New opportunities on semi-inclusive processes from ^{3}He at CLAS12 at JLab

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For the JLab-MIT collaboration

Massachusetts Institute of Technology

Correlation in Partonic and Hadronic Interactions (CPHI)

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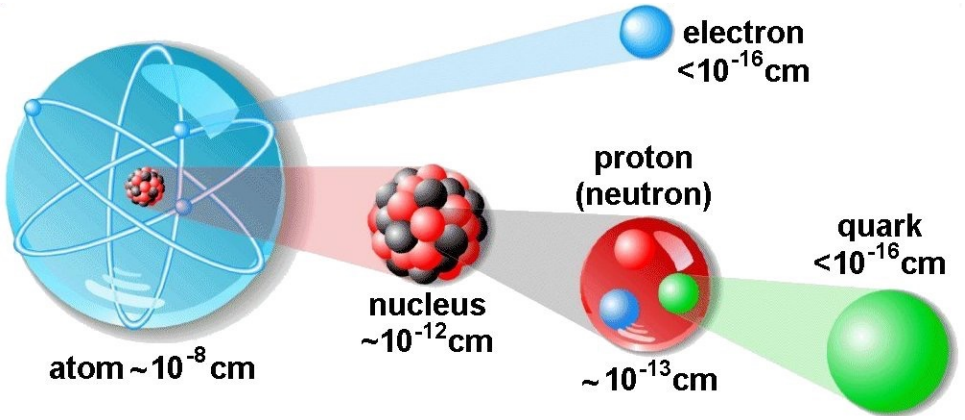
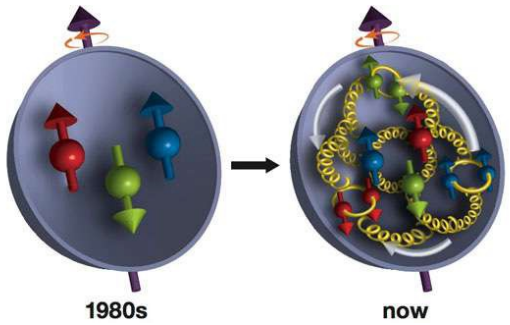
Outline

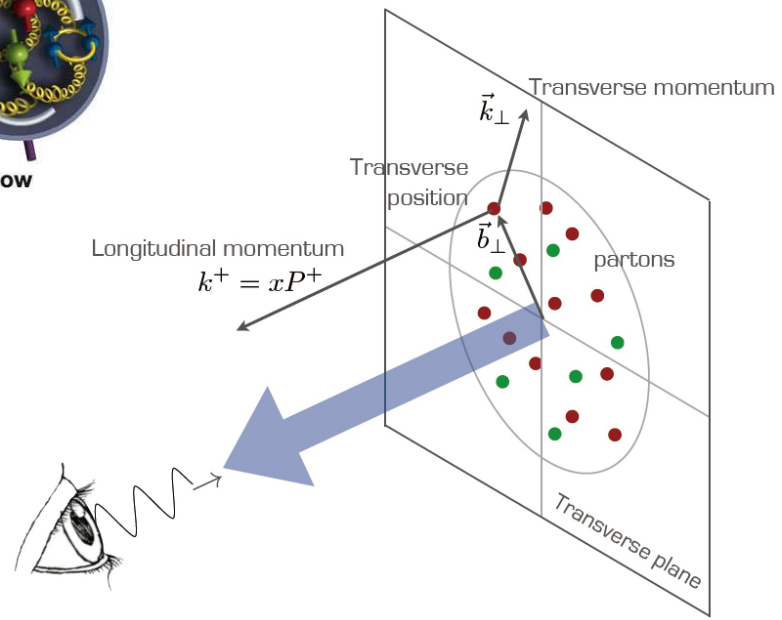
- Introduction
- Experiment C12-20-002 at JLab
- Polarized 3He target at CLAS12
- Outlook
- Summary

3D imaging of the nucleon

- Nucleons – building blocks of the visible matter in the universe
- Internal dynamics of the nucleon
  - Charge distribution
  - Spin distribution
  - Quark momentum distribution
  - …
- Nucleon structure: from 1D to 3D
  - Generalized parton distribution (GPD)
  - Transverse momentum dependent parton distribution (TMD)

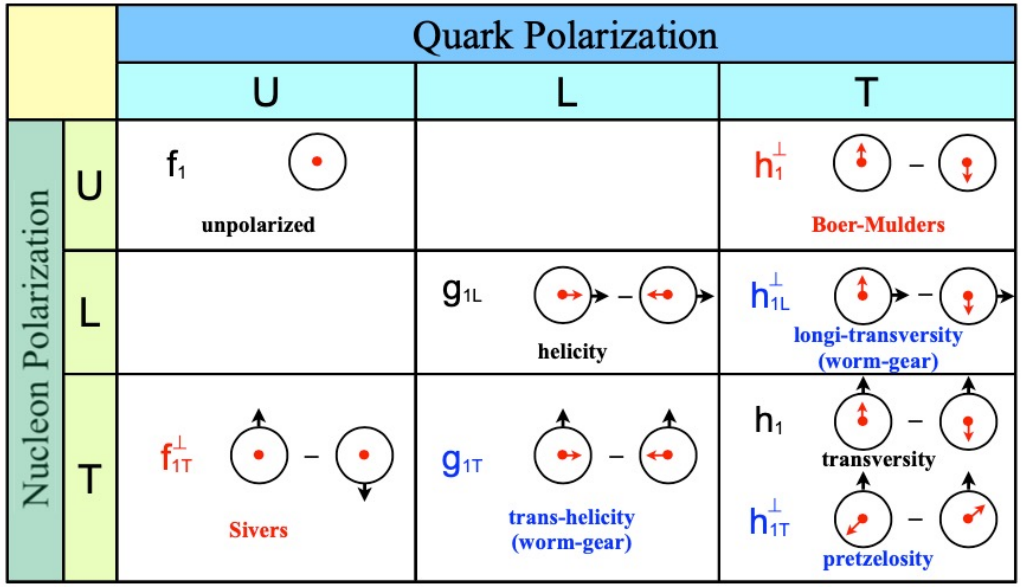






Semi-inclusive deep inelastic scattering (SIDIS)

- Golden channel to study TMD physics



$$\frac{d\sigma}{dxdydzdP_T^2 d\phi_h d\phi_S}$$

$$= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda_e \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h$$

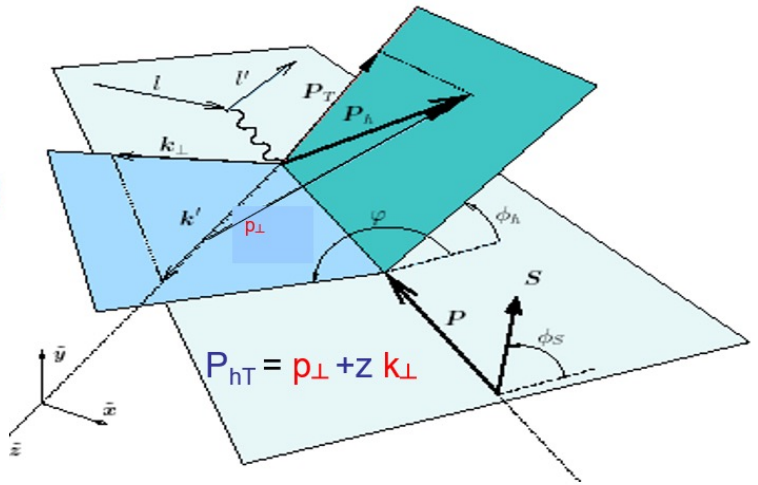
$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)} F_{UL}^{\sin\phi_h} \sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h} \sin 2\phi_h \Big] + \lambda_e S_L \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} F_{LL}^{\cos\phi_h} \cos\phi_h \Big]$$

$$+ S_T \Big[(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}) \sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S)$$

$$+ \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

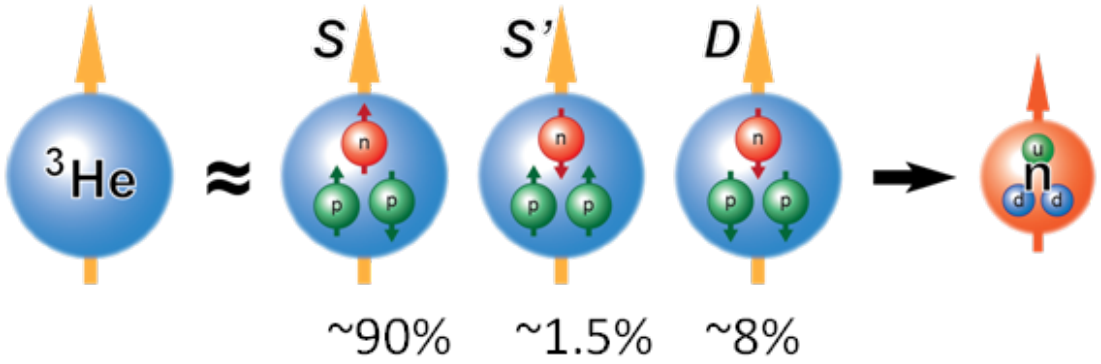
$$+ \lambda_e S_T \Big[\sqrt{1-\epsilon^2} F_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S)$$

$$+ \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \Big] \Big\}$$



Nuclear spin-polarized ^{3}He

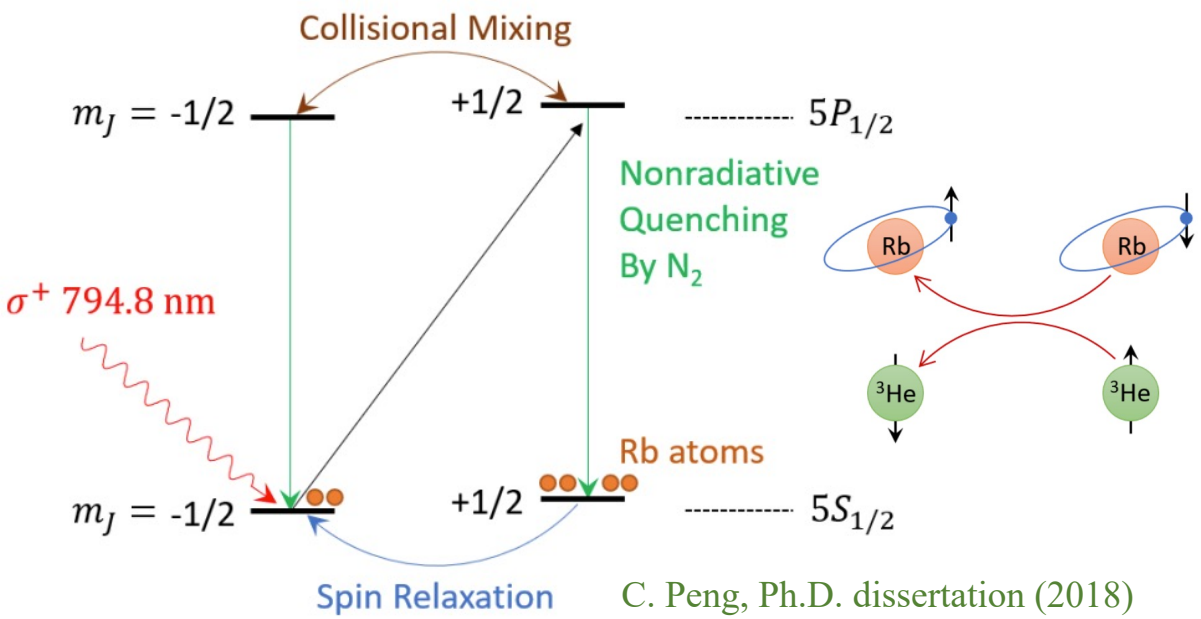
- Spin-polarized ^{3}He nucleus: **effective spin-polarized neutron target**



- Polarized ^{3}He targets at Jefferson Lab
  - SEOP, 60% in-beam polarization in 10-bar gases
  - 7 experiments approved for 12 GeV upgrade
- Polarized ^{3}He ion source at RHIC for the future EIC
  - MEOP, concept developed by BNL-MIT collaboration
  - High magnetic field (5 T) at BNL's Electron Beam Ionization Source

Optical pumping techniques for polarized ^{3}He

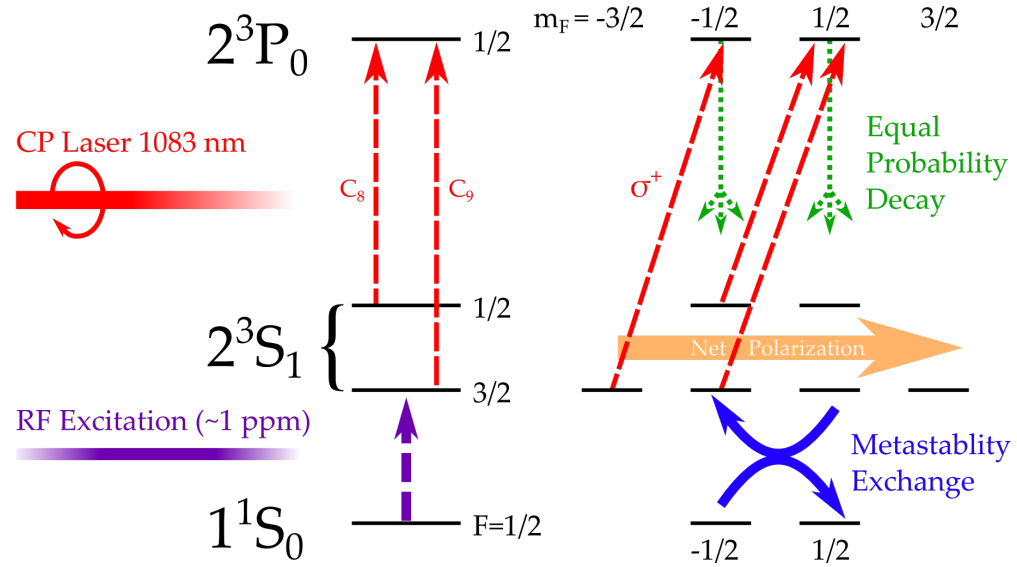
Spin-exchange optical pumping (**SEOP**)



C. Peng, Ph.D. dissertation (2018)

- Optically pump alkali-metal atoms in mixture
- Spin exchange between alkali electrons and ^{3}He nuclei
- Large pressure range (1 to 13 bar)
- Low pumping rate

Metastability-exchange optical pumping (**MEOP**)



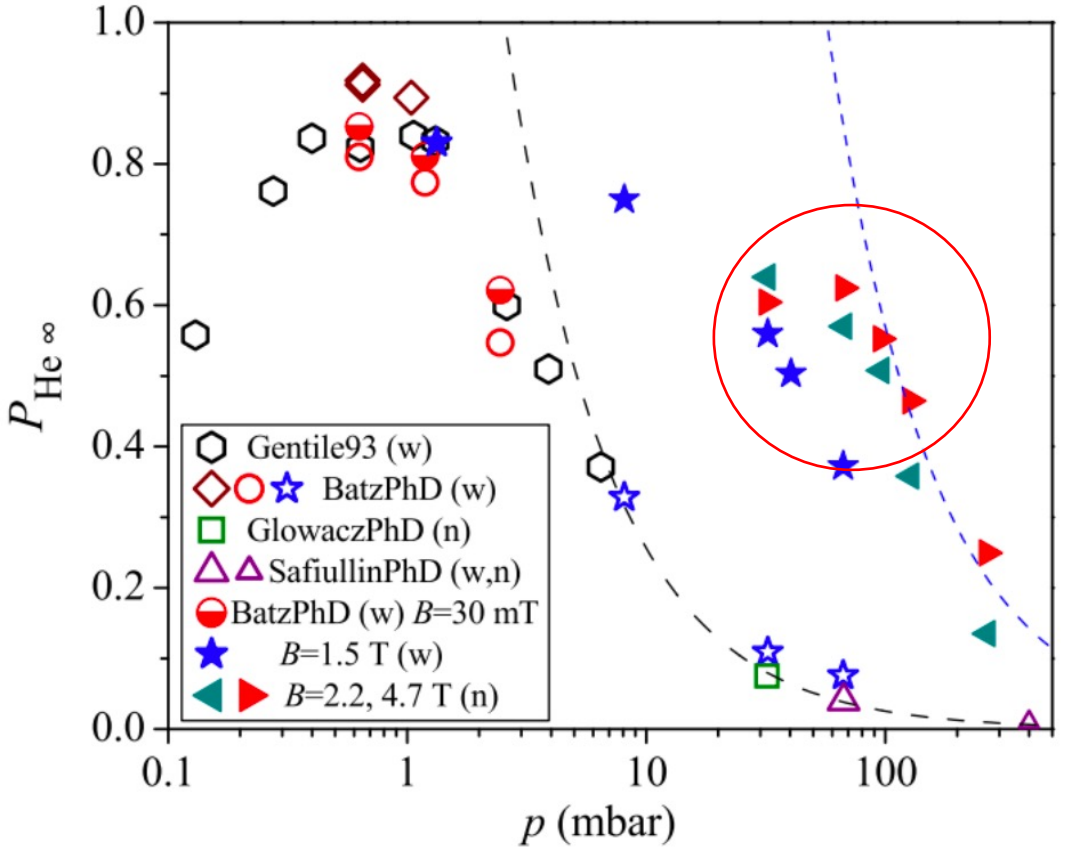
F.D. Colegrove, L.D. Schearer, G.K. Walters Phys. Rev. Lett. 132, 2561 (1963)

- Optically pump metastable-state ^{3}He
- Spin transfer via metastability exchange collision
- Limited pressure range (~1 mbar)
- High pumping rate

Path to polarized ^{3}He in high magnetic field

- SEOP: untenable in high field due to increasing wall relaxation
- MEOP: weak hyperfine coupling
- High-field MEOP development
  - Motivated by NMR medical imaging demand (Kastler Brossel Lab, Paris)
  - Found MEOP effective at higher pressures
  - Successfully produced nearly 60% polarization at 100 mbar and 4.7 T

A. Nikiel-Osuchowska *et al.*, Eur. Phys. J. D **67**, 200 (2013)

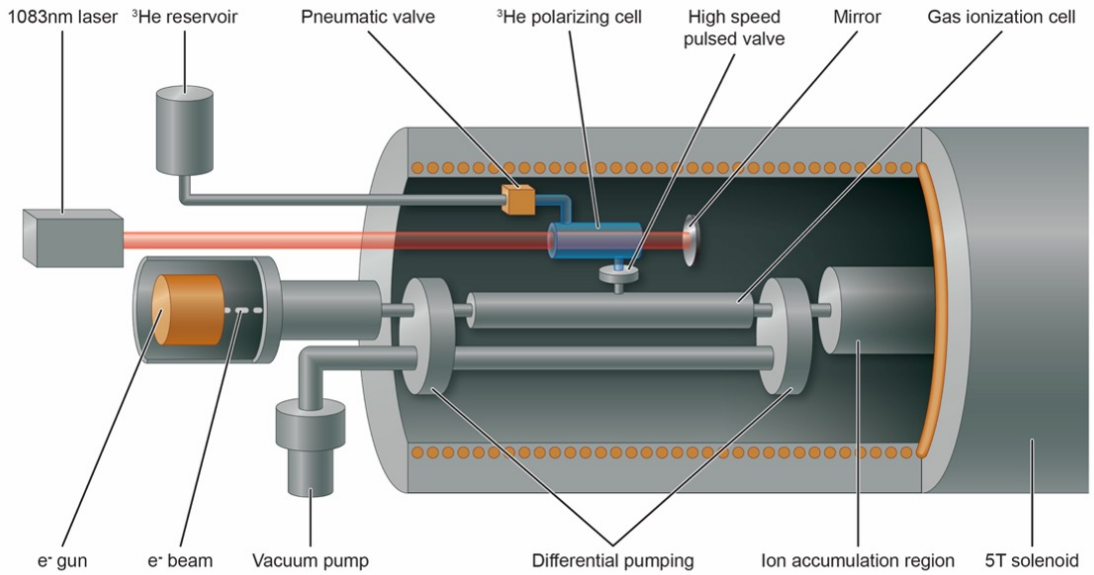


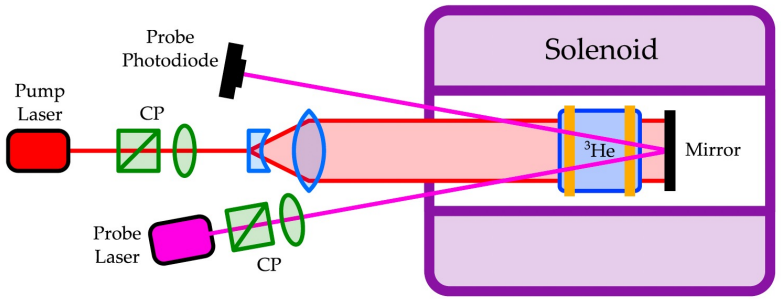
- ○ Open symbols: low field (1 – 3 mT)
- ■ Filled symbols: high field (1.5 – 4.7 T)

T.R. Gentile *et al.*, Rev. Modern Phys. **89**, 045004 (2017)

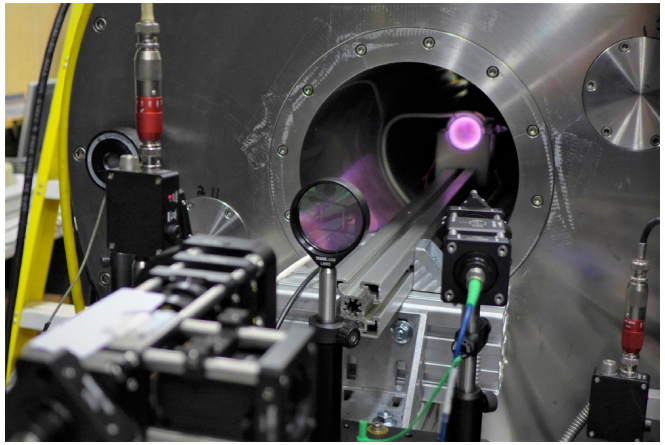
BNL-MIT development of high magnetic field MEOP

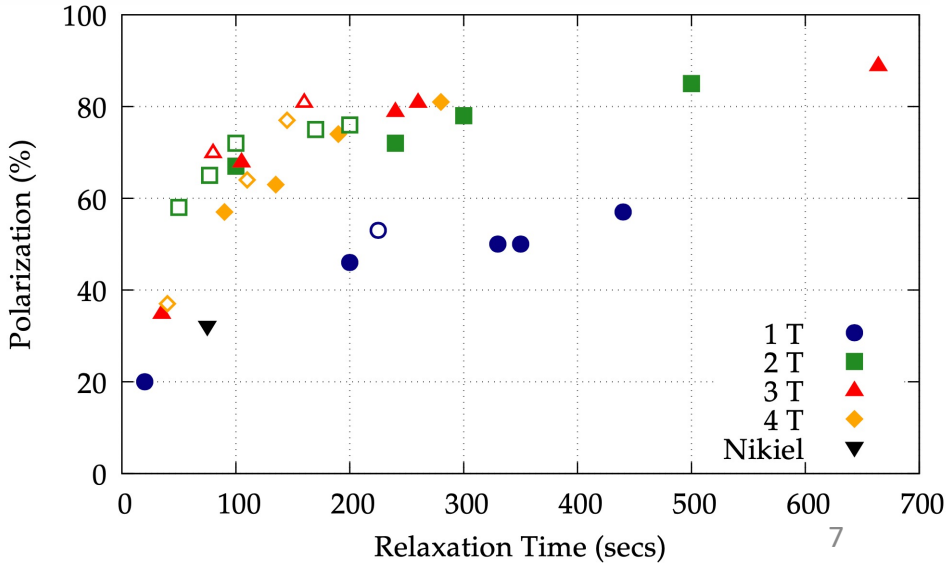
- Polarized ^{3}He ion source for the EIC at RHIC at Brookhaven National Lab
- Electron Beam Ion Source operates at 5 T
- MEOP within 5 T field, transfer into EBIS for ionization and extraction





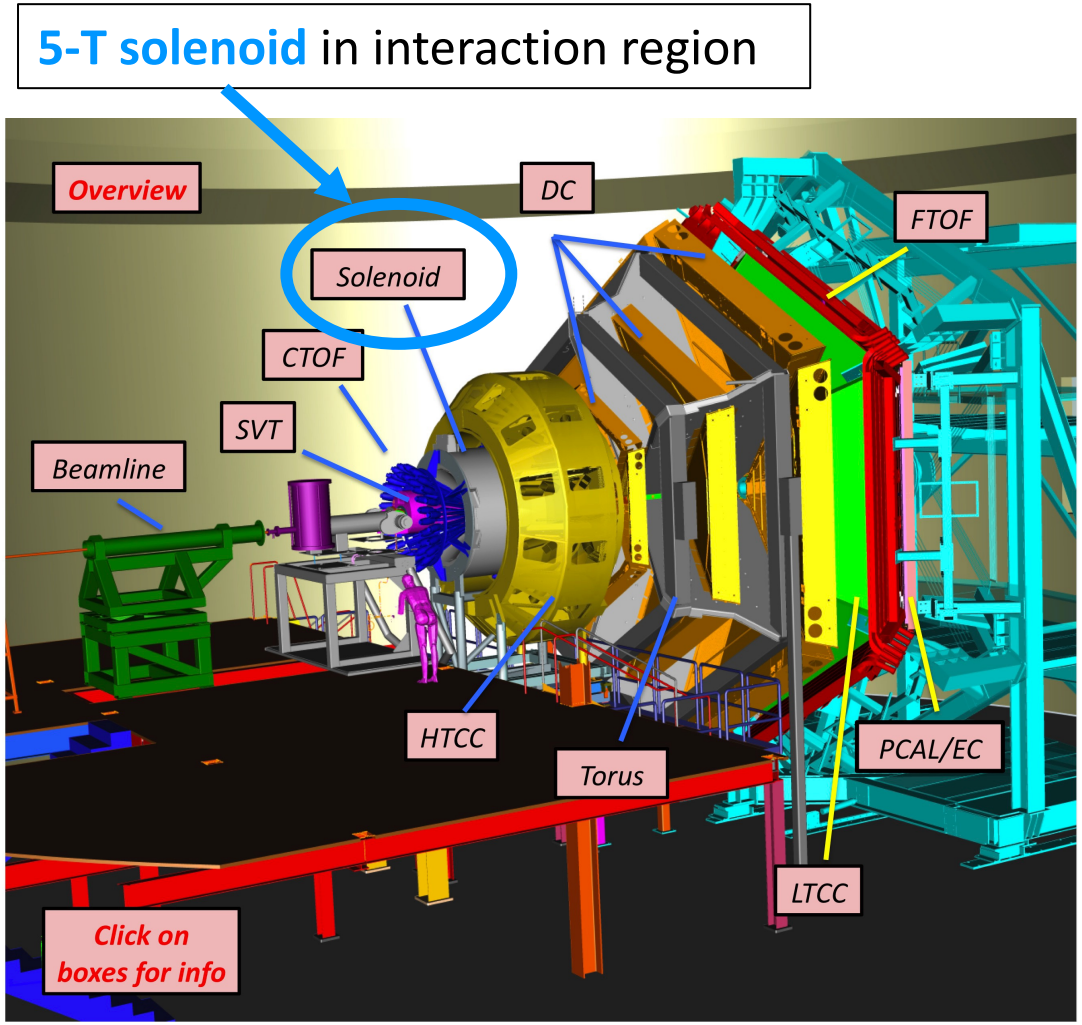
J.D. Maxwell *et al.*, Nucl. Instr. and Meth. A **959,** 161892 (2020)





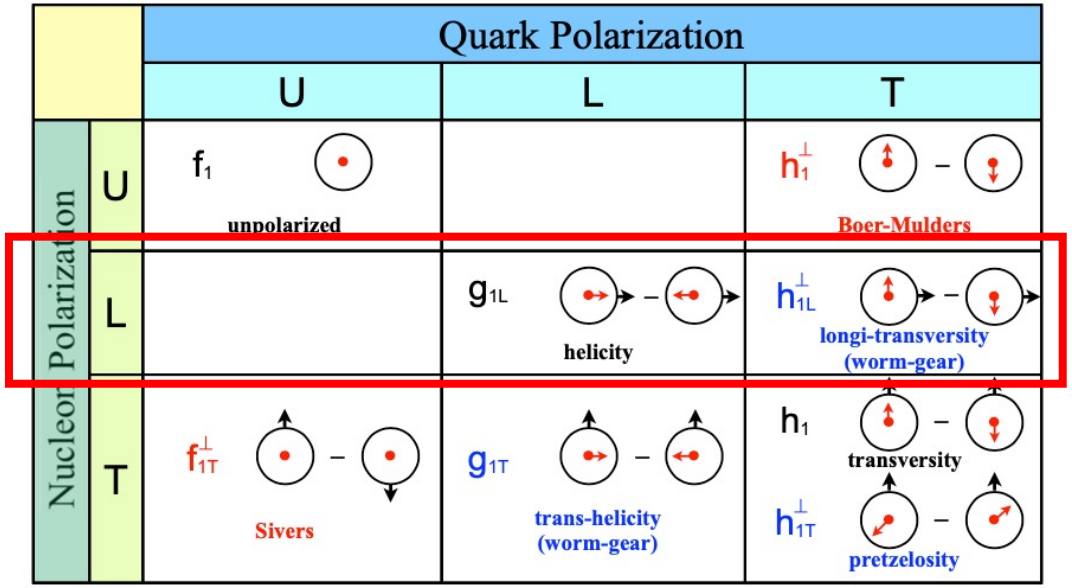
Proposed experiment using polarized ^{3}He at CLAS12 at JLab

- CLAS12: CEBAF Large Acceptance Spectrometer for operation at 12 GeV
  - High luminosity electron scattering
  - Multi-particle final-state response
- **C12-20-002: A program of spin-dependent electron scattering using a polarized ^{3}He target at CLAS12**
  - Spokespeople: H. Avakian, J. Maxwell, R. Milner, and D. Nguyen.
  - Approved with A- rating conditionally on the high-field MEOP target development
- Novel target design to accommodate to the standard CLAS12 configuration



New opportunities on SIDIS from polarized ^{3}He at CLAS12

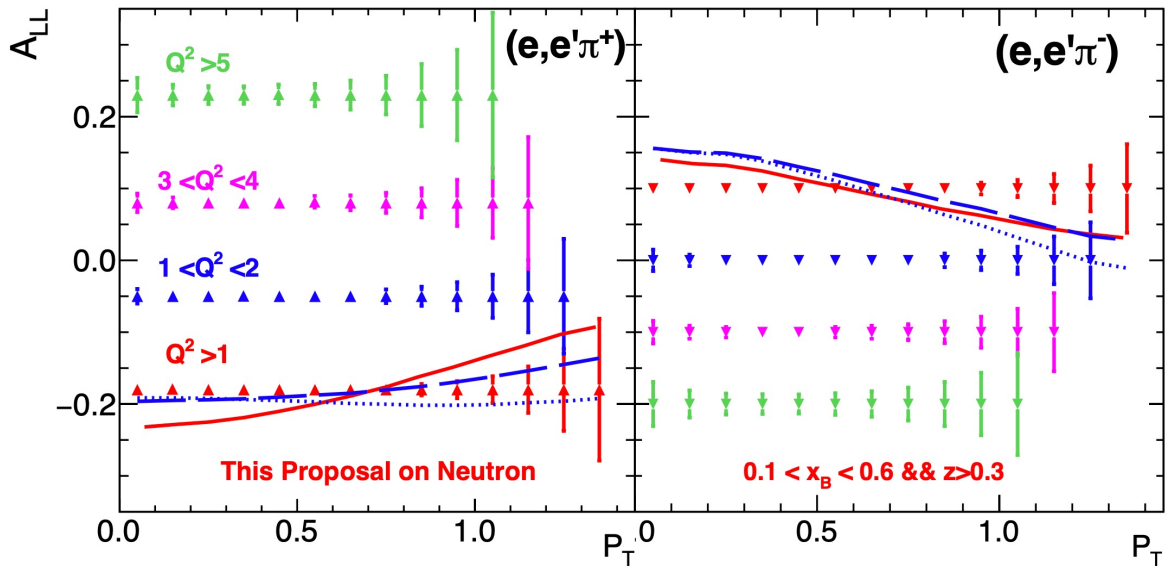
- Longitudinally polarized ^{3}He target
- Measurements on the single-spin asymmetry $A_{UL}^{sin2\phi} = \frac{F_{UL}^{sin2\phi}}{F_{UU,T}}$ and double-spin asymmetry $A_{LL}^{cos\phi} = \frac{F_{LL}^{cos\phi}}{F_{UU,T}}$
- Access to helicity and $h_{1L}^{\perp}$
- Access to the Collins fragmentation

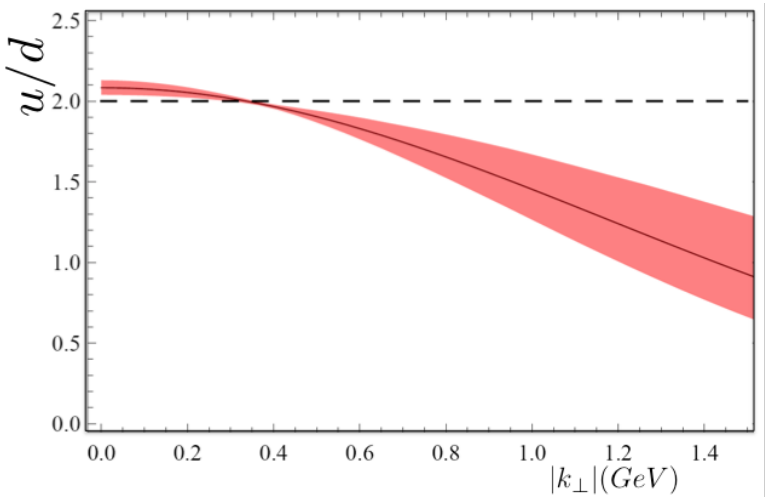


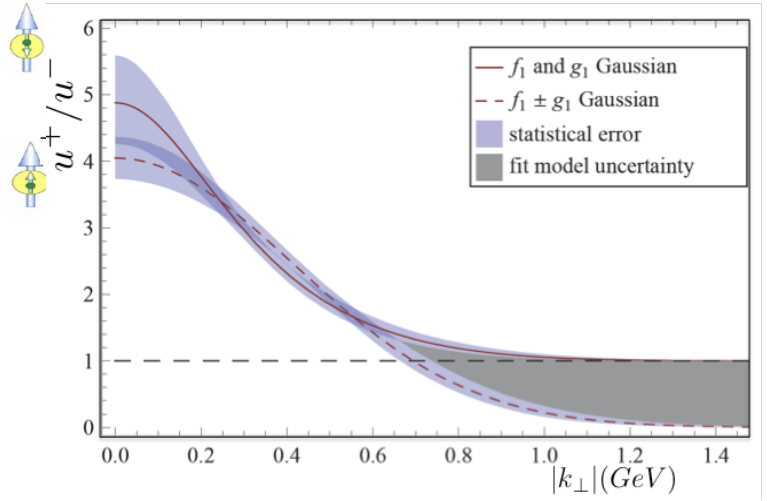
$$F_{UL}^{\sin 2\phi_h}(x,z,P_T) = \mathcal{C}\left[-\frac{2(\hat{h}\cdot k_\perp)(\hat{h}\cdot \mathbf{p}_\perp) - (\mathbf{p}_\perp \cdot k_\perp)}{M_N m_h} h_{1L}^{\perp}(x,Q^2,k_\perp^2) H_1^{\perp}(z,Q^2,p_\perp^2)\right]$$

New opportunities on SIDIS from polarized ^{3}He at CLAS12

- Large P_T and Q^2 ranges covered at CLAS12
  - $1 < Q^2 < 9$ (GeV/c)^2
  - $0 < P_T < 1.3$ (GeV/c)
- P_T dependence of TMDs
- Flavor and spin dependence in transverse momentum distributions



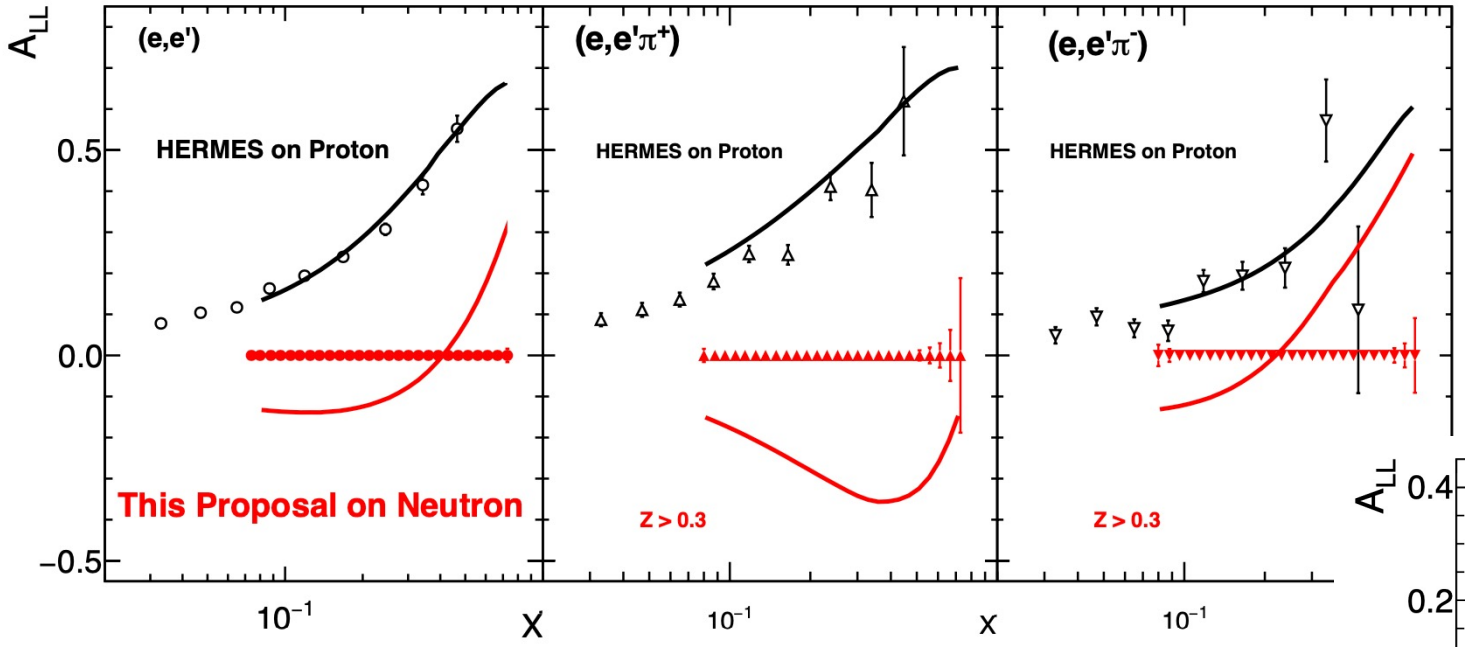




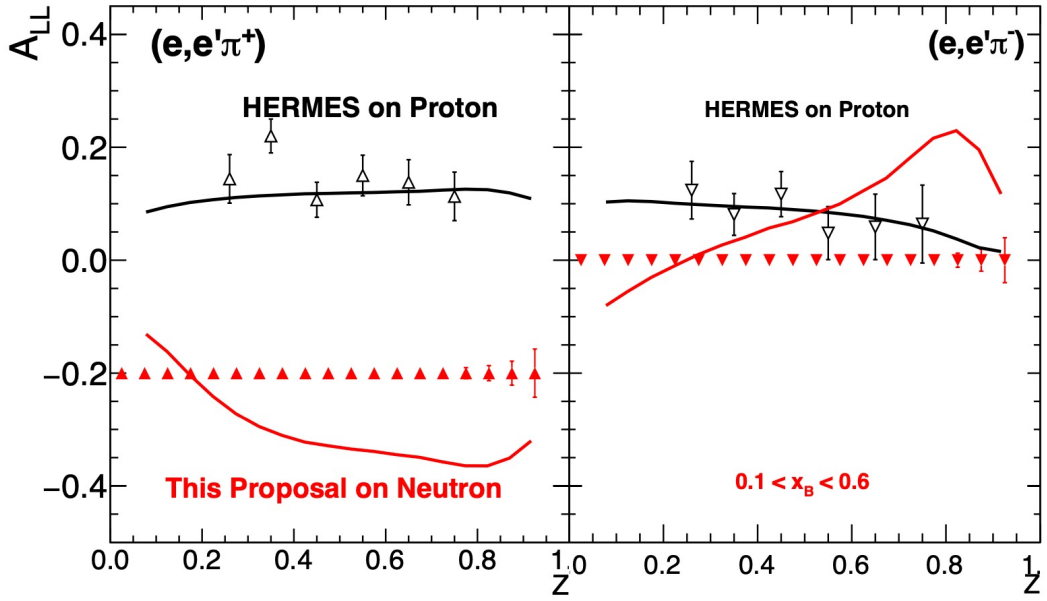
S. Bastami et al., JHEP 06, 007 (2019)
B. U. Musch, arXiv:0907.2381

B. U. Musch, Ph. Hägler, J. W. Negele, and A. Schäfer, Phys. Rev. D 83, 094507

Statistical projections on π^+/π^-

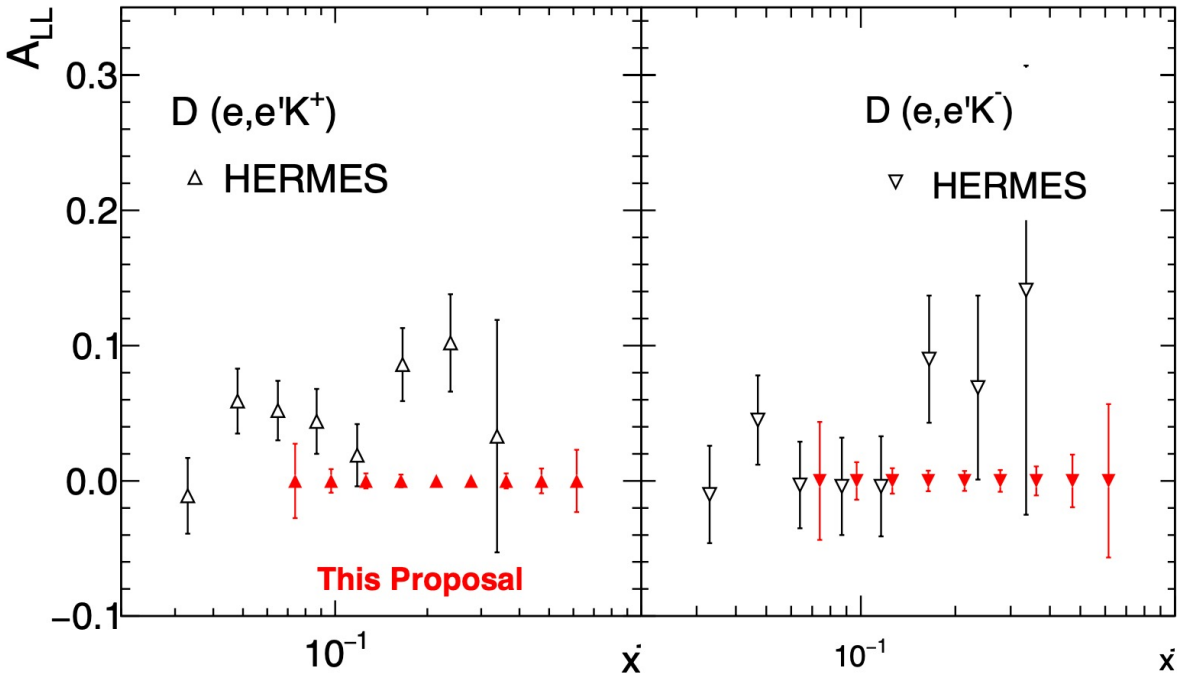


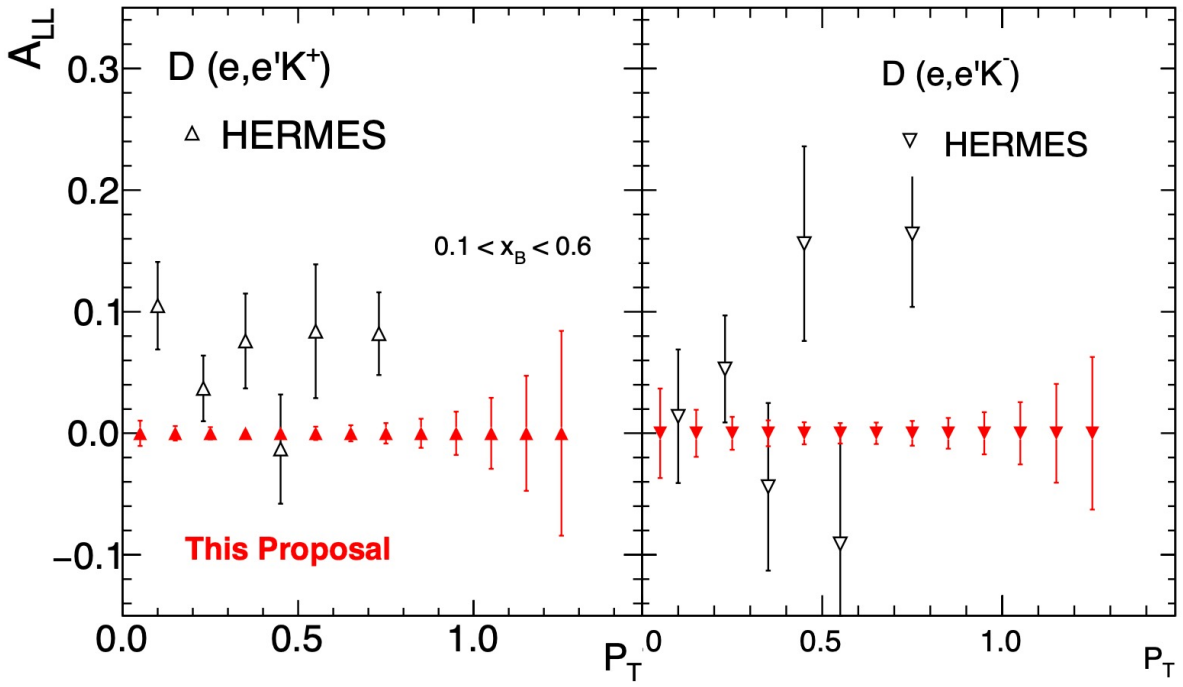
30 days of beam time at luminosity of 2.7×10^{34} nucleons/cm^2/s



K. Ackerstaff et al., Phys. Lett. B 464, 123 (1999)
A. Airapetian et al., Phys. Rev. D 99, 112001 (2019)
M. Gluck, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 63, 094005 (2001)
D. de Florian, R. Sassot, and M. Stratmann, J. Phys. Conf. Ser. 110, 022045 (2008)

Statistical projections on K^+/K^-

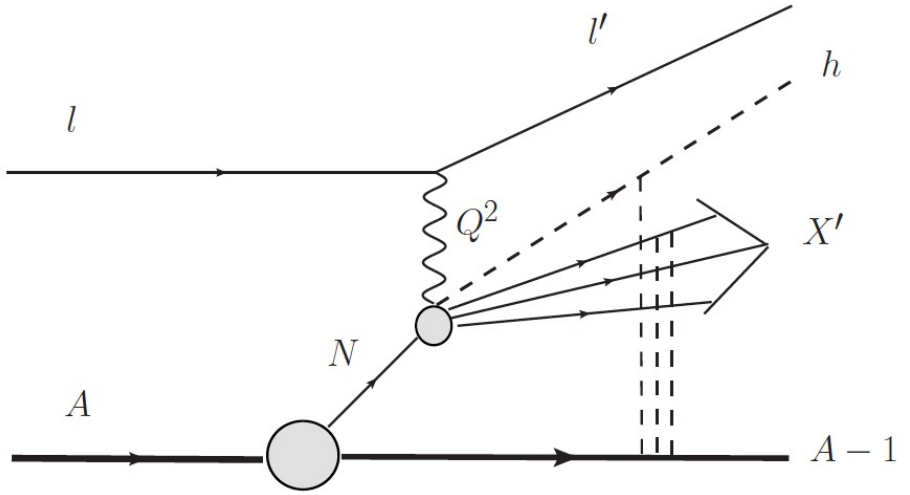




A. Airapetian et al., Phys. Rev. D 99, 112001 (2019)

Other scientific opportunities

- Nuclear corrections to SIDIS
  - Plane wave impulse approximation
  - Final state interaction with spectator nucleons can be significant
  - Generalized eikonal approximation
  - Comparison to other light nuclear targets such as deuteron, ND_3, NH_3, …
- Tagged DIS
- Deeply virtual exclusive processes
- Quasi-elastic scattering
- Transversely polarized target



L. Kaptari et al., Phys. Rev. C 89, 035206 (2014)

Polarized ^{3}He target for CLAS12

Creating a New Target for CLAS12

Double-Cell Cryo Target

- Polarize at 300 K
- Transfer to 5 K target cell
- Density increase 60×

+

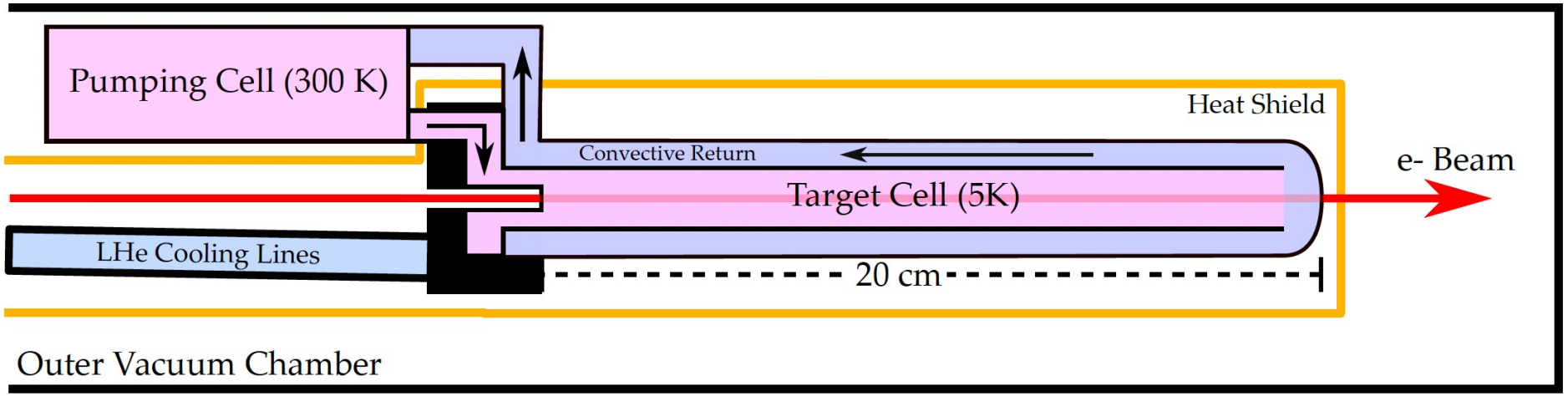
High Field MEOP

- High Polarization (~60%)
- High magnetic fields (5 T)
- Pressure increase 100×

- By combining established technologies: a new polarized target
  (Maxwell, Milner, NIM A, 2021.)
- Achieve 5.4 amg, roughly half JLab SEOP target gas density
- Polarize within 5 T solenoid: CLAS12 standard configuration

Polarized ^{3}He target for CLAS12

Conceptual design



Pumping cell (293 K)

- Borosilicate glass cell
- MEOP to 60% polarization
- Annular cylindrical volume

Target cell (5 K)

- 100 cm^3, 20-cm aluminum cell coated with cryogenic layer
- Cooled by LHe heat exchanger
- Luminosity: 2.7×10^{34} nucleons/cm^2/s at 0.5 μA beam current

J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)

Polarized ^{3}He target for CLAS12

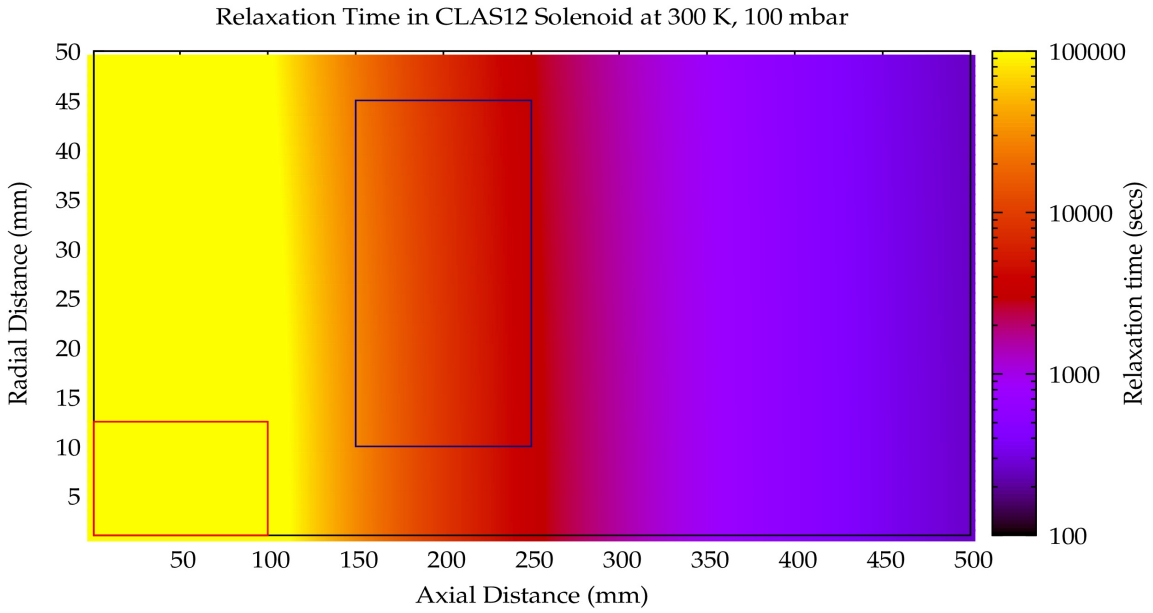
^{3}He relaxation

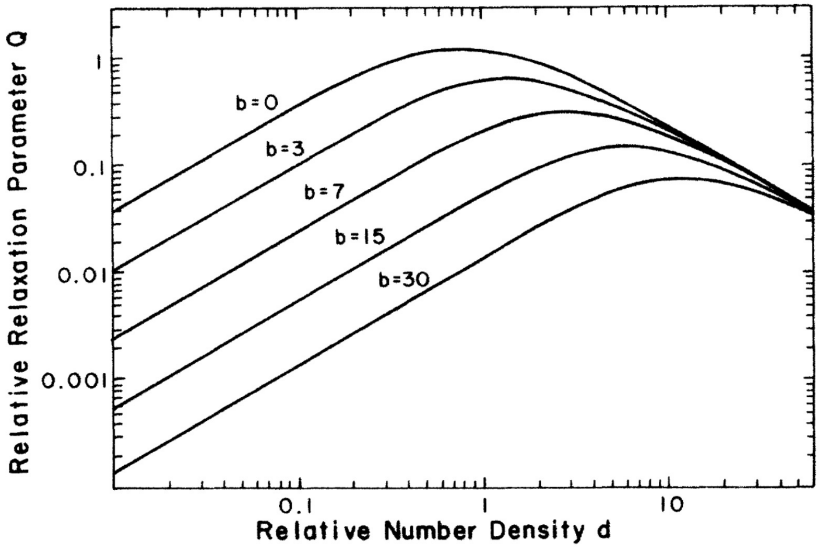
- Wall relaxation: borosilicate glass and coating for aluminum
- Field gradient:
  - 10^4 seconds relaxation

  time around the pumping region

  J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)
- Ionizing radiation:
  - $^3He_2^+$ molecular
  - suppressed with higher field

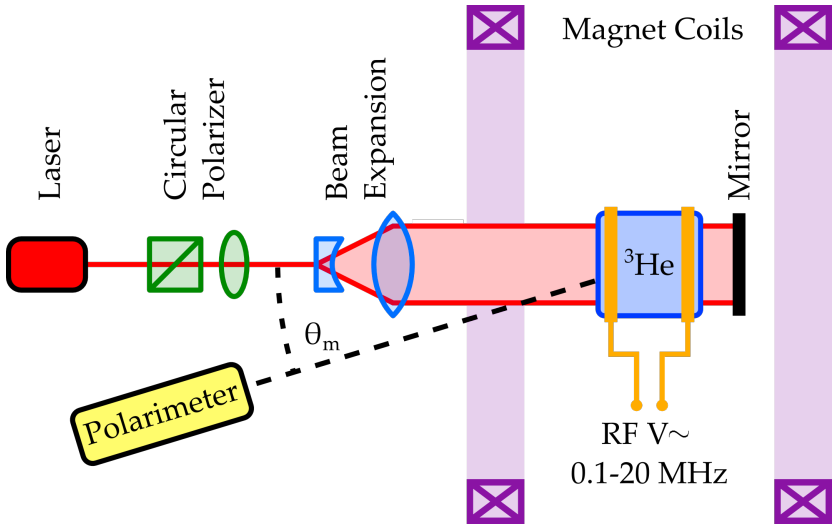
  K. Bonin *et al.*, Phys. Rev. A **37**, 3270 (1988)

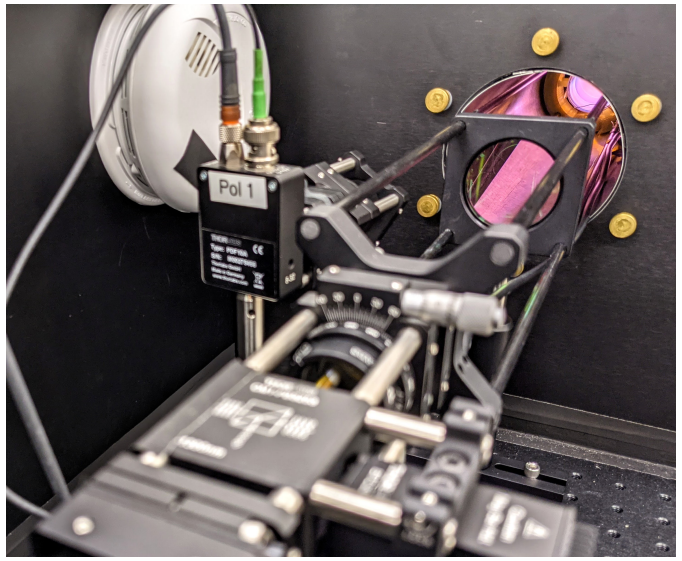


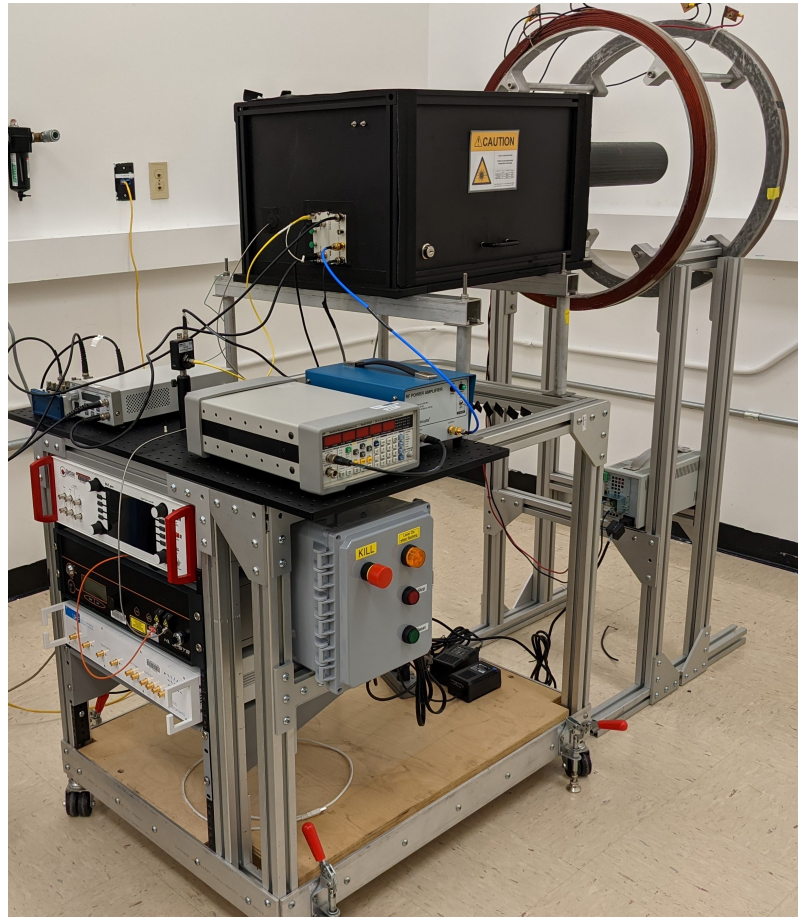


Polarized ^{3}He target for CLAS12 - progress

- Low-field tests completed
  - Sealed ^{3}He cell at ~1mbar
  - Helmholtz pair provides ~30 Gauss magnetic field
  - Achieved 70% nuclear polarization with 1400 seconds relaxation time



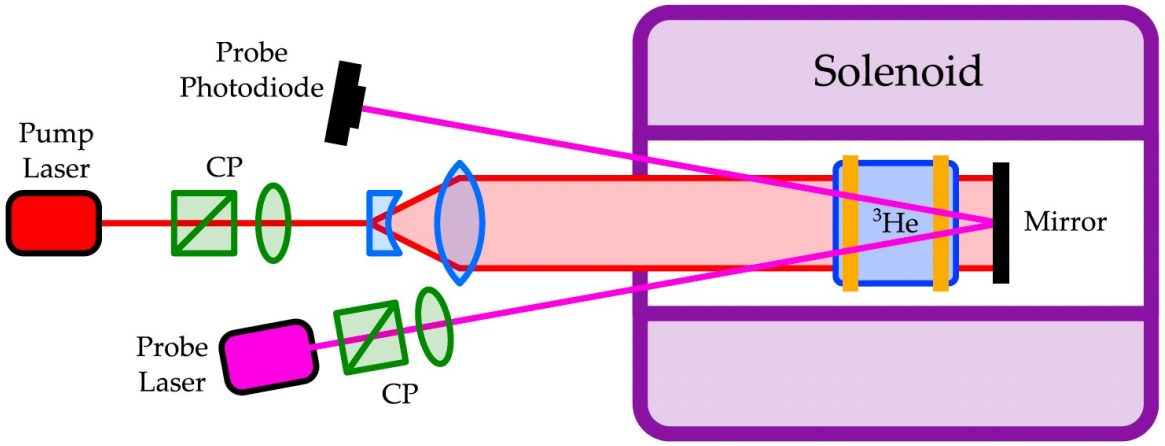




J.D. Maxwell, C.S. Epstein and R.G. Milner, Nucl. Instr. and Meth. A **764,** 215 (2014)

Polarized ^{3}He target for CLAS12 - progress

- High-field tests ongoing
  - Sealed ^{3}He cell first
  - 5T warm-bore solenoid
  - 1083 nm probe laser
  - Next: varied pressure tests



J.D. Maxwell *et al.*, Nucl. Instr. and Meth. A **959,** 161892 (2020)

Projected schedule for CLAS12 polarized ^{3}He target development

- High-field polarization with sealed cells by March 2022
- Polarization at varied pressures by summer 2022
- Double cryogenic cell prototype constructed by January 2023
- Double cryogenic cell prototype beam tests by January 2024
- Target system in CLAS12 by January 2025

Summary

- Proposal approved in 2020 conditionally on successful target development
- Novel MEOP polarized ^{3}He target designed for CLAS12 high field at JLab
- Offers new opportunities to probe nucleon structures using spin-dependent electron scattering from polarized ^{3}He
- Development on target testing system intensively ongoing at JLab
- Possibility for transverse target once longitudinal polarization proven

Acknowledgement

JLab-MIT collaboration for CLAS12 polarized ^{3}He:

- **MIT**: Dr. Xiaqing Li, Prof. Richard Milner
- **JLab**: Dr. James Maxwell, Dr. Dien Nguyen, Dr. Harut Avakian

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Thanks for your attention!