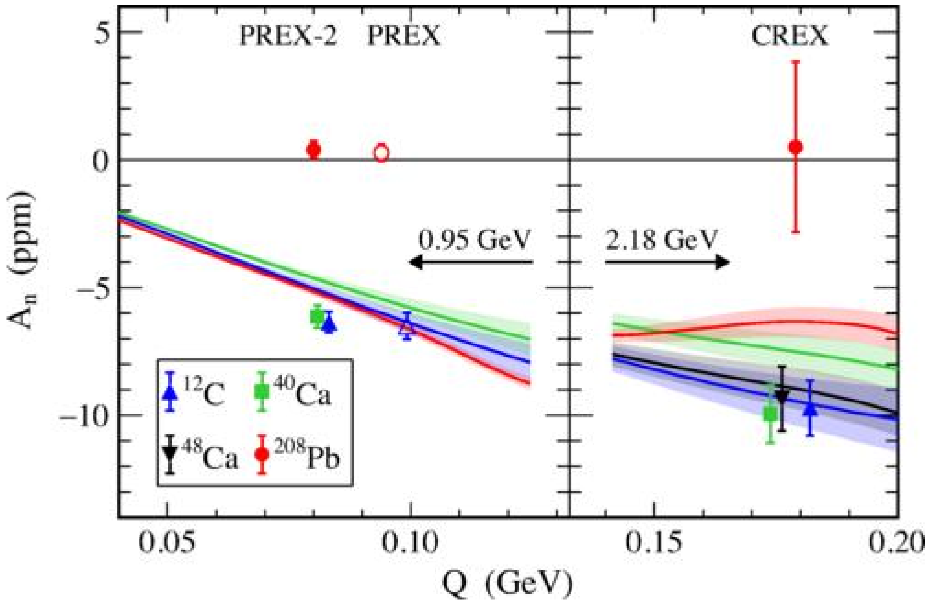


Exp. data vs calculation ($A_{\perp}^{\vec{e}p}$)

- surprising discrepancies between theory and exp. data
- observed at different laboratories
- not only in $\vec{e}p$, but also in $\vec{e}A$

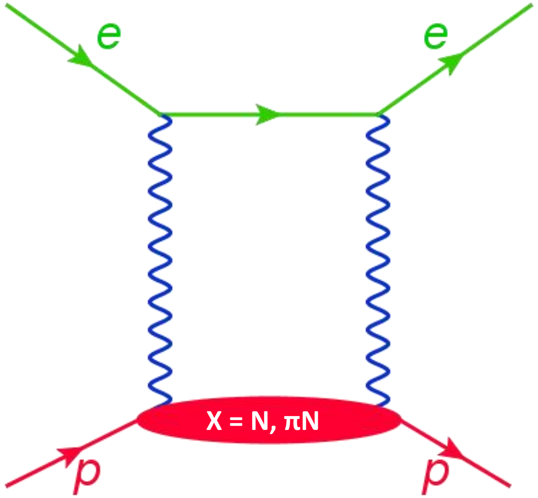


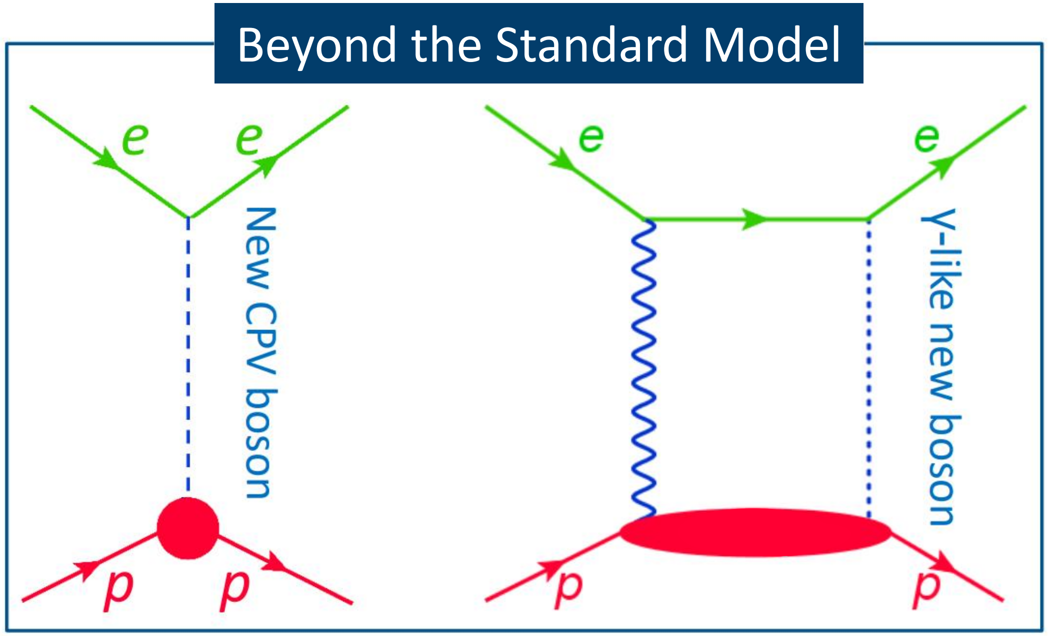
A4 @ MAMI
Phy. Rev. Lett. 124, 122003 (2020)
Phy. Rev. Lett. 94, 082001 (2005)



PREX, PREXII, CREX @ JLab
Phy. Rev. Lett. 109, 192501(2012)
Phy. Rev. Lett. 128, 142501(2022)

How to understand the surprise





- More intermedite state?

- MAID database and CLAS data need improvement?

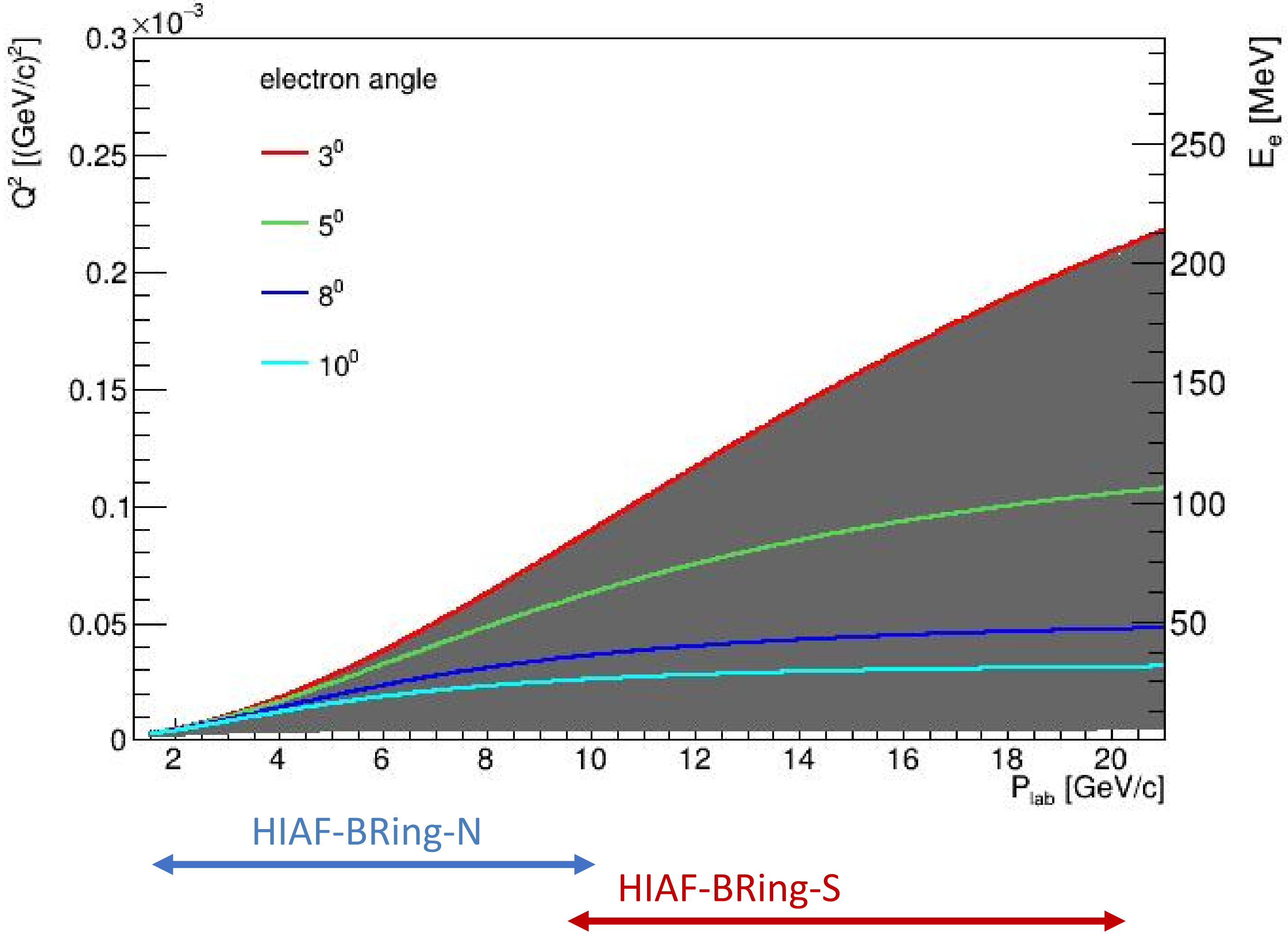
- **New unknown boson?**

➢ Hard to test new-physics hypothesis in $\vec{e}\mathrm{p} \to \mathrm{ep}$
  - Possible intermediates: X = N, πN … → **Non-pQCD uncertainty**
  - Lorentz effect with transverse $\vec{e}$ beam → $A_{\perp} \propto \frac{m_e}{E} \sim 10^{-6}$ **(tiny signal)**

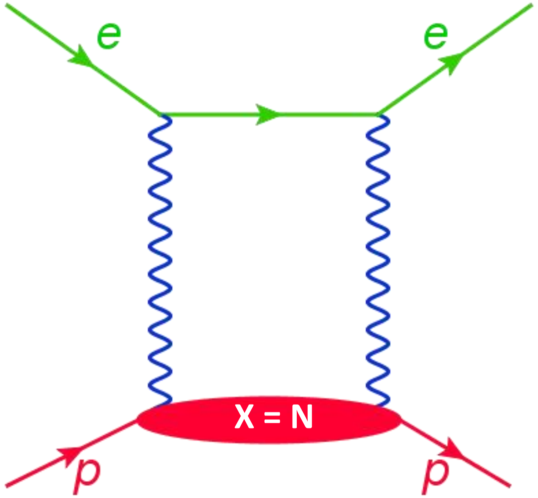
New idea: $p\vec{e} \to pe$?

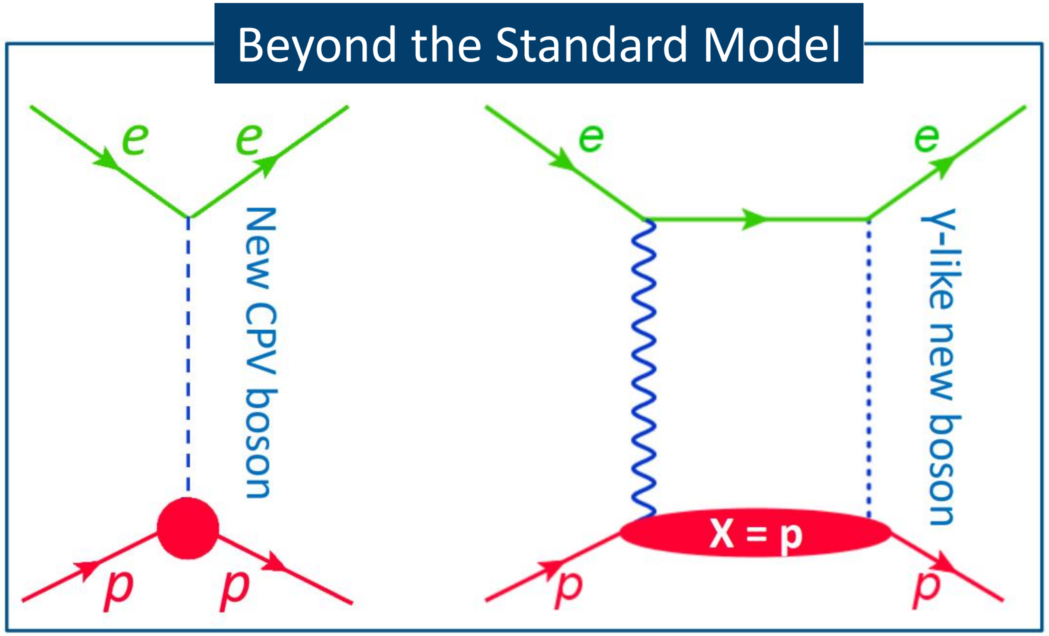
With proton beam and electron target, ultra low $Q_2 (< 1 \times 10^{-5})$ accessed in pe scattering

Reminder: Q_2 in ep scattering ($10^{-2} \sim 10^{-1}$)



Transverse spin asymmetry: p$\vec{e}$ vs $\vec{e}$p





- **New unknown boson?**

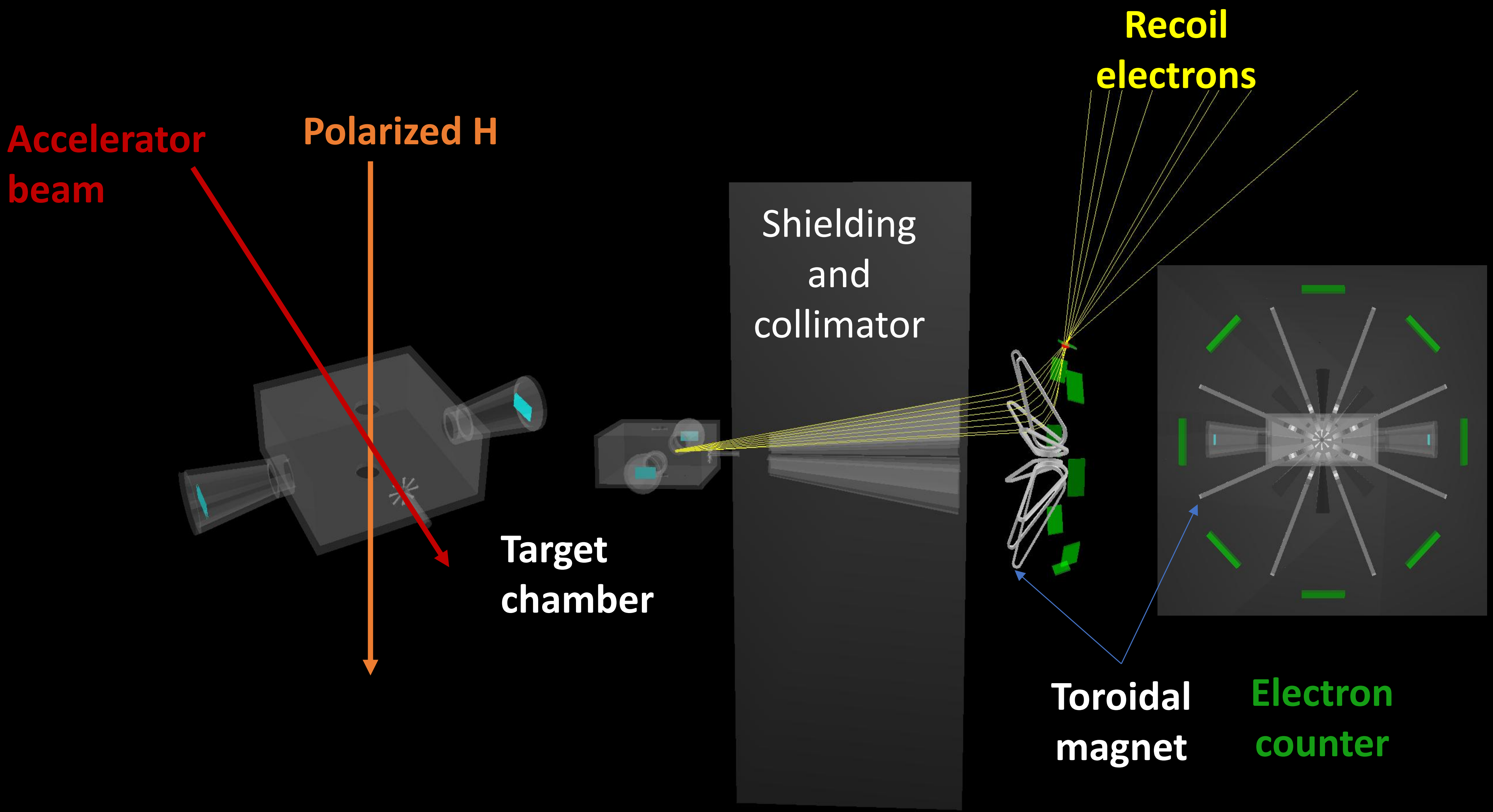
➢ In $\vec{e}$p → ep

- possible intermediates: X = N, πN ... → **Non-pQCD uncertainty**
- Lorentz effect wit transverse $\vec{e}$ beam → $A_\perp \propto \frac{m_e}{E} \sim 10^{-6}$ **(tiny signal)**

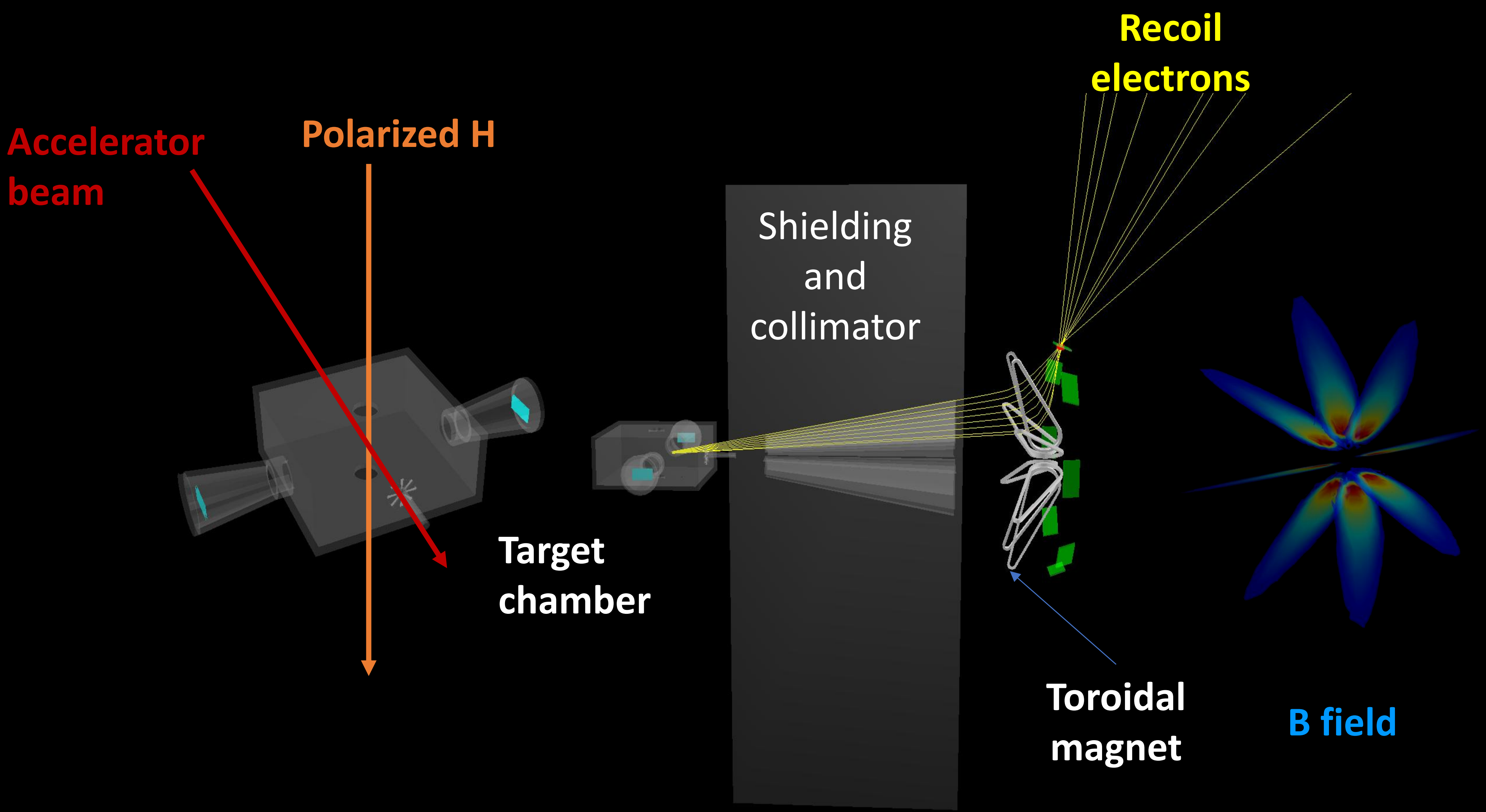
➢ In p$\vec{e}$ → pe (very-low $\mathbf{Q_2}$)

- X = N → $A_\perp$ calculated with **G_E and G_M (no theoretical uncertainty)**
- No Lorentz effect → $A_\perp$ increases by 3 orders

Detection system

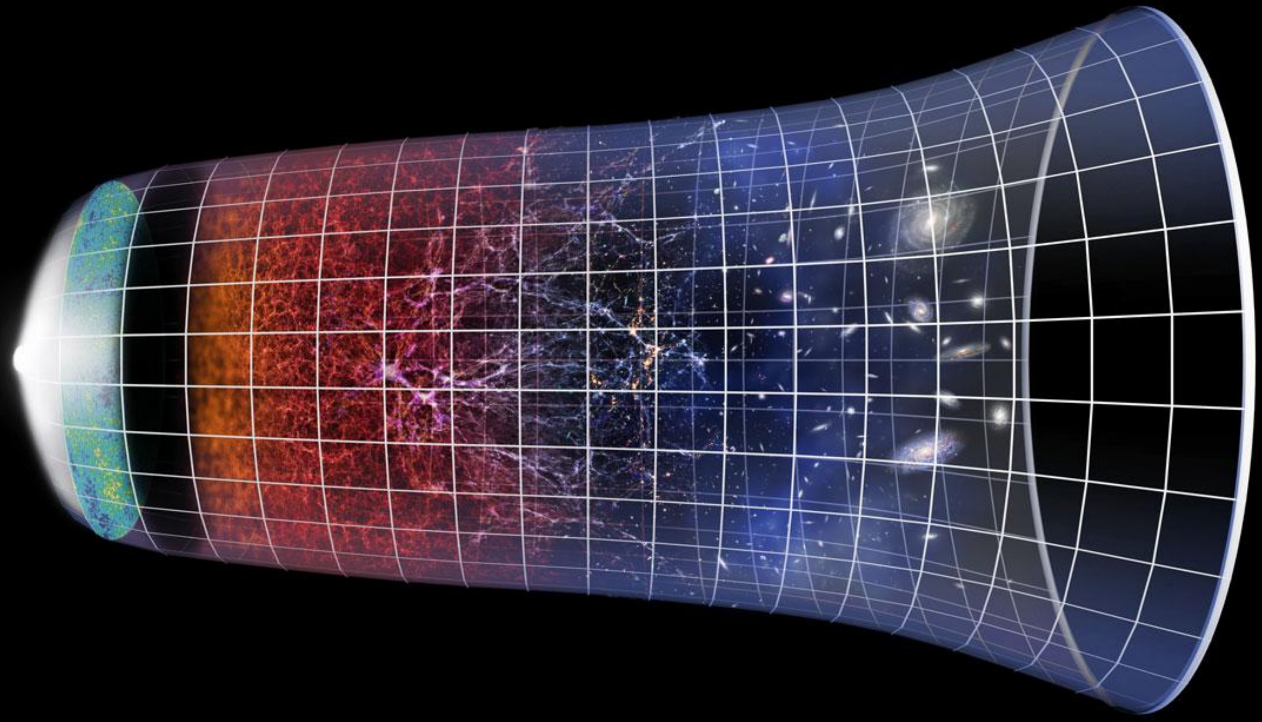


Detection system



Test of time-reversal symmetry

Why time-reversal asymmetry?



Big Bang → ~~CP~~ → Today

Excess of mater in the universe

Observation

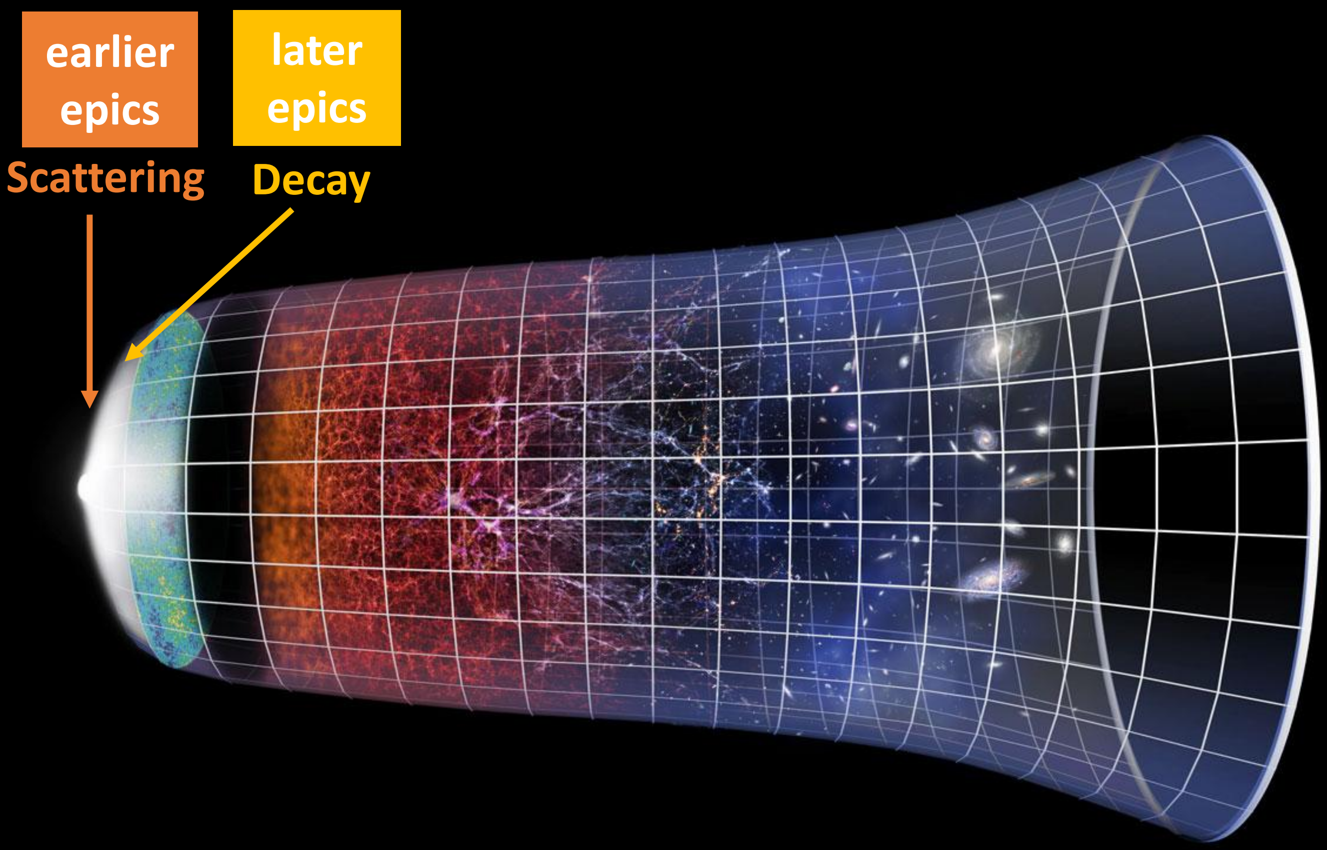
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

SM predication $\sim 10^{-18}$

New sources of CP violation must exist

$CP \xleftrightarrow{CPT} T$

Why time-reversal asymmetry?



Big Bang → $\cancel{CP}$ → Today

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$$CP \xleftrightarrow{CPT} T$$

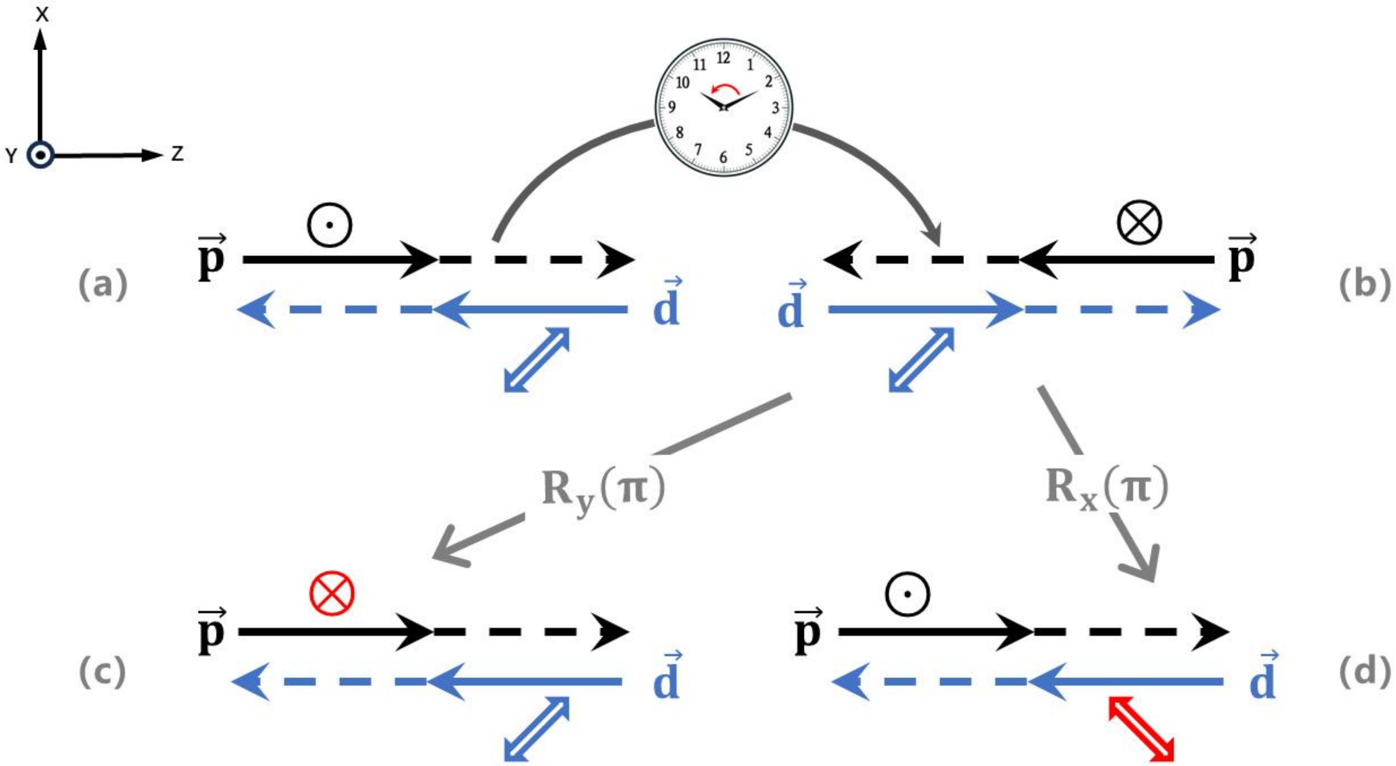
Test time-reversal symmetry with $\vec{p}\,\vec{d}$ scattering

What is time reversal?

- Flip momentum and spin for all particles
- Exchange initial and final states

Test time-reversal symmetry with $\vec{p}\,\vec{d}$ scattering

Parity conserving (unlike EDM)
Time-reversal violating



What is time reversal?

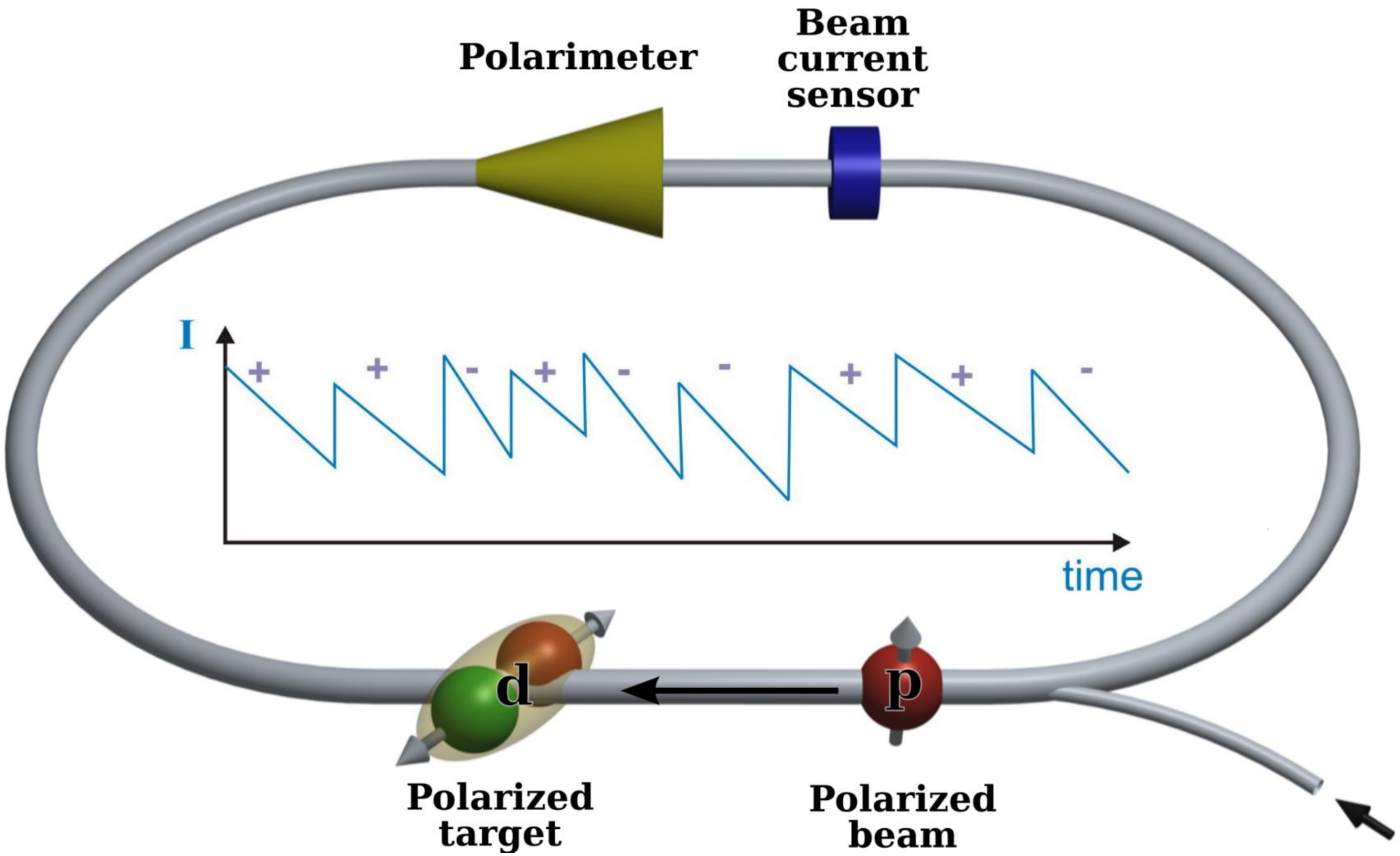
- Flip momentum and spin for all particles
- Exchange initial and final states
- Equivalent to spin flip (at forward scattering/$\theta = 0^{\circ}$)
- Optical theorem

$$\frac{4\pi}{k} Im\, F^{el}(0^{\circ}) = \sigma_{total}$$

$$\sigma^{\uparrow}_{total} = \bar{\sigma}_{total}(1 + P_Y \cdot P_{XZ} \cdot \mathrm{A}_{Y,XZ})$$

$$\sigma^{\downarrow}_{total} = \bar{\sigma}_{total}(1 - P_Y \cdot P_{XZ} \cdot \mathrm{A}_{Y,XZ})$$

What do we need

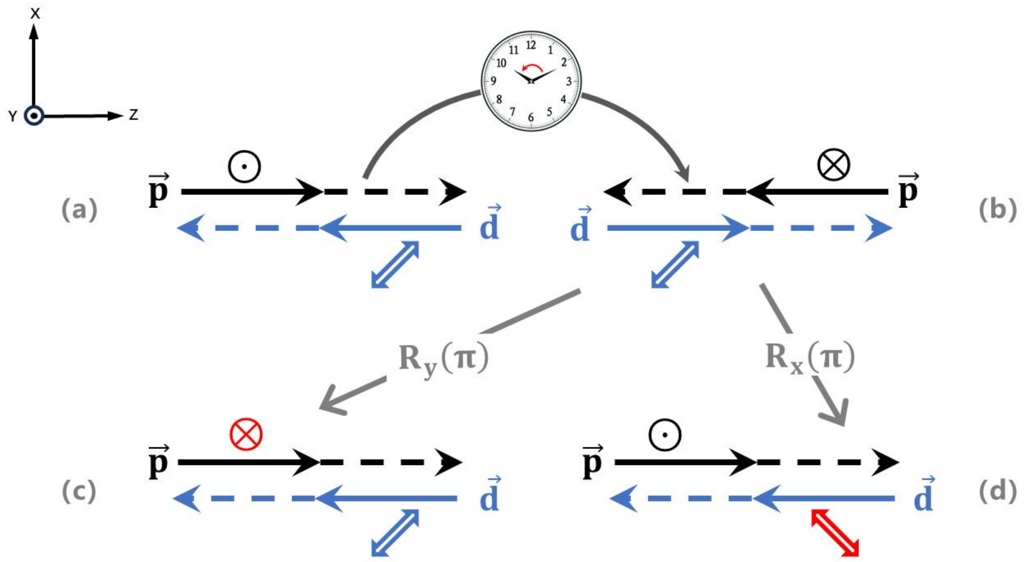


plot adopted from PAX and TRIC publications

$$\sigma_{total}^{\uparrow\downarrow} = \bar{\sigma}_{total}(1 \pm P_Y \cdot P_{XZ} \cdot A_{Y,XZ})$$

- **polarized proton -> P_Y**
- **polarized deuteron -> P_{XZ}**
- **beam current monitor -> $\sigma_{total}^{\uparrow\downarrow}$**

Test of time-reversal symmetry



Proposed since early 1990s

H. E. Conzett. Null tests of time-reversal invariance. Phys. Rev. C 48, 423 (1993)

https://tric-experiment.hiskp.uni-bonn.de/

https://www.fz-juelich.de/en/ikp/ikp-2/research/previous-list/tric

P. Lenisa et al. EPJ Tech. Instr. (2019) 6

Challenges

- ✓ **Signal asymmetry ($A_{y,xz}$)**
- Instrumental background asymmetry: nonperfect beam/target parameters ($\Delta E,\ \Delta X, \Delta X', \Delta I \ldots$)
- Physical background asymmetry: residual vector polarization of deuteron ($P_y \rightarrow A_{y,y}$)

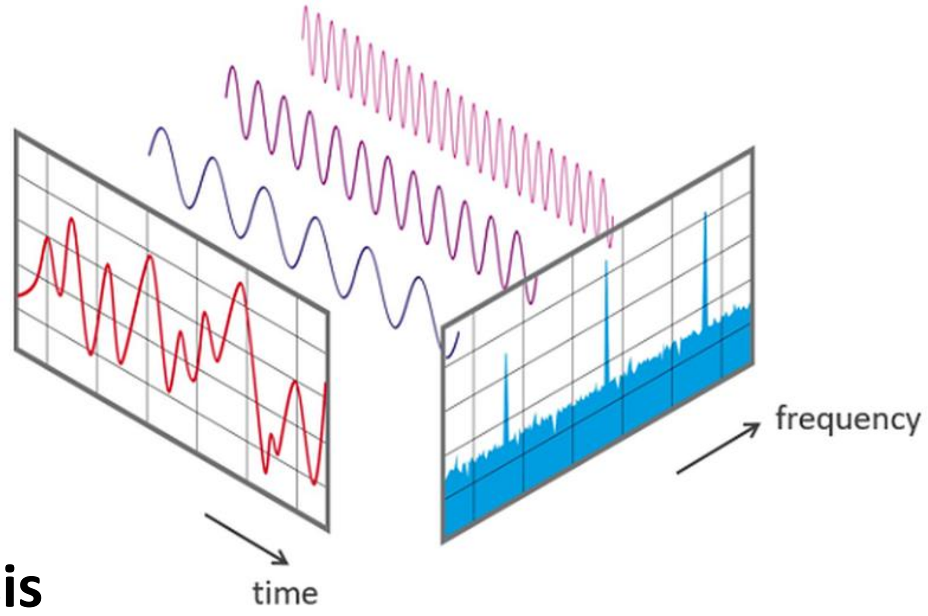
New approach to search for parity-even and parity-odd time-reversal violation beyond the Standard Model in a storage ring

N.N. Nikolaev, F. Rathmann , A.J. Silenko, Yu.N. Uzikov

Phys. Lett. B 811, 135983 (2020)

Main idea

- Conceived in the JEDI collaboration
- **Beam polarization rotates** with an RF solenoid
- Experimental asymmetry oscillates
- False asymmetry easily separated via **Fourier analysis**



Test of time-reversal symmetry

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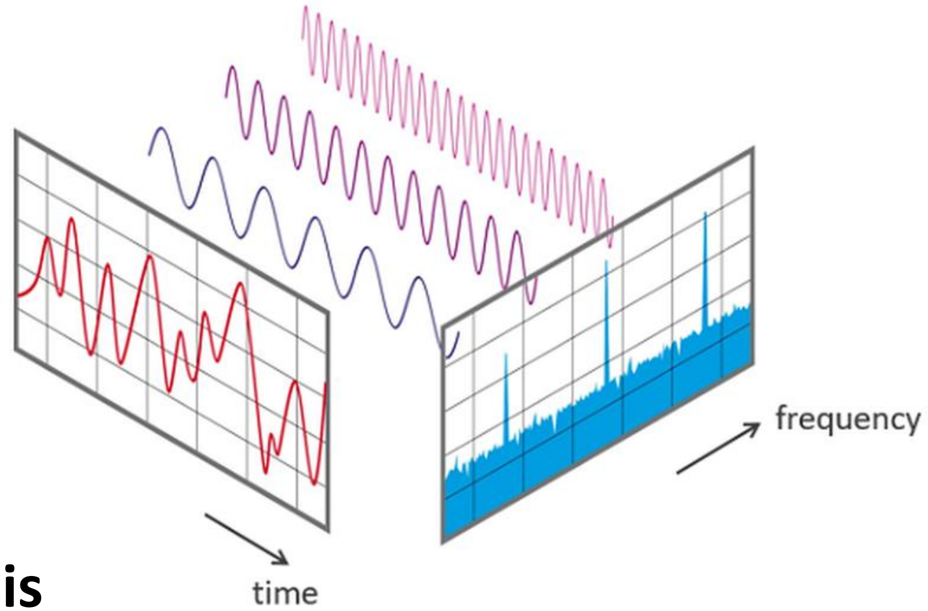

Spin-rotating polarized target?

Spin-rotating target

Spin-rotating polarized target

- Atoms polarized in pol. H/D gas target
- Electron spin aligned with the holding field at interaction point
- Proton/deuteron spin attached to electron spin (HF not too strong)
- Up to now, only static holding fields are used: transverse, longitudinal or superposed
- **How to make a rotating field?**
  - Triple coils driven by 3-phase rf current (proposed in this talk)
  - Static dipole $\vec{B}$ superposed by perpendicular RF $\vec{B}$
    - proposed for NICA
    - private communication with N.N. Nikolaev

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To my great delight, just days after being inspired by their fantastic paper, I was introduced to Prof. Nikolaev, who had been trying to contact the HIAF-SPIN team, when we surprisingly found out that we had similar ideas!!!

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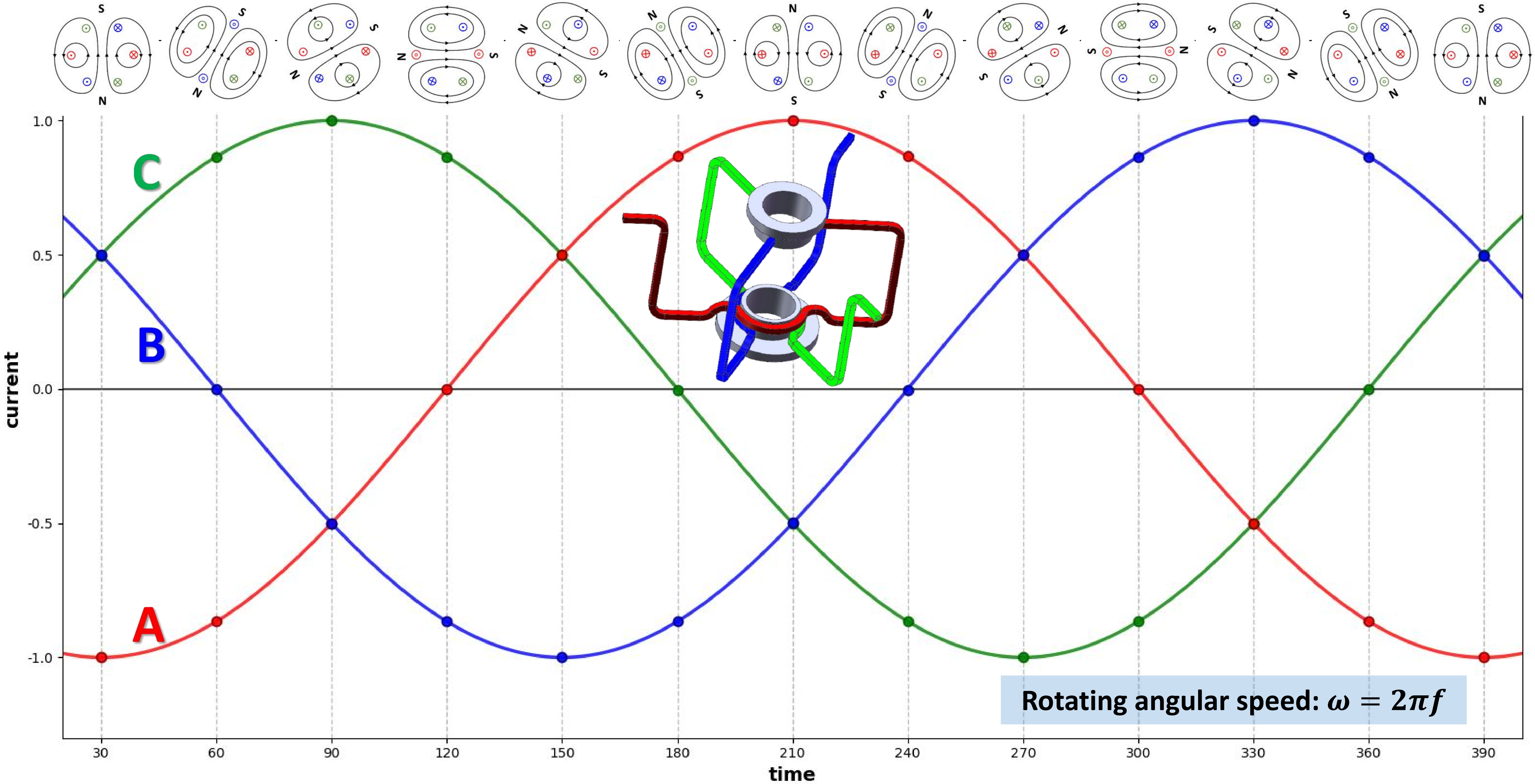
  - B. Gou, ..., N. N. Nikolaev and Yu. N. Uzikov, **Spin physics at HIAF**, in: Proc. of 26th International Symposium on Spin Physics — PoS(SPIN2025), Tsingtao, China, 2025.
  - B. Gou, V. P. Ladygin, N. N. Nikolaev, F. Rathmann, A. J. Silenko, Yu. N. Uzikov, **Fresh Look at Polarized Deuterons at the Nuclotron/NICA & HIAF and Beyond,** Natural Sci. Rev. 3200802 (2026)

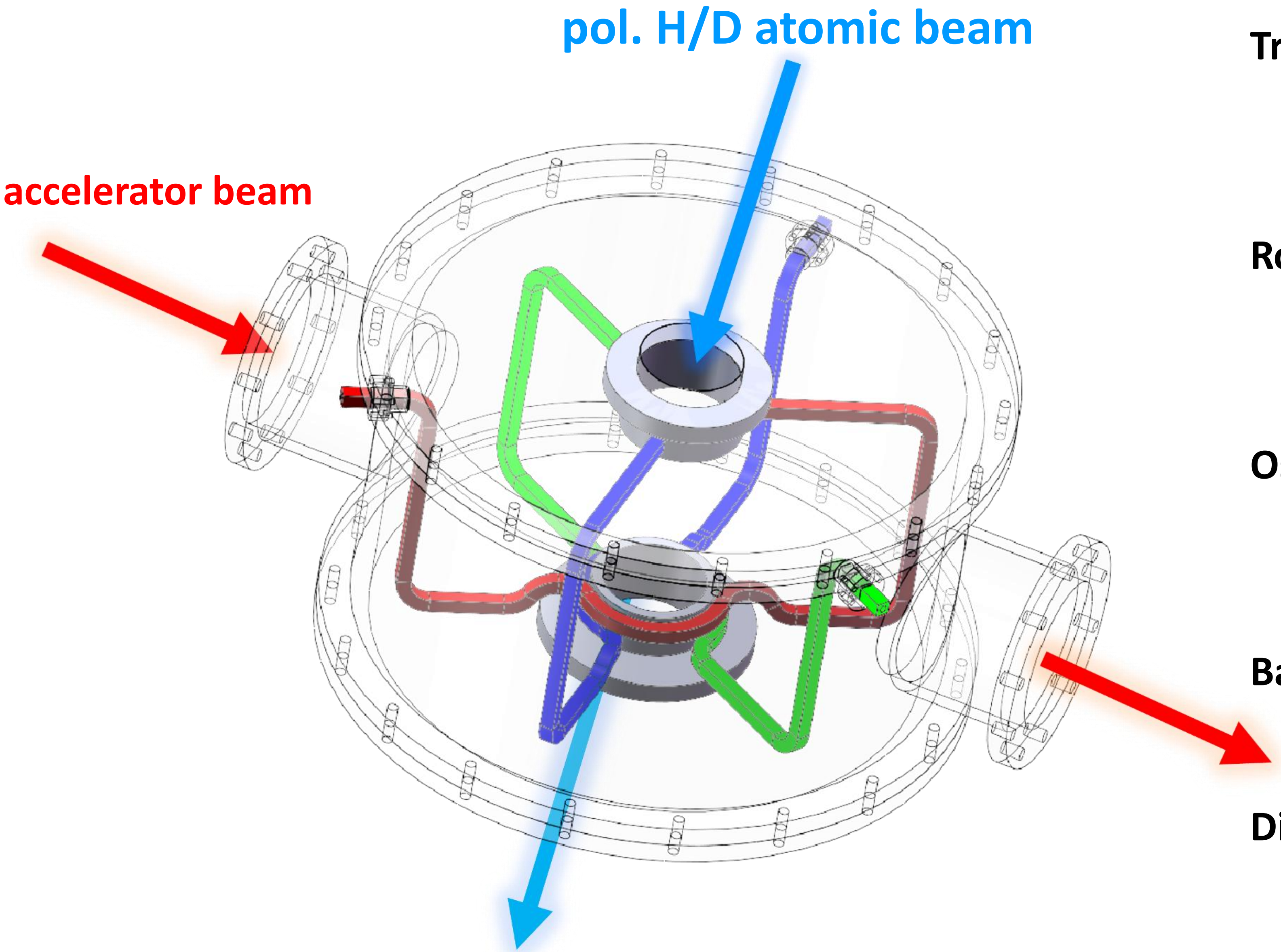
More collaborations and synergies on spin Physics between NICA and HIAF in the future!

Rotating magnetic field



Rotating angular speed: $\omega = 2\pi f$

Spin-rotating polarized target



Triple coil (ABC) carrying 3-phase AC

⬇

Rotating dipole $\vec{\mathrm{B}}$ & spin

⬇

Oscillating physical asymmetry

⬇

Background symmetry separated by FT

Discovery potential

- ☐ Time reversal violation ($\vec{p}\vec{d}$)
- ☐ Parity violation ($\mathrm{p}\vec{p}$)
- ☐ …

Summary

- Tools for spin physics at HIAF being developed
  - Polarized ion source (built)
  - Polarized beam acceleration (investigated)
  - Polarized target (funded)

- Physics with polarized beam/target at HIAF
  - Atomic, nuclear and hadron physics
  - New physics search with $p\vec{e}$
  - Test of time-reversal invariance with $\vec{p}\vec{d}$
  - Spin-rotating polarized target

Thank you!

Welcome to HIAF
For Great Physics and Collaboration!