JULY 13, 2026

POLARIZED IONS SOURCES AND BEAMS FOR EIC

EPIOS

ZEIN-EDDINE MEZIANI
ON BEHALF OF
THE EPIOS SCIENTIFIC CONSORTIUM

With thanks to: Deepak Raparia, Frank Rathmann, Jaydeep Datta and Richard Milner

POLARIZED ION SOURCES AND BEAMS FOR EIC

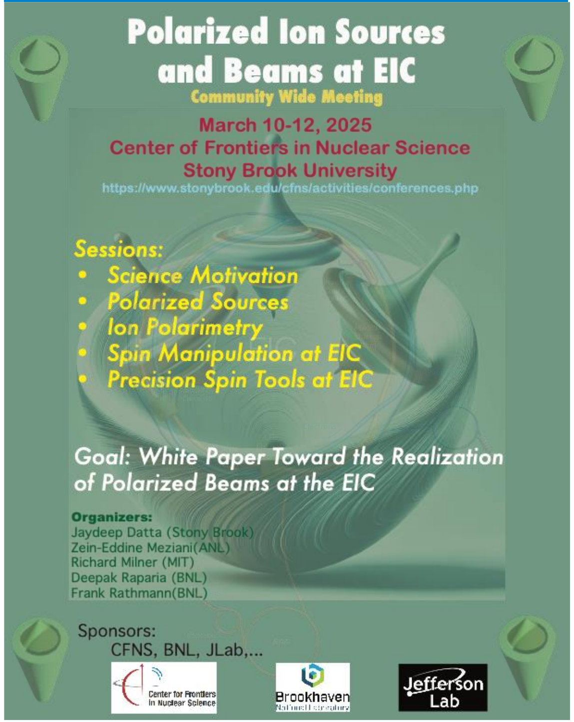
On behalf of the EIC Polarized IOn Source (EPIOS) Scientific Consortium

- Community wide meeting & White paper outcome
  - Goals
  - Status of Polarized Ion Sources
  - Polarimetry requirements
- EPIOS scientific consortium
  - "*raison d'être*"
- Scientific case for polarized light nuclei
- Status of polarized ion source development
- Conclusion

COMMUNITY-WIDE MEETING

Polarized Ion Sources and Beams for EIC

Poster Advertisement



Meeting date and location

March 10-12, 2025

Center for Frontiers in Nuclear Science

Stony Brook University

New York

Organized by

Deepak Raparia (BNL)

Frank Rathmann (BNL)

Jaydeep Datta (Stony Brook)

Richard Milner (MIT)

Zein-Eddine Meziani (ANL)

GOALS OF THE WORKSHOP

The ultimate goal is to unravel the role of quarks and gluons in nuclei beyond the nucleon-meson picture as well as search for exotic phenomena using the nucleus and its spin as a QCD laboratory

- to raise the visibility in the EIC and spin communities of the exciting scientific case for spin measurements;
- to assess, in the context of the considerable scientific motivation, the status of ion-source developments for the EIC;
- to identify critical path research and development essential for a successful polarized EIC scientific program and that can be implemented on day-1;
- to motivate the education and training of a new generation of young physicists with expertise in spin-polarization technology. This will be essential for realization of the EIC polarized program.

EPIOS WHITE PAPER

PHYSICAL REVIEW C **113**, 060501 (2026)

Perspective

Realizing the scientific program with polarized ion beams at the future BNL Electron Ion Collider

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(EPIOS Scientific Consortium)

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MAJOR POINTS ARISING FROM THE MEETING

Executive summary

- It must be realized that the adaptation of a well-understood polarization technique into a reliable ion source operating at maximum performance injecting with high reliability into an accelerator requires **a sustained research and development effort by a critical mass of suitably skilled personnel for about a decade.**
  - Requirements include 70% beam polarization and relative polarization uncertainty $\Delta P/P$=1% for electrons and hadrons.

- If we consider the major polarization experimental efforts in nuclear physics over the last half-ceuniversity-based research groups played an essential role in developing the technical capabilities and in attracting and training the generations of physicists who carriedntury, out the research.
- The EIC science **demands the widest available range of polarized ions, and innovative source technologies must be pursued.**
- The EIC accelerator design team must make it a priority to develop ion spin control and manipulation from source to collisions of the **deuteron ^{3}He, ^{6}Li, and ^{7}Li nuclei.**

MAJOR POINTS ARISING FROM THE MEETING

Executive summary (continued)

- **Artificial intelligence** and **machine learning (AI-ML) can** serve as both accelerators of research and development (through fast modeling, optimization, and control) and amplifiers of discovery (through advanced data analysis and anomaly detection). Their integration will be key to meeting the ambitious polarization goals of the EIC.
- It is recommended that **a specific amount of funding be set aside to target research and development associated with the realization of polarized ion beams at EIC.** This would support the education and training of young physicists with the necessary expertise.
- It is recommended that a focused multi-week program on the science case for polarized ion beams at EIC be organized at the Institute for Nuclear Theory in the next year.
- It is recommended that an annual summer school for young physicists on the science and technical realization of polarized ion beams at EIC be established. Existing summer schools and the U.S. Particle Accelerator School can be leveraged to include relevant lectures and classes.
- It is **recommended that the BNL Tandem be utilized to secure the future with polarized *d*** and ^6Li ions, as there is not sufficient space available for these sources at the BNL Electron Beam Ionization Source (EBIS)
- We identify the BNL Alternating Gradient Synchrotron (AGS) as a **very valuable platform to carry out beam studies of polarized sources, polarized beams, and spin manipulators in the era when the BNL Relativistic Heavy Ion Collider (RHIC) is dark.** We recommend that EPIOS and the BNL Collider Accelerator Department (BNL-CAD) together consider the possibilities and develop a plan that takes advantage of the AGS

MAJOR POINTS ARISING FROM THE MEETING

Critical point

Workforce

- We identify a significant research and development effort across national and international laboratories and universities that is required over about a decade to realize the polarized ion beams and estimate (based on previous experience) that it will require about 20 full-time equivalent (FTE) over 10 years (or a total of about 200 FTE-years) of personnel, including graduate students, postdoctoral researchers, technicians, and engineers.
- We need to start now! Cannot improvise later

Next Generation

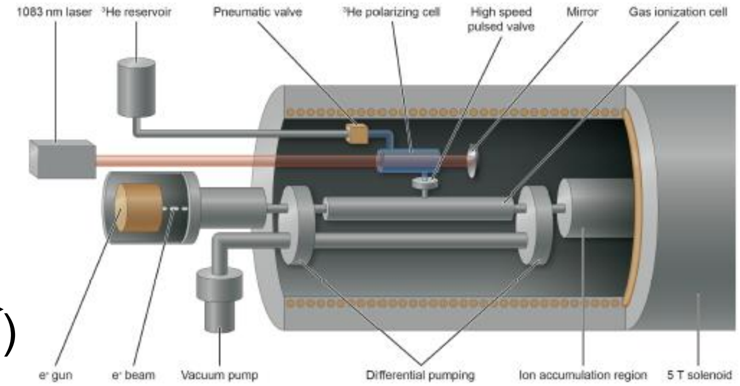
- Attracting, educating, and training a new generation of physicists in experimental spin techniques will be essential for the successful realization.

Therefore, we call on undergraduate students, graduate students and postdocs interested in learning about polarized sources, beams and polarimetry to get in touch with the EPIOS consortium

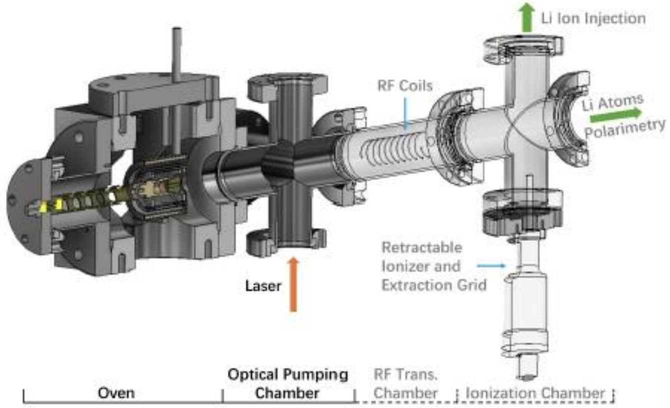
POLARIZED ION SOURCES

Overall status and availability

- The EIC will use
  - polarized **protons** ($\overrightarrow{1/2}$) and **helions** ($\overrightarrow{1/2}$)
  - later on possibly **deuterons** ($\vec{1}$), and
  - heavier nuclei like **lithium**, i.e., ^{6}Li ($\vec{1}$) and ^{7}Li ($\overrightarrow{3/2}$)
- **Ion Sources for**
  - polarized protons (available)
  - polarized ^{3}He (needs work)
  - polarized deuterons
    - will be inherited from Jülich (in the near future, then needs work)
    - not trivial for Hadron Storage Ring (HSR) as G_d = -0.143 is small (needs work)
  - polarized lithium (needs a lot of work)



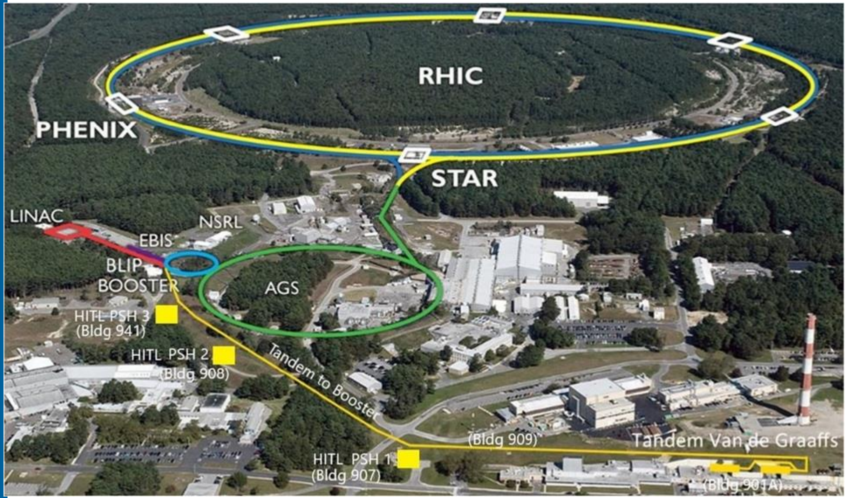
Musgrave et al.,PoS PSTP2019, 043 (2020).



Conceptual illustration of the proposed Li ion source

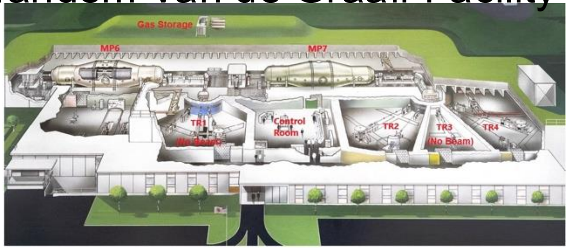
USING THE COSY D$^-$ ION SOURCE AT BNL

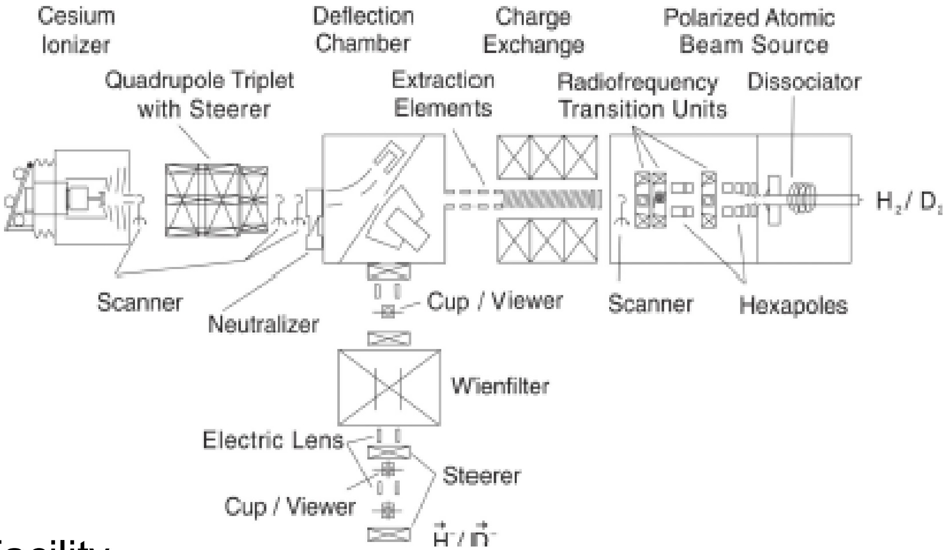
Proposal to locate the Polarized Deuterium Ion Source at the Tandem Van de Graaff Facility



BNL C-AD Complex

Tandem Van de Graaff Facility





Scheme of the polarized ion source at COSY

STATUS OF THE CONSORTIUM ACTIVITIES

EPIOS (EIC Polarized IOn Source) scientific consortium formed to continue to advance the realization of polarized ion beams at EIC.

- Plan meetings about every six months: Stony Brook, ANL, MIT,……
  - Held a first meeting in March 2025 and a second meeting in March 2026 at Stony Brook
  - Proposed an INT scientific workshop for 2027, it was approved but will be held in Spring 2027at Stony Brook due to the budget situation of the INT.
  - Explored the initiation of annual summer school
- Proposed and held DNP Workshop on ***Polarized Ion Beams at EIC*** at the DNP meeting in Chicago Oct 17-20, 2025. Another Workshop is proposed for the DNP meeting in Philadelphia Oct. 2026.
- Funds are being sought for the development of the polarized deuteron source as well as ^{6}Li - ^{7}Li sources.

SCIENCE CASE FOR POLARIZED ION BEAMS AT EIC

Beyond polarized protons beam and unpolarized ions beams

- To provide polarized neutron targets
- To study how the nucleon's quark and gluon spin distributions can be modified in the nucleus
- To access the nuclear generalized parton distributions (GPDs) and transverse momentum distributions (TMDs) that allow the full three-dimensional imaging of nuclei and the neutron similar to the proton case
- To carry out pioneering searches for spin-1 and higher components, e.g. ***exotic gluons***, in the nucleus

POLARIMETRY

Requirements for hadron beams in EIC

- The EIC promises to provide proton beam polarization of $P \geq 0.7$ with a relative uncertainty of $\Delta P/P \leq 1\%$
- Absolute proton beam polarization calibration relies on measured nuclear polarization of atomic jet using Breit-Rabi polarimeter.
- Polarization calibration needed for each ion species, as presently applied to protons:
  - Elastic scattering of identical particles where the beam polarization is inferred from a known target polarization
  - $\vec{p}\,\vec{p}$ elastic scattering, $^{3}\vec{He}$-$^{3}\vec{He}$ elastic scattering, $\vec{d}\,\vec{d}$ elastic scattering and $^{6}\vec{Li}$-$^{6}\vec{Li}$ elastic scattering
- Polarization calibration of other species also from nuclear polarization measurements of atomic targets using Breit-Rabi or similar type polarimeter.

See Evgeny Shulga (BNL), Monday afternoon

EXPERIMENTAL CONSIDERATIONS

Experimental advantages of an Electron–Ion Collider

- realization of pure electron-nuclear scattering, unlike current fixed-target experiments, where the polarized nucleus is frequently embedded in a significant amount of extraneous material;
- straightforward control of the ion spin direction from transverse to longitudinal with respect to the beam direction;
- detection of particles scattered close to the beamline;
- efficient tagging of spectator systems, which travel in the laboratory with high energy close to the beam direction.

EIC NAS SCIENCE PILLARS

How do quarks, gluons, and orbital angular momentum contribute to proton spin?

Spin is a fundamental property of matter. All elementary particles but Higgs carry spin.

Spin of composite particles such as the proton cannot be explained by a static picture but are caused by the **interplay of properties and interactions of quarks and gluons inside.**

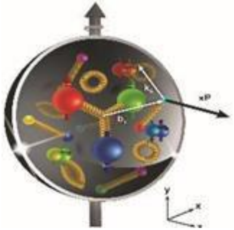
SPIN

Does the mass of visible matter emerge from quark-gluon interactions?

Atom:
Binding/Mass = 0.00000001
Nucleus:
Binding/Mass = 0.01
Proton:
Binding/Mass = 100

The EIC will determine an important term contributing to the **proton mass,** the so-called QCD trace anomaly.

MASS



How are quarks and gluons distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties **emerge from them and their interactions?**

How can we understand their **dynamical origin in QCD?**

What is the relation to **Confinement?**

3D-Imaging

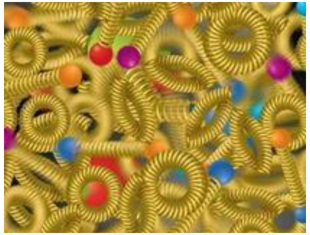
How do the confined hadronic states emerge from quarks and gluons?

Is the structure of a **free and bound** nucleon the same?

How do quarks and gluons **interact with a nuclear medium?**

How do the quark-gluon interactions **create nuclear binding**?

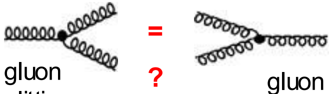
QCD in Nuclei



Does gluon density in nuclei saturate at high energy?

How many gluons can fit in a proton?

How does **a dense nuclear environment affect** the quarks and gluons, their correlations and interactions?



gluon splitting

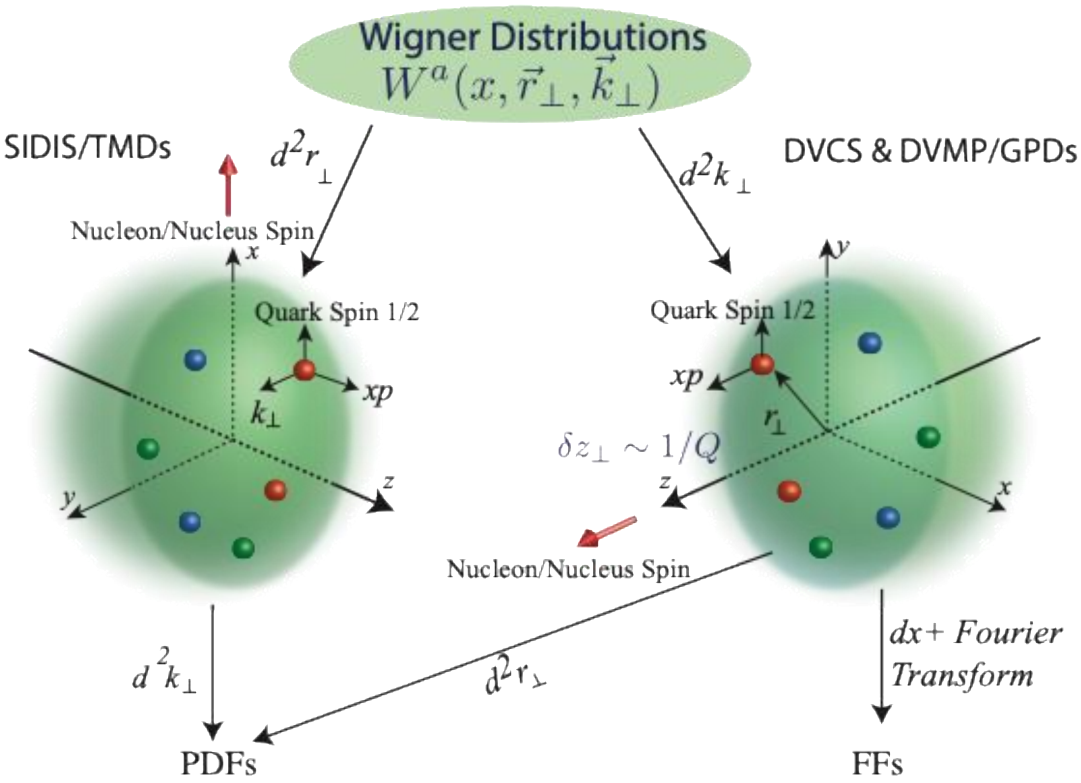
gluon recombination

Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

MASTER PLAN OF TOMOGRAPHY

3D partonic structure unraveling from the ground up



FLAVOR SPIN DISTRIBUTION AT Q^2 = 10 GEV^2

Data on ^{3}He as a neutron target are essential to improve on the down quark distribution in the nucleon

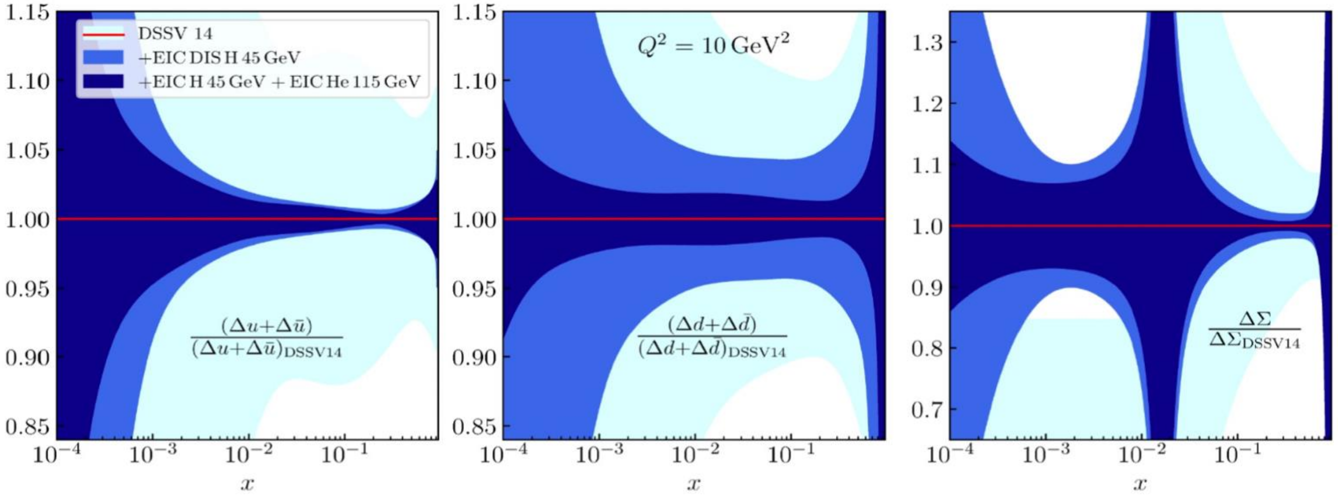


FIG. 2: The impact of projected inclusive scattering data off polarized proton and ^{3}He beams at the EIC on the relative uncertainties of the extracted up, down and quark singlet helicity distributions.

I. Borsa, G. Lucero, R. Sassot, E. Aschenauer and A. S. Nunes Phys. Rev. D. 102, 094018 (2020)

FROM SPIN ½ TO SPIN 1

Transverse momentum distributions for a spin-½ and a spin-1 systems

Leading Quark TMDPDFs — Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = − Boer-Mulders
L		g_1 = − Helicity	$h_{1L}^\perp$ = − Worm-gear
T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = − Worm-gear	h_1 = − Transversity; $h_{1T}^\perp$ = − Pretzelosity

leading twist / target polarization	quark operator: γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^i\gamma_5$
U	f_1 = unpolarized		$h_1^\perp$ = − Boer-Mulders
L		g_1 = − helicity	$h_{1L}^\perp$ = − worm gear 1
T	$f_{1T}^\perp$ = − Sivers	g_{1T} = − worm gear 2	h_1 = − transversity; $h_{1T}^\perp$ = − pretzelosity
TENSOR	$f_{LL}(x,\boldsymbol{k}_T^2)$, $f_{LT}(x,\boldsymbol{k}_T^2)$, $f_{TT}(x,\boldsymbol{k}_T^2)$	$g_{1TT}(x,\boldsymbol{k}_T^2)$, $g_{1LT}(x,\boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x,\boldsymbol{k}_T^2)$, h_{1TT}, $h_{1TT}^\perp$, h_{1LT}, $h_{1LT}^\perp$

$$b_1 = \sum_q e_q^2 (b_1^q + b_1^{\bar q}), \qquad b_2 = 2x b_1$$

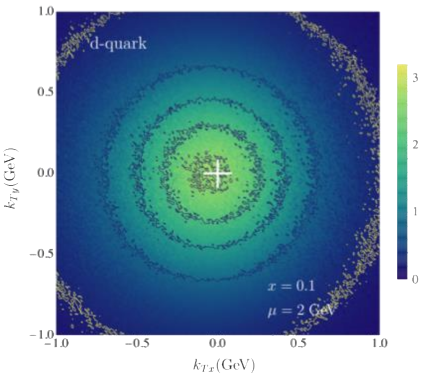
$$b_1^q = \frac{1}{2}\int d\vec{k}_T f_{LL}^q(x, k_T^2)$$

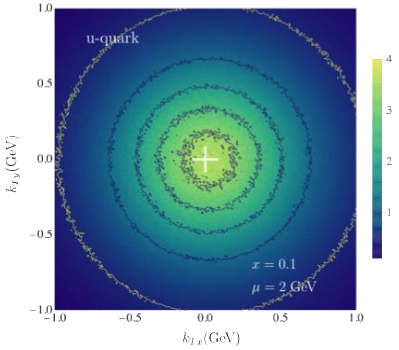
In DIS we are familiar with b_1, b_2, b_3 and b_4

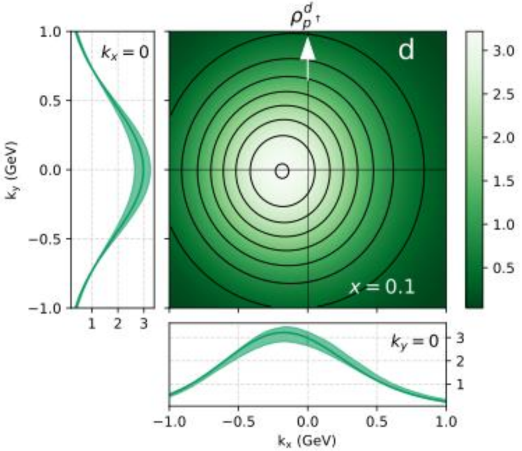
At leading twist b_1 is dominant b3 and b4 appear at twist-4

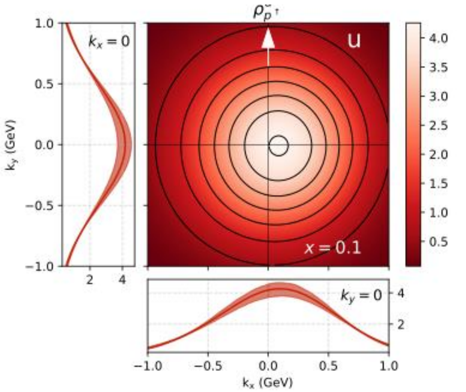
TOMOGRAPHIC SCANS IN MOMENTUM SPACE (TMD HANDBOOK)

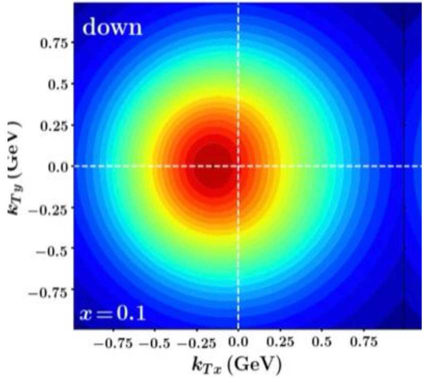
Momentum space quark densities at Björken x= 0.1 at a scale μ = 2 GeV

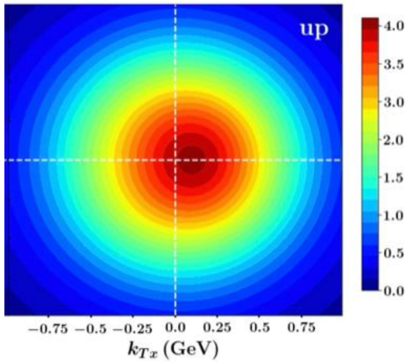


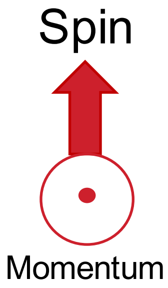








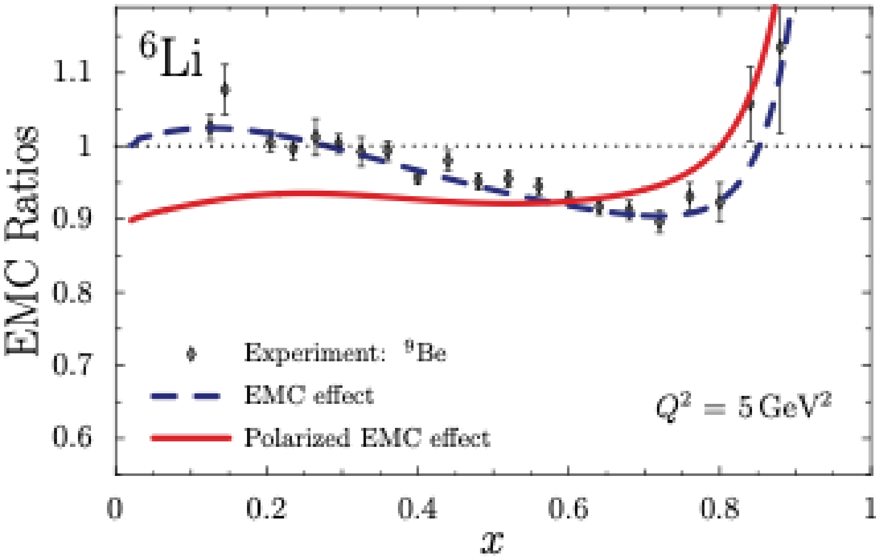


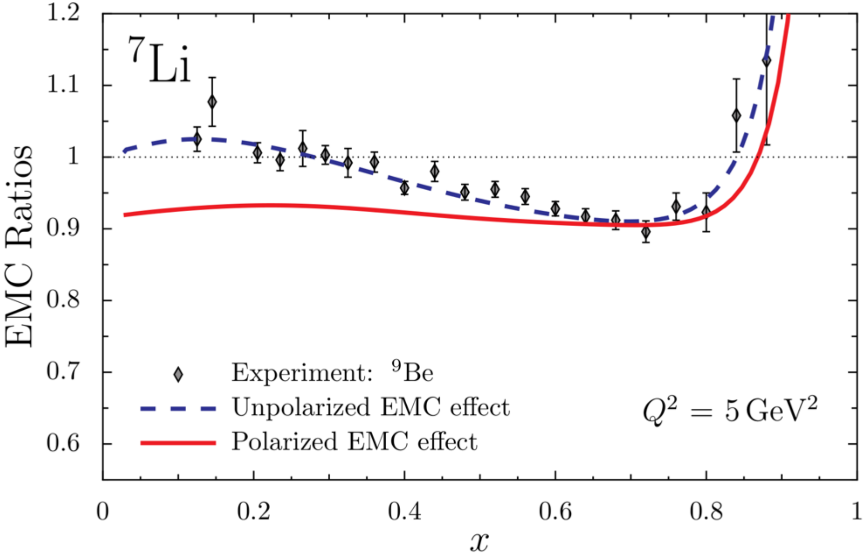


Density of unpolarized quarks using the Sivers functions

POLARIZED EMC EFFECT

Is the nucleon spin structure modified in the nuclear medium?





$$R^A_{\mathrm{EMC}} := \frac{F_{2A}(x)}{Z\,F_{2p}(x) + N\,F_{2n}(x)} \simeq \frac{F_{2A}(x)\big|_{\mathrm{ISO}}}{F_{2D}(x)}$$

$$\Delta R^A_{\mathrm{EMC}} := \frac{g_{1A}(x)}{P_p\,g_{1p}(x) + P_n\,g_{1n}(x)}$$

I. Cloët and W. Bentz and T. Thomas PLB **642**, 210 (2006)

EXOTIC GLUON STATES IN NUCLEI

A signal of gluon transversity in Spin-1 systems

$$\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi} \mathrm{Tr}\, \mathcal{Q}^2 x^2 \int_x^1 \frac{dy}{y^3} [g_{\hat{x}}(y, Q^2) - g_{\hat{y}}(y, Q^2)]$$

- $\Delta(x, Q^2)$ is an expression of how much more momentum of a transversely polarized particle is carried by gluons aligned rather than perpendicular, making $\Delta(x, Q^2)$ a signal of gluonic transversity.

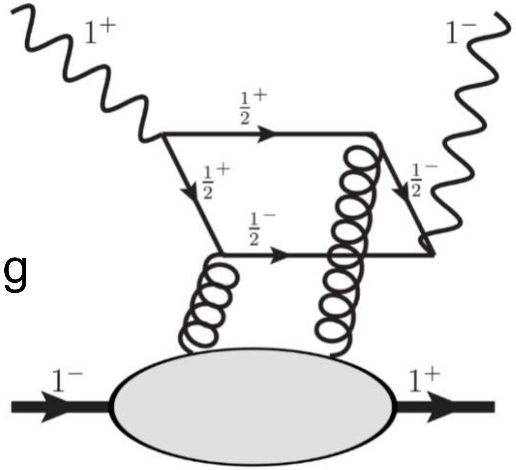


FIG. 4: Example of leading DIS process sensitive to $\Delta(x, Q^2)$ [63].

POLARIZED ION SOURCE R&D

- **Polarized proton**
  - ✓ OPPIS reliability and performance
- **Polarized deuteron**
  - ✓ COSY deuteron source being transferred to BNL
  - ✓ likely utilize BNL tandem
- **Polarized He-3**
  - ✓ optically pumped source using EBIS being developed by BNL-MIT coll.
  - ✓ 6 MeV polarization measurement planned when RHIC ends operations
  - ✓ absolute polarimeter using existing ABS source under development
- **Polarized Li-6 and Li-7**
  - ✓ optically pumped source development getting underway at ANL

THE MAGNITUDE OF THE CHALLENGE

The scale of the workforce

- OPPIS: multi-decade, 30 physicists, 10 engineers, 5 postdocs/students
- HERMES H/D target: 40 graduate student years, 50 postdoc/senior years
- HERMES He-3 target: 10 graduate student years, 12 postdoc senior years, two years of engineering
- SLAC He-3 target: 35 person years
- SLAC H/D target: 20 person years
- Ongoing He-3 source development at BNL: 12 physicists, 4 postdocs

Scale of EIC polarized ion source effort is estimated as ~ 200 FTE

See Table V of the White paper

OPTIMIZING R&D FOR MOVING FORWARD

AGS is an essential test bench for development of polarized sources and beams

- We have of order a decade to develop the polarization technology that is essential for EIC science. This includes:

    - polarized ion sources (^{2}H, ^{3}He, ^{6}Li and ^{7}Li)

    - polarimeters

    - spin manipulation in AGS and RHIC using solenoids and snakes

- We require maximum stable polarization and collision luminosity at the IP.
- The AGS is a local to EIC, is an integral element of the EIC accelerator and should be made available after RHIC operations cease.

CONCLUSION

Excerpts from the Abstract of the White Paper

Polarized ion beams at the Electron Ion Collider (EIC) are essential to address some of the most important open questions at the twenty-first century frontiers of understanding of the fundamental structure of matter. Here, we summarize the science case and identify polarized ^{2}H, ^{3}He, ^{6}Li, and ^{7}Li ion beams as critical technology that will enable experiments which address the most important science. Furthermore, we discuss the required ion polarimetry and spin manipulation at the EIC. The current EIC accelerator design is presented. We identify a significant research and development effort across national and international laboratories and universities that is required over about a decade to realize the polarized ion beams and estimate (based on previous experience) that it will require about 20 full-time equivalent (FTE) over 10 years (or a total of about 200 FTE-years) of personnel, including graduate students, postdoctoral researchers, technicians, and engineers. Attracting, educating, and training a new generation of physicists in experimental spin techniques will be essential for the successful realization. Artificial intelligence and machine learning are seen as having significant potential for both acceleration of research and development and amplification of discovery in the optimal realization of this unique quantum technology on a cutting-edge collider. The research and development effort is synergistic with research in atomic physics and fusion energy science.

STUDENTS AT EVERY LEVEL, FROM UNDERGRADUATES TO POSTDOCS, WHO ARE INTERESTED IN POLARIZED SOURCES, BEAMS, OR POLARIMETRY SHOULD GET IN TOUCH WITH THE CONSORTIUM AT

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THANK YOU!