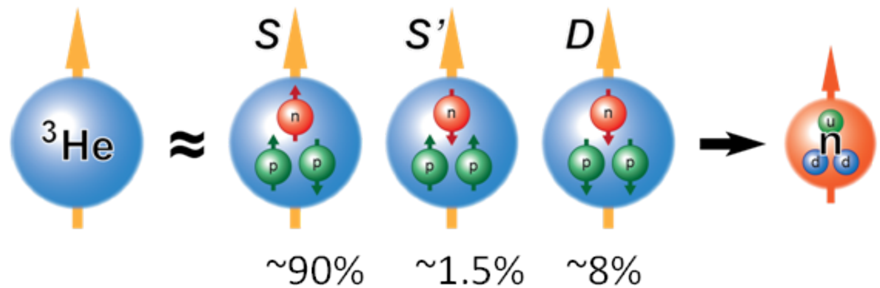
Status of Consideration of Polarized ^{3}He Target in CLAS12

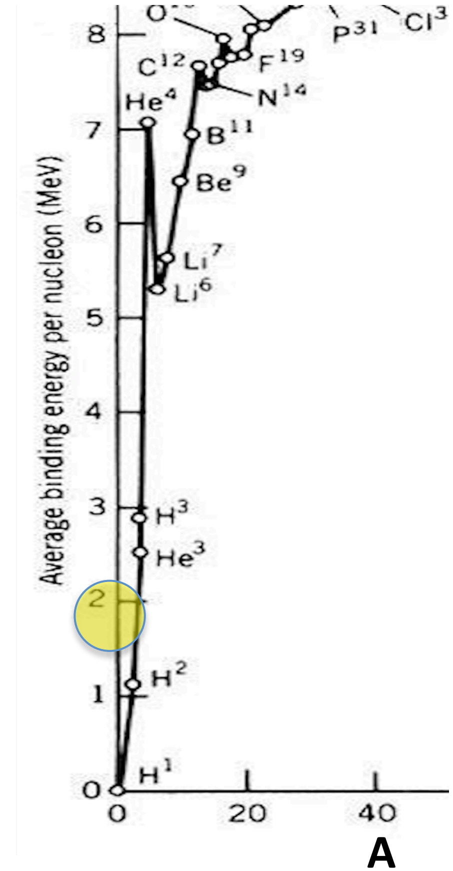
- Physics summary
- Target conceptual design

  (J. Maxwell and RM)
- Path forward

Neutron Spin Structure Function $g_1^n(x,Q^2)$



Neutron polarization: 87%
Proton polarization: 2.7%



- Has been successfully used at MIT-Bates, IUCF, AmPS, SLAC, Mainz, HERMES, JLab
- Quasielastic (e,e'n) scattering yields elastic neutron FF: $G_M^n(Q^2)$, $G_E^n(Q^2)$
- In inclusive spin-dependent electron scattering, precision measurements of $g_1^n(x,Q^2)$ can be made
- Together with measurements of $g_1^p(x,Q^2)$, the Bjorken Sum Rule can be tested.
- ***In spin-dependent DIS if one tagged the spectator proton and deuteron, could one access the spin structure functions of the deuteron and proton in ^{3}He?***

$$|^3\mathrm{He}\uparrow> = (n\uparrow)\,[(p\uparrow p\downarrow) - (p\downarrow p\uparrow)]$$

Pure S-state

$$= (n\uparrow p\uparrow)_{(J=1,M=1)}(p\downarrow) - (n\uparrow p\downarrow)_{(J=1,0,M=0)}(p\uparrow)\ .$$

For the np system, we have $J = 1, 0$ with

$$|1,1> = (n\uparrow p\uparrow)$$

$$|1,0> = \frac{1}{\sqrt{2}}[(n\uparrow p\downarrow + n\downarrow p\uparrow]$$

$$|1,-1> = (n\downarrow p\downarrow)$$

$$|0,0> = \frac{1}{\sqrt{2}}[(n\uparrow p\downarrow - n\downarrow p\uparrow)]\ .$$

We can then write

$$(n\uparrow p\downarrow)_{(J=1,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right]$$
$$(n\downarrow p\uparrow)_{(J=0,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> - |0,0>\right] \ ,$$

which allows us to express the ^{3}He $\uparrow$ spin- state as

$$|^3\mathrm{He}\uparrow>= |1,1> (p\downarrow) - \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

When normalized, this becomes

$$|^3\mathrm{He}\uparrow>= \frac{1}{\sqrt{2}}|1,1> (p\downarrow) - \frac{1}{2}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

Similarly, it follows that

$$|^3\mathrm{He}\downarrow>= \frac{1}{\sqrt{2}}|1,-1> (p\uparrow) - \frac{1}{2}\left[|1,0> - |0,0>\right](p\downarrow) \ .$$

We can then write

$$(n\uparrow p\downarrow)_{(J=1,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right]$$
$$(n\downarrow p\uparrow)_{(J=0,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> - |0,0>\right] \ ,$$

which allows us to express the ^{3}He $\uparrow$ spin- state as

$$|^3\mathrm{He}\uparrow> = |1,1>(p\downarrow) - \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

When normalized, this becomes

$$|^3\mathrm{He}\uparrow> = \frac{1}{\sqrt{2}}|1,1>(p\downarrow) - \frac{1}{2}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

Similarly, it follows that

$$|^3\mathrm{He}\downarrow> = \frac{1}{\sqrt{2}}|1,-1>(p\uparrow) - \frac{1}{2}\left[|1,0> - |0,0>\right](p\downarrow) \ .$$

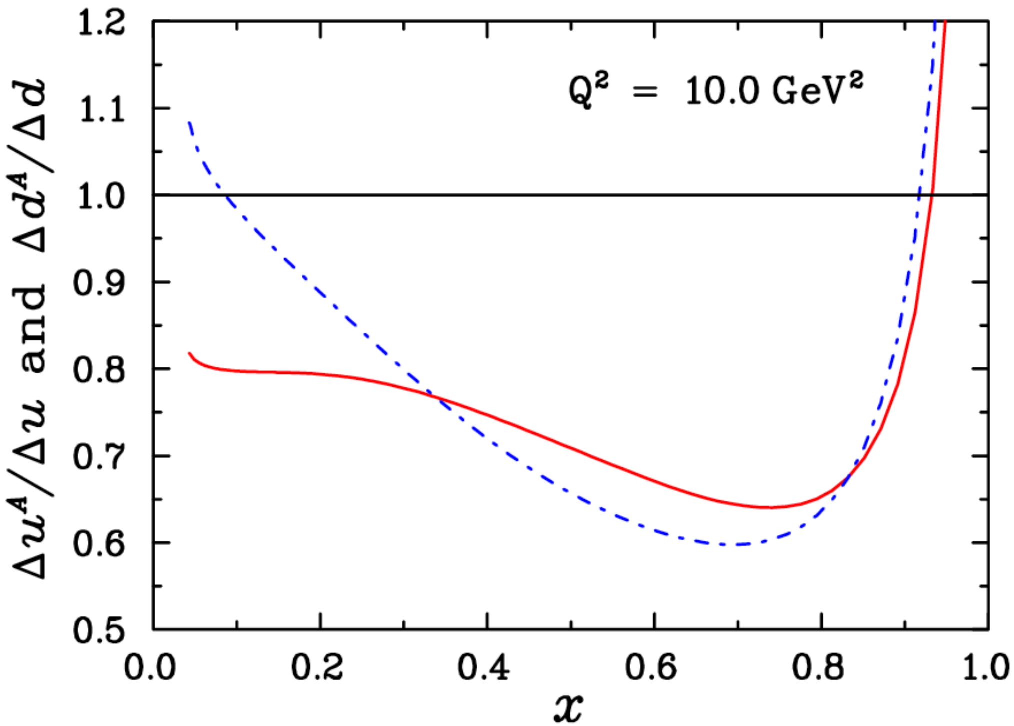
- **Tagged deuteron:** Scattering from the $|0,0>$ state cannot contribute. Thus, measurement of $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e'd_{\mathrm{spectator}})$ in DIS kinematics is equivalent to scattering from a negatively polarized proton 66% of the time and 33% of the time from a positively polarized proton. This is equivalent to scattering from the polarized proton in ^{3}He with -33% polarization. This makes polarized ^{3}He an effective polarized proton target.

- **Tagged proton:** 50% of the time, the scattering arises from the $|1,1>$ state, 25% from the $|1,0>$ state and 25% from the $|0,0>$ state. In forming the spin-asymmetry A in the DIS process $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e'p_{\mathrm{spectator}})$ there will be a contribution from scattering from the deuteron A_{ed}, the contribution arising from the $|1,0>$ state will cancel and there will a correction arising from a contribution A_{corr} from scattering from the np pair in the $|0,0>$ state, i.e.

$$A \sim \frac{2}{3}A_{ed} + \frac{1}{3}A_{corr} \ . \tag{29}$$

How large is A_{corr}?

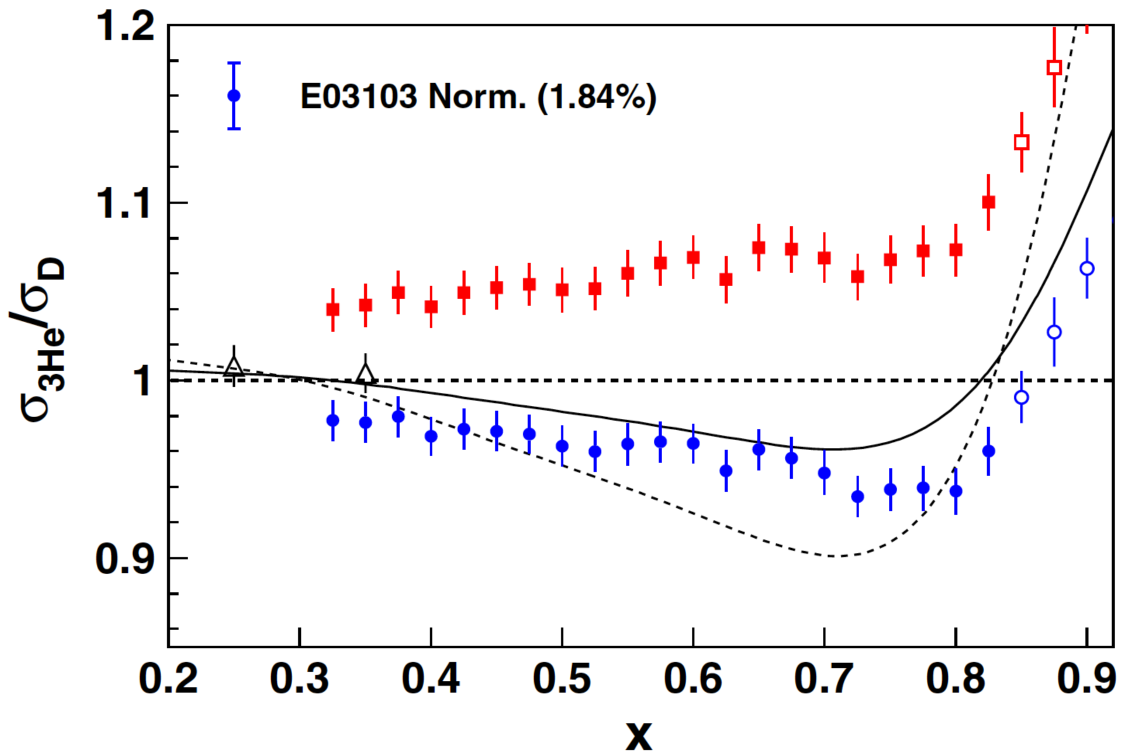
Spin-dependent EMC Effect



Cloet et al, PRL 95, 052302 (2005)

FIG. 4 (color online). Ratio of the quark distributions in nuclear matter to the corresponding free distributions, at a scale of $Q^2 = 10$ GeV^2. The solid line represents $\Delta u^A(x)/\Delta u(x)$ and the dot-dashed line $\Delta d^A(x)/\Delta d(x)$. Note, these distributions are the full quark distributions and hence include antiquarks generated through Q^2 evolution.

Unpolarized EMC Effect in ^{3}He



J. Seely et al. PRL 103 202301 (2009)

FIG. 3 (color online). EMC ratio for ^{3}He [17]. The upper squares are the raw ^{3}He/^{2}H ratios, while the bottom circles show the isoscalar EMC ratio (see text). The triangles are the HERMES results [10] which use a different isoscalar correction. The solid (dashed) curves are the SLAC *A*-dependent fits to carbon and ^{3}He.

R.B. Wiringa *et al.*, Phys. Rev. C **89**, 024305 (2014)

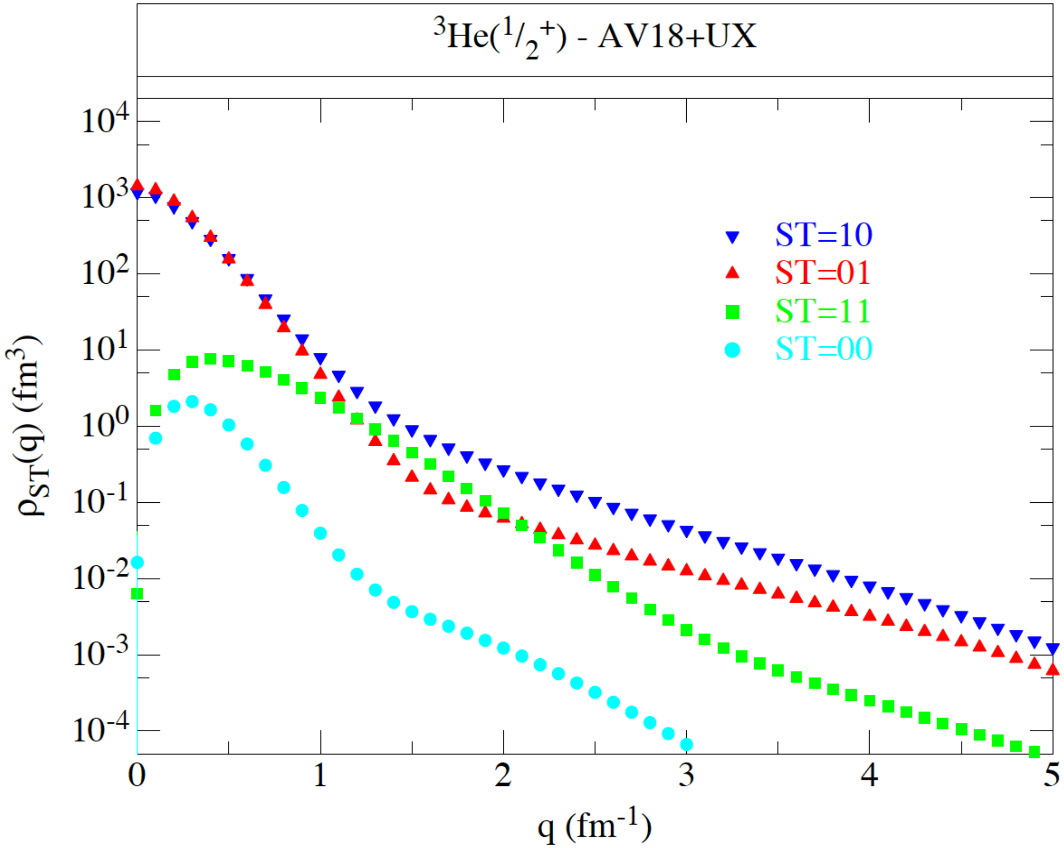


FIG. 8. Momentum distributions of nucleon-nucleon pairs by spin (S) and isospin (T) in ^{3}He in fm^3 calculated using variational Monte-Carlo techniques from [9].

Quasielastic Nucleon Knockout

S-state

$^{3}\overrightarrow{\mathrm{He}}(\vec{p}, pN)$

IUCF

2% S'-state!

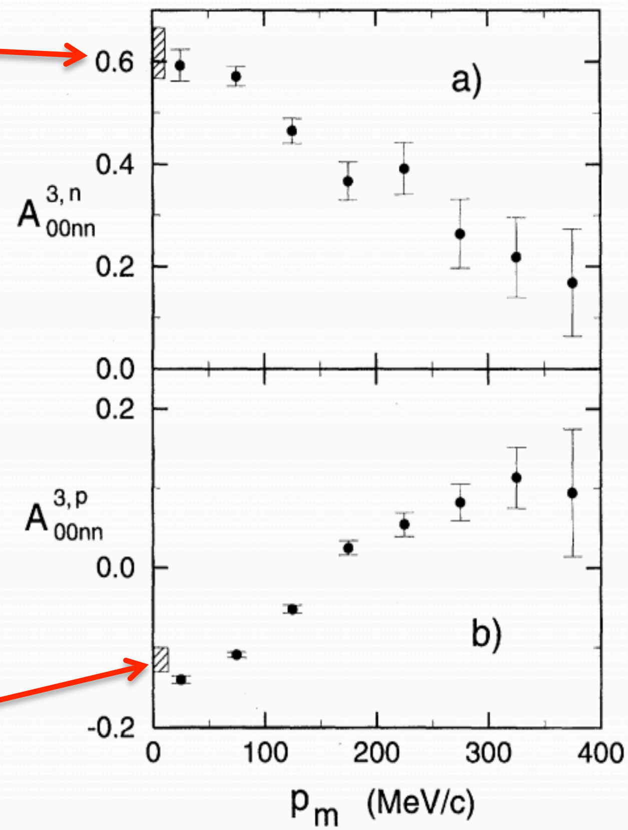
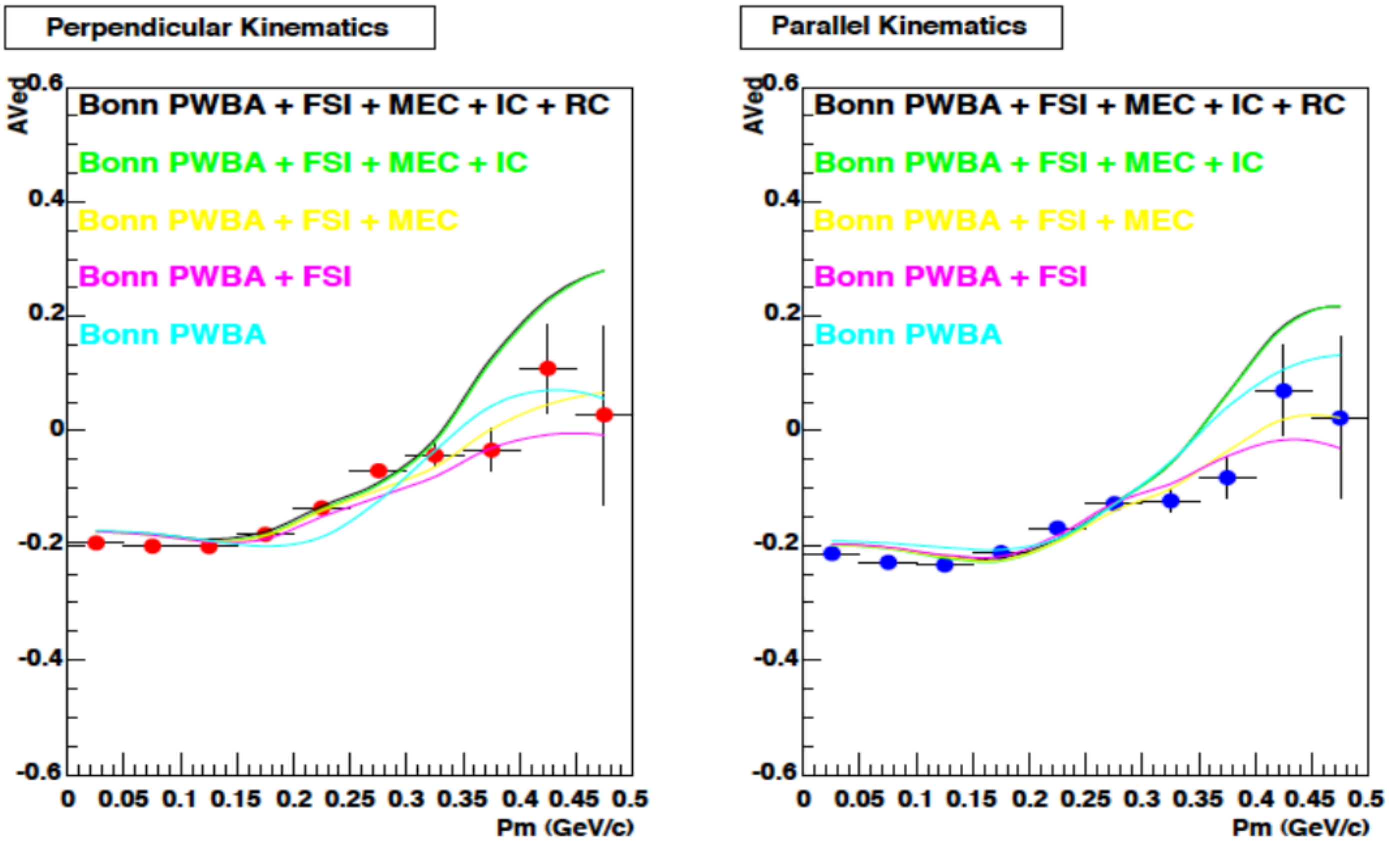


FIG. 3. The missing momentum distribution of (a) $A_{00nn}^{3,n}$ in $^{3}\mathrm{He}(p, pn)$ for $|q| > 500$ MeV/c, (b) $A_{00nn}^{3,p}$ in $^{3}\mathrm{He}(p, 2p)$. The error bars reflect only the statistical errors. In addition there is an error band of ± 0.03 due to luminosity uncertainties. The shaded boxes in each panel at $p_m = 0$ indicate the range of PWIA predictions allowed by various phase shift solutions for the free observables.

M.A. Miller et al., PRL **74**, 502 (1995)

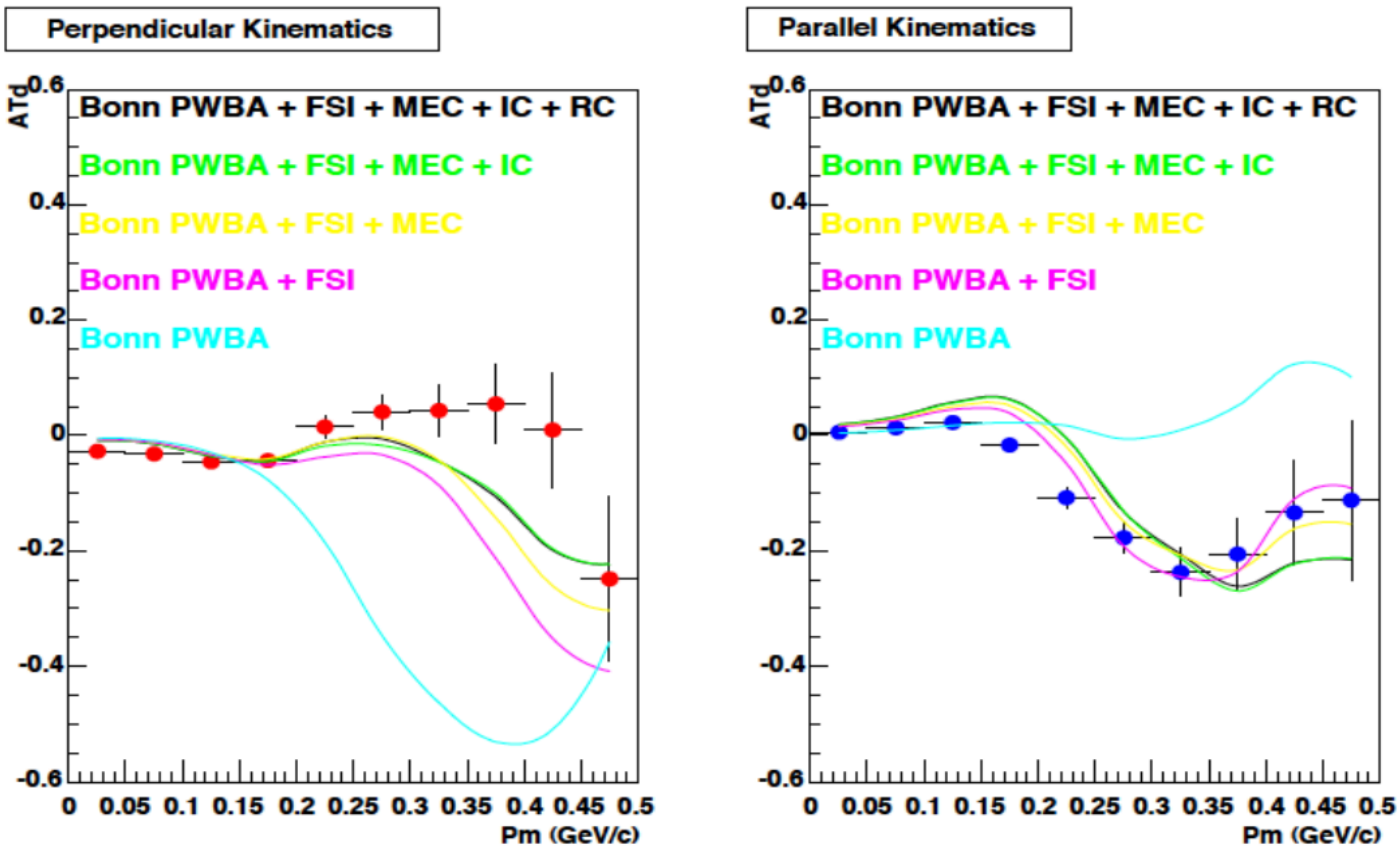
$^2\vec{H}(\vec{e},e'p)$ Vector Asymmetries

BLAST: A. DeGrush et al., PRL 119, 182501 (2017)

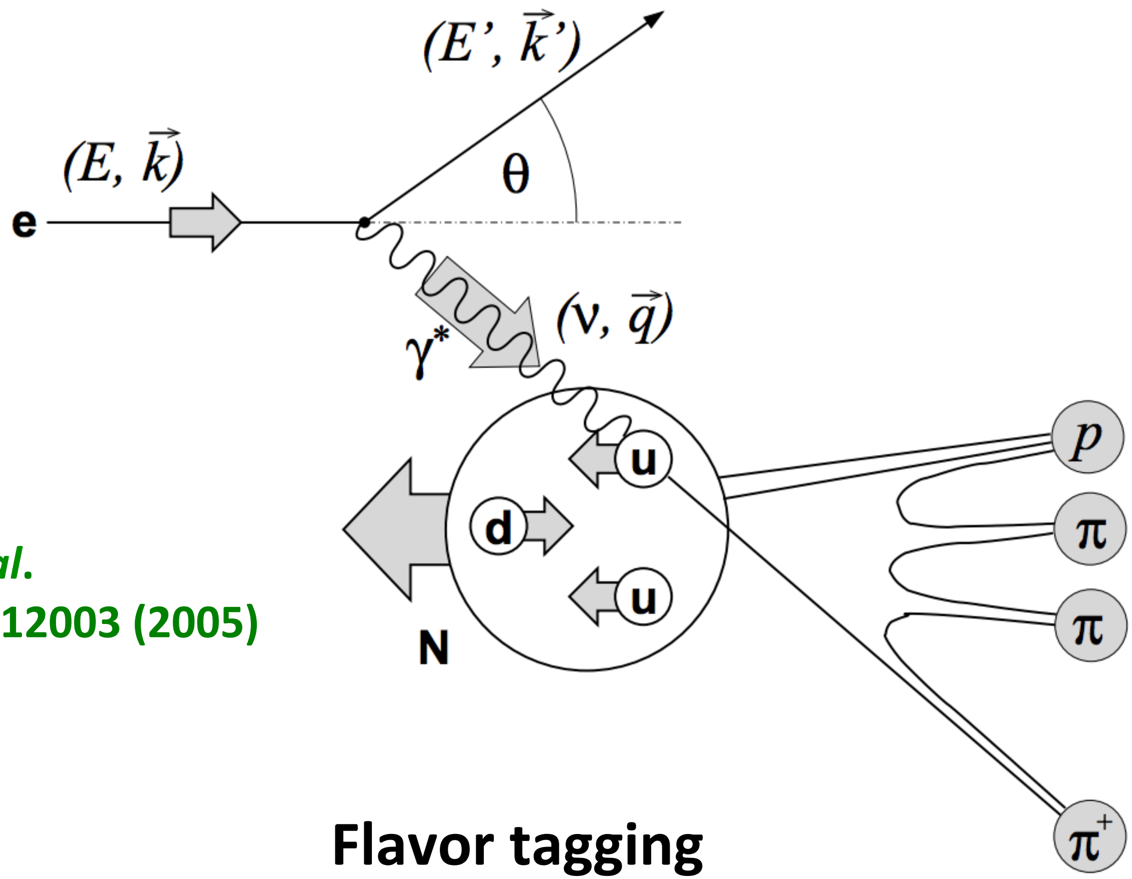


$^{2}\overleftrightarrow{H}(\vec{e},e'p)$ Tensor Asymmetries

BLAST: A. DeGrush et al., PRL 119, 182501 (2017)



Semi-Inclusive DIS

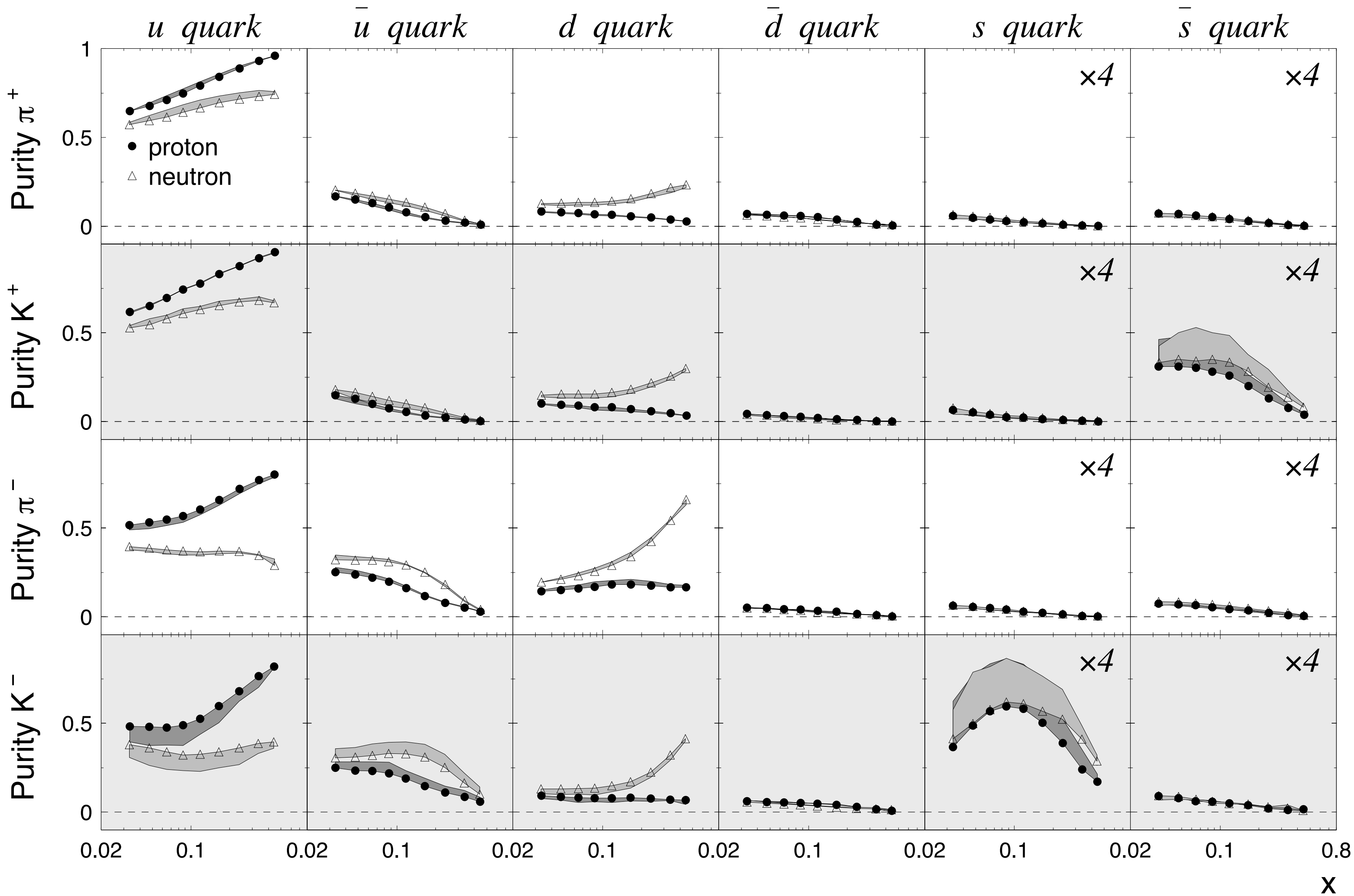


HERMES
A. Airapetian *et al*.
Phys. Rev. D 71, 012003 (2005)

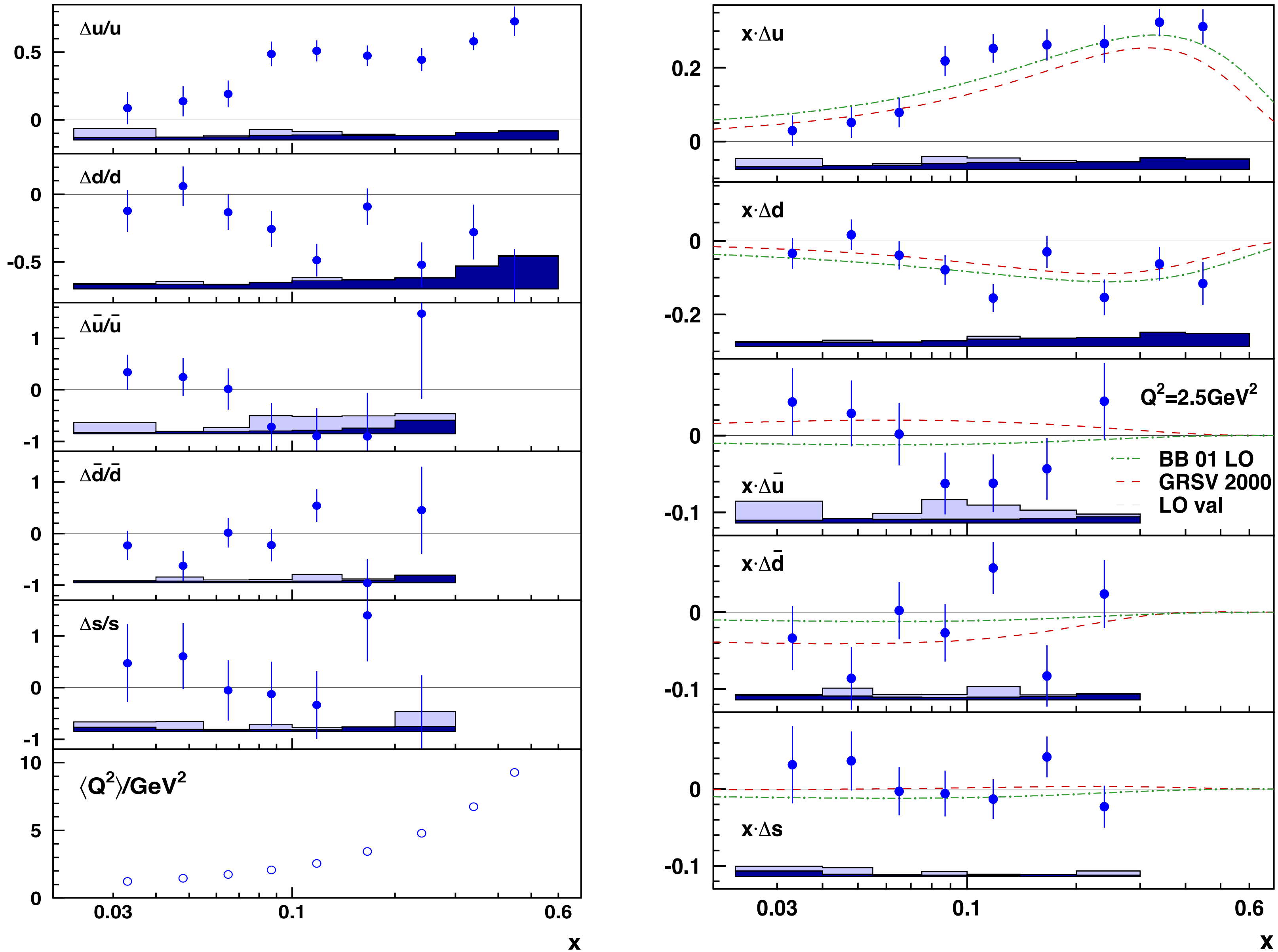
Flavor tagging

$$P_q^h(x_i) = \frac{N_q^h(x_i)}{\sum_{q'} N_{q'}^h(x_i)}.$$

Purities

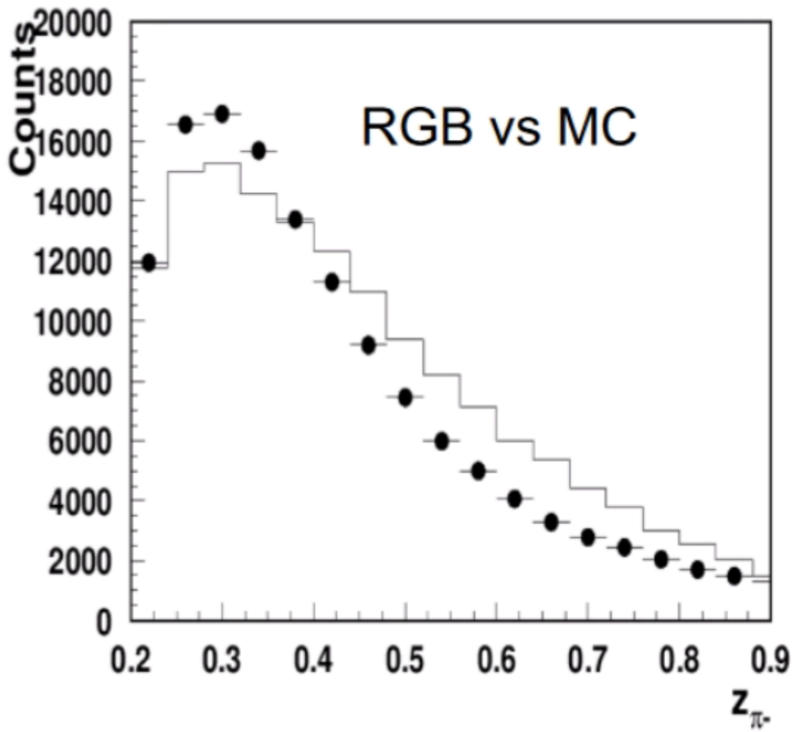


Quark Polarizations

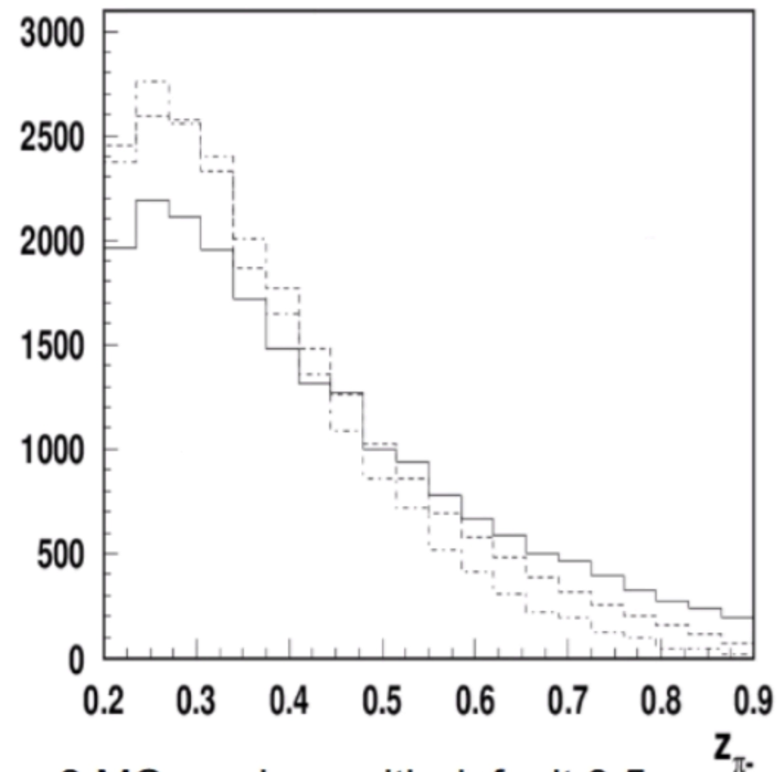


H. Avakian

z-distributions



MC with default settings underestimates π- at small z, and overestimates at large



3 MC versions with default 0.5 (solid), 0.7(dashed) and 0.9(dot-dash) fractions of ρ

DPANA, May 2 10

Polarized Light Flavor Sea

A_L for longitudinal W production

arXiv: 1812.04817

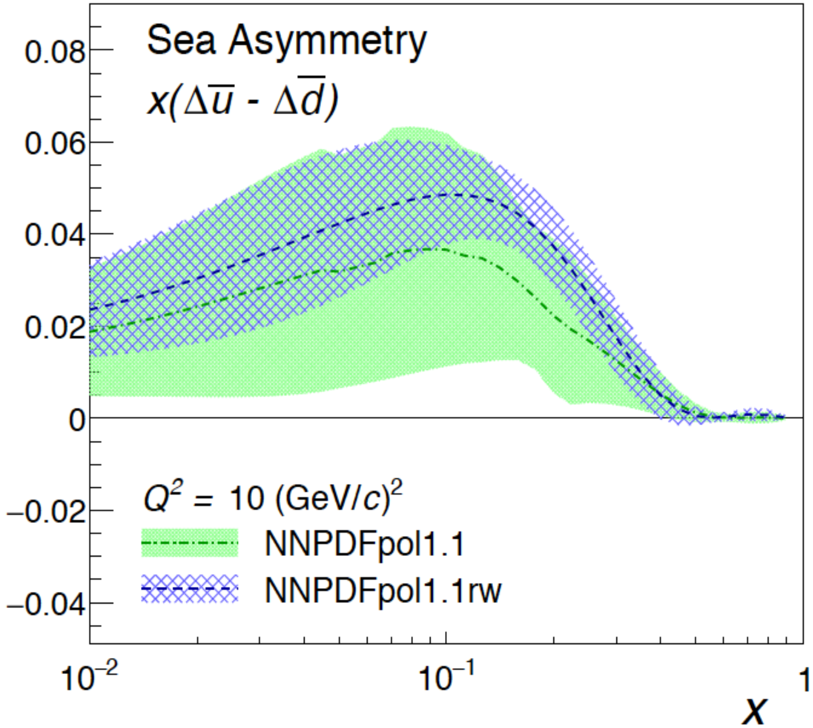


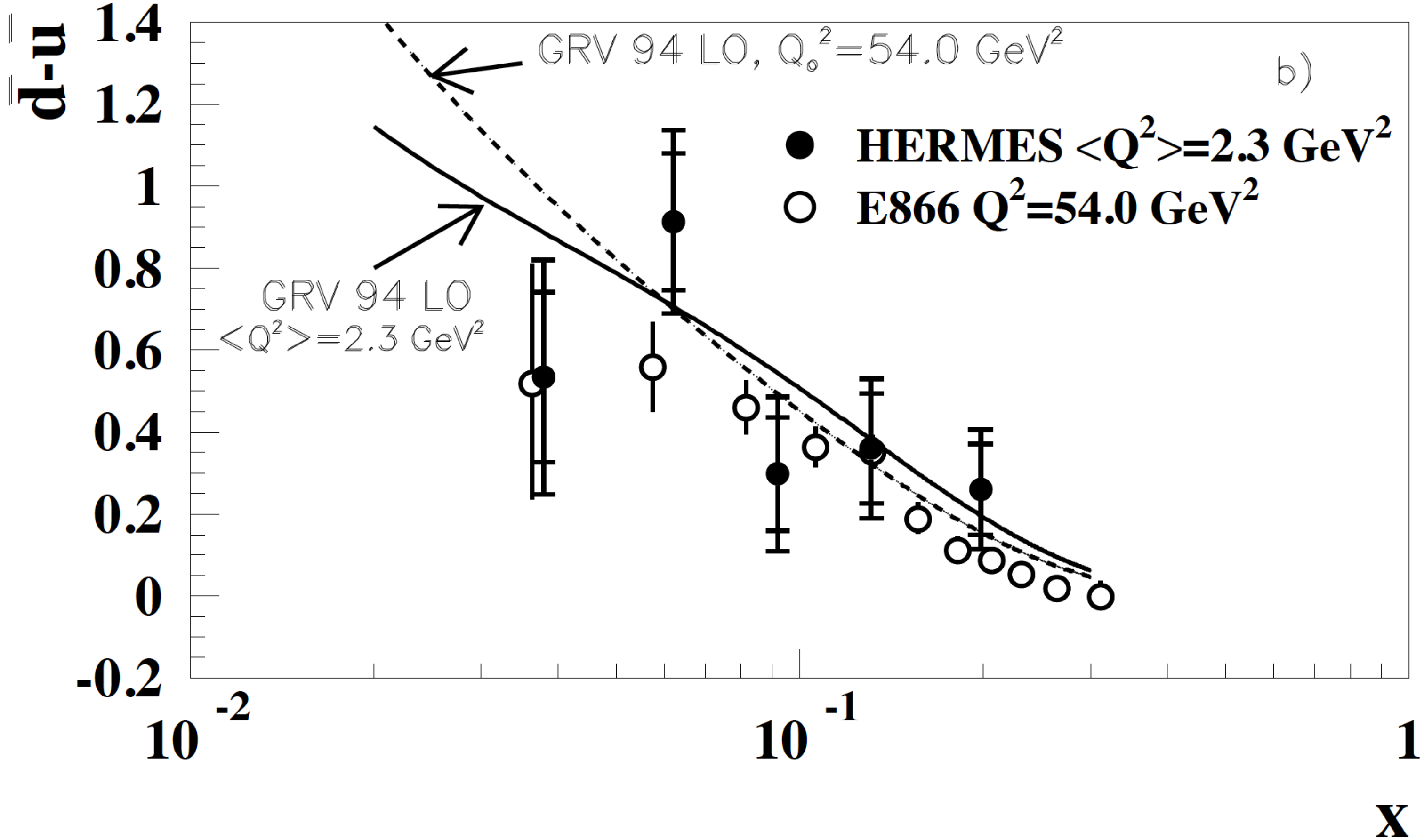
FIG. 6. The difference of the light sea-quark polarizations as a function of x at a scale of $Q^2 = 10\,(\mathrm{GeV}/c)^2$. The green band shows the NNPDFpol1.1 results [1] and the blue hatched band shows the corresponding distribution after the STAR 2013 $W^{\pm}$ data are included by reweighting.

5% asymmetry at Q^2 = 10 (GeV/c)^2 and x = 0.1

Can this be seen in SIDIS?

Flavor Asymmetry of Light Quark Sea

K. Ackerstaff et al., PRL **81**, 5519 (1998)



Neutron GPDs from ^{3}He

M. Rinaldi and S. Scopetta
Phys. Rev. C **87**, 035208 (2013)

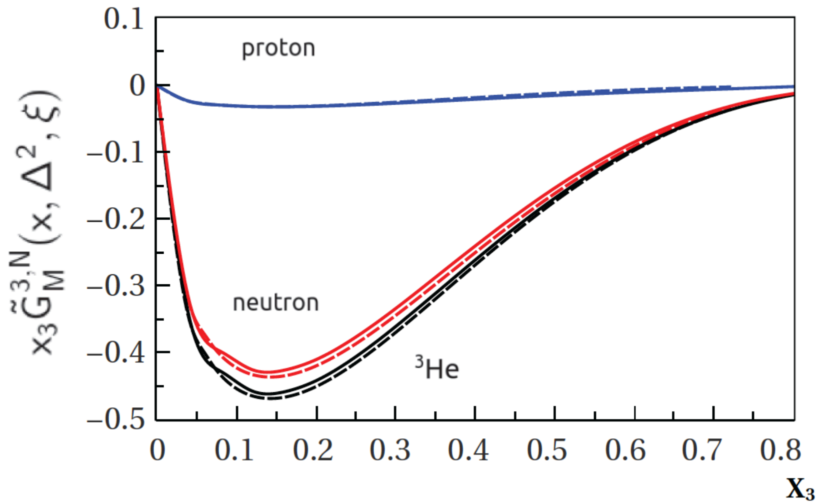


FIG. 6. (Color online) The quantity $x_3\tilde{G}_M^3(x, \Delta^2, \xi)$ of ^{3}He in the forward limit, together with the proton and neutron contribution (solid lines), compared with the approximations to these quantities given by the factorized form of Eq. (21) (dashed lines).

For later convenience, let us define the following auxiliary function, given simply by the sum of the GPDs H_q^A and E_q^A for a given target A of spin-$\frac{1}{2}$:

$$\tilde{G}_M^{A,q}(x, \Delta^2, \xi) = H_q^A(x, \Delta^2, \xi) + E_q^A(x, \Delta^2, \xi). \quad (3)$$

This function, owing to Eq. (2), fulfills obviously the following relation:

$$\int_{-1}^{1} dx\, \tilde{G}_M^{A,q}(x, \Delta^2, \xi) = F_1^{A,q}(\Delta^2) + F_2^{A,q}(\Delta^2) \equiv G_M^{A,q}(\Delta^2), \quad (4)$$

$G_M^{A,q}(\Delta^2)$ being the contribution of the quark of flavor q to the magnetic ff of the target A.

A fundamental result is Ji's sum rule (JSR) [3], according to which the forward limit of the second moment of the unpolarized GPDs is related to the component, along the quantization axis, of the total angular momentum of the quark q in the target A, J_q^A, according to

$$J_q^A = \int_{-1}^{1} dx\, x\, \tilde{G}_M^{A,q}(x, 0, 0). \quad (5)$$

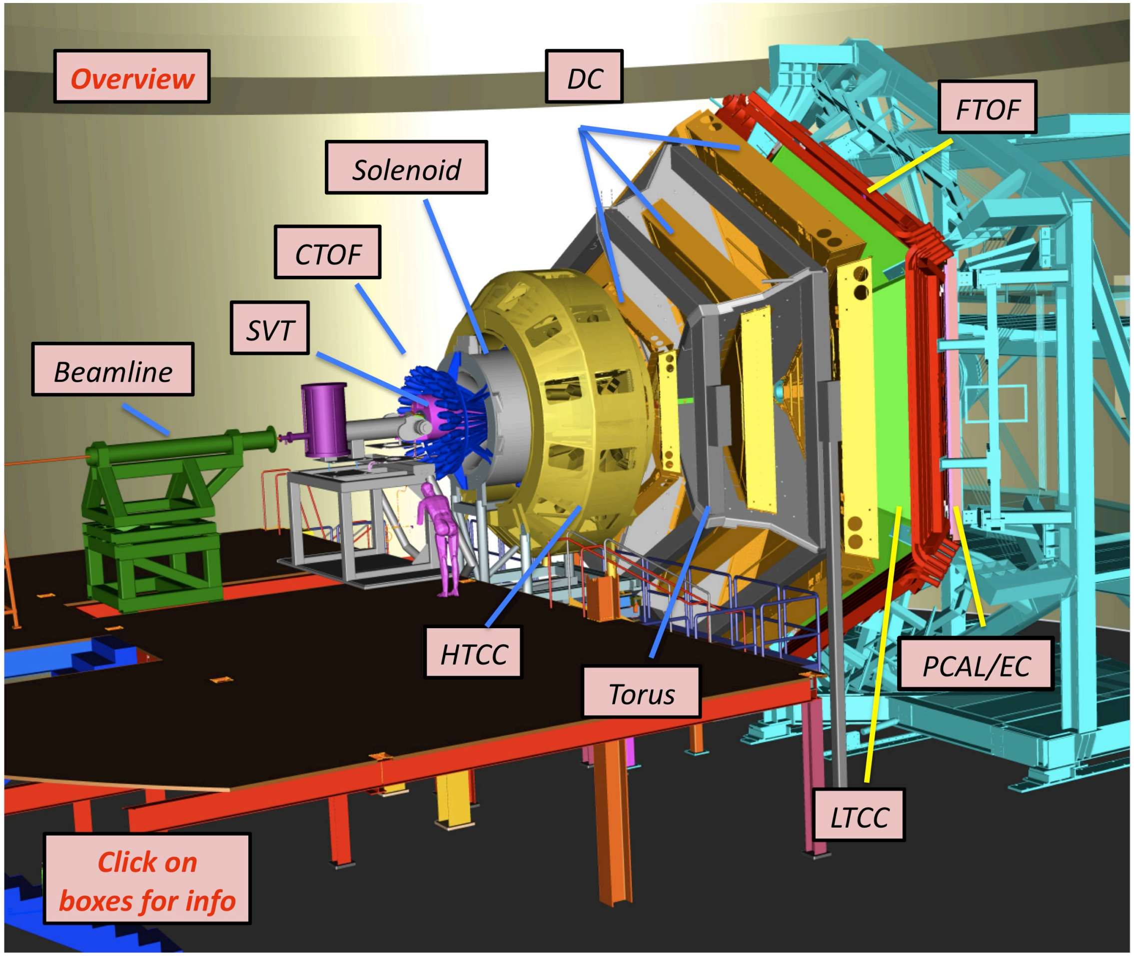
The combination $\tilde{G}_M^{N,q} = H_q^N + E_q^N$ is therefore needed to study the angular momentum content of the nucleon N, through the JSR, and OAM could be obtained from J_q^A, being the helicity content measurable in DIS and SiDIS.

Summary of Physics
Hard scattering with long. polarization

- Inclusive DIS: $g_1^n(x,Q^2)$, Bjorken SR
- Tagged inclusive DIS: spin-dependent EMC effect
- SIDIS: flavor tagging, Δu, Δd, Δs
- DVCS: Neutron GPDs

- Quasielastic nucleon knockout: ground state spin-isospin structure, high-momentum correlated pairs

CLAS12 Detector



Polarized ^{3}He Gas Target Technology

- Gas polarized by optical pumping: MEOP or SEOP
- Targets used at MIT-Bates, TRIUMF, IUCF, SLAC, HERMES, Mainz, JLab
- To date, all OP done at low field, ~ 30 Gauss
- Can implement conventional polarized ^{3}He target in CLAS12 if
    1. the central solenoid is removed
    2. the target is located upstream of CLAS12
    3. ^{3}He is polarized in low field and injected into high field

1 and 2 involve a major modification of CLAS12. **Assume that we do not want to do that.** It is challenging to maintain high polarization with 3.

- BNL-MIT collaboration since 2012 has been funded to develop a polarized ^{3}He ion source for RHIC using existing EBIS, and has successfully developed high field (~ 5 T) MEOP.
- Raises the interesting possibility to OP directly within the 5T CLAS12 solenoid and thus requires no reconfiguration of the CLAS12 detector.

Conceptual Design of a Polarized ^{3}He Target for the CLAS12 Spectrometer

James Maxwell[1] and Richard Milner[2]

[1]Jefferson Lab, Newport News, VA
[2]Laboratory for Nuclear Science, MIT, Cambridge, MA

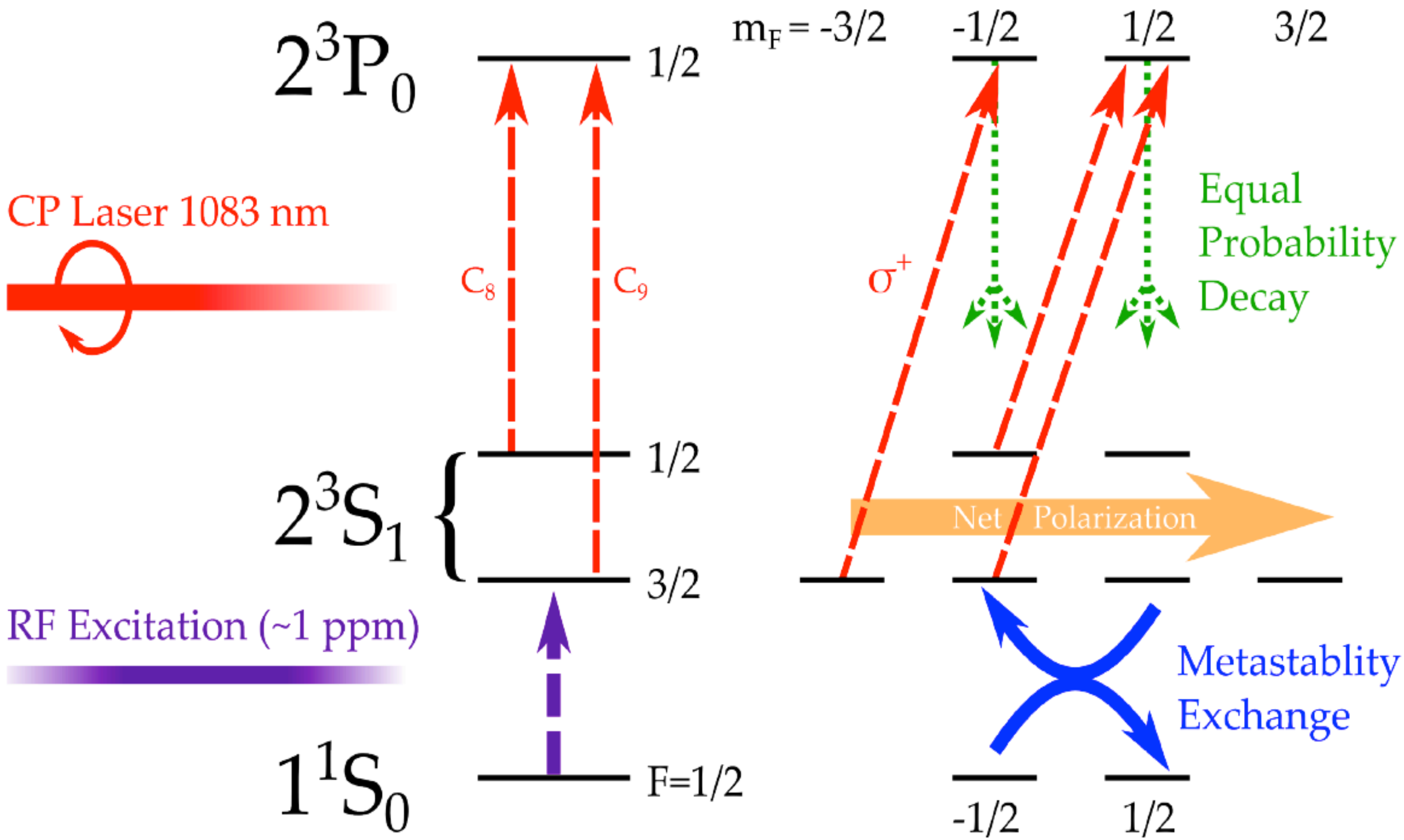
November 14, 2019

Informal review by Polarized Target Group indicates no showstoppers.

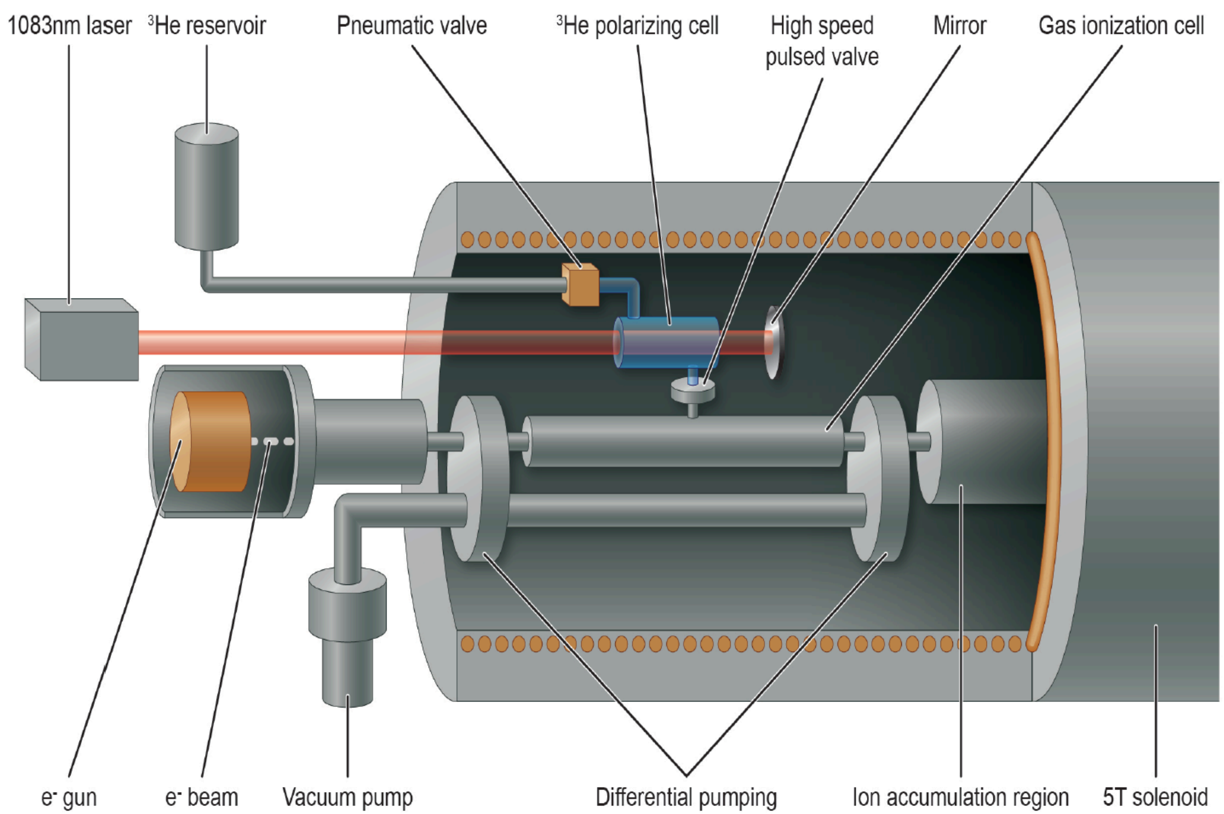
Abstract

We present a conceptual design for a polarized ^{3}He target for Jefferson Lab's CLAS12 spectrometer in its standard configuration. This two-cell target will take advantage of advancements in optical pumping techniques at high magnetic field to create 60% longitudinally polarized ^{3}He gas in a pumping cell inside the CLAS12 5 T solenoid. By transferring this gas to a 20 cm long, 5 K target cell, a target thickness of 3×10^{21} ^{3}He/cm^2 will be produced, reaching the detector's specified maximum luminosity with a beam current of 2.5 μA.

Will be distributed as JLab report and be available on the arXiv



2^3P_0
1/2
m_F = -3/2
-1/2
1/2
3/2
CP Laser 1083 nm
C_8
C_9
σ^+
Equal
Probability
Decay
2^3S_1
1/2
3/2
Net Polarization
RF Excitation (~1 ppm)
Metastablity
Exchange
1^1S_0
F=1/2
-1/2
1/2



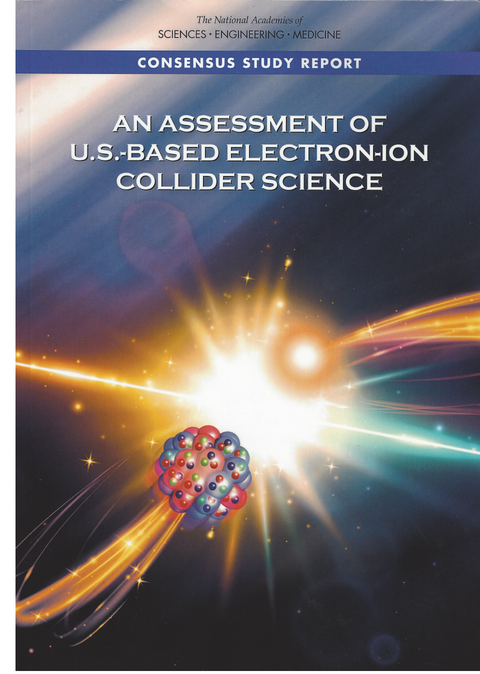


FIG. 5. Schematic layout of polarized ^{3}He ion source under development by a BNL-MIT collaboration using optically pumped polarized ^{3}He atoms directed into the existing Electron Beam Ionization Source.

Polarized ^{3}He expected in RHIC in the early 2020s

Two 5 T Solenoids for Extended EBIS

Polarized ^{3}He ions in RHIC anticipated in early 2020s

Arrived at BNL March 2018

Enhanced Polarization of Low Pressure ^{3}He through Metastability Exchange Optical Pumping at High Field

J.D. Maxwell*, C.S. Epstein, R.G. Milner, M. Musgrave

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA USA

J. Alessi, G. Atoian, E. Beebe, A. Pikin, J. Ritter, A. Zelenski

Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY USA

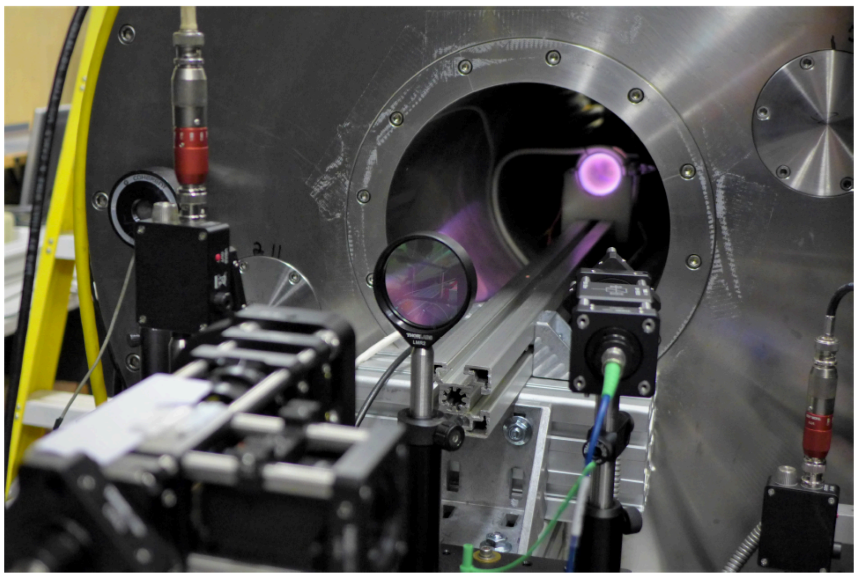


Figure 3: Photograph of the polarizing apparatus and EBIS spare solenoid warm bore. In the foreground are the pumping laser circular polarization optics. The probe laser fiber enters a circular polarizer on the right, and after passing through the cell the probe light is reflected by a mirror back to a photodiode on the left. The sealed cell is illuminated by the RF discharge plasma in pink; for this photograph it is much brighter than is effective for optical pumping.

arXiv: 1812.06139

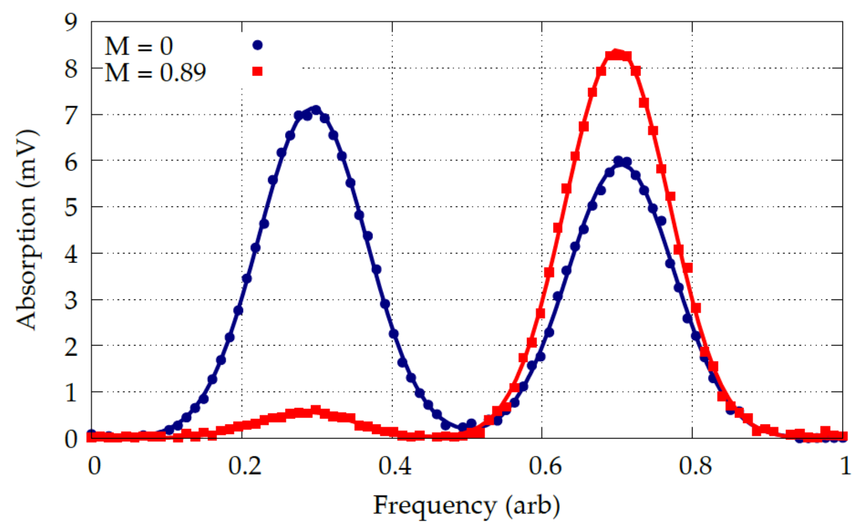


Figure 4: Example probe laser absorption signals with sample nuclear polarization at 0 and 89%, using a 1 torr sealed cell at 3 T. Both probe transition peaks are visible for each signal, as are the side-by-side Gaussian fits used to extract the peak amplitudes for analysis.

Impressive Performance

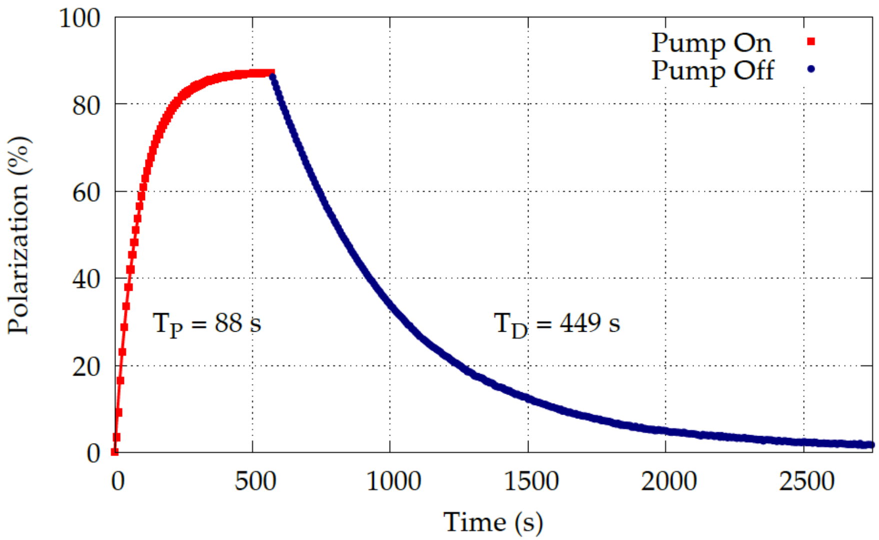


Figure 5: Typical pump and relaxation cycle at 2 T, showing exponential pumping build-up time T_P with the optical pumping active, and the relaxation time T_D after the pumping laser is blocked at 560 s.

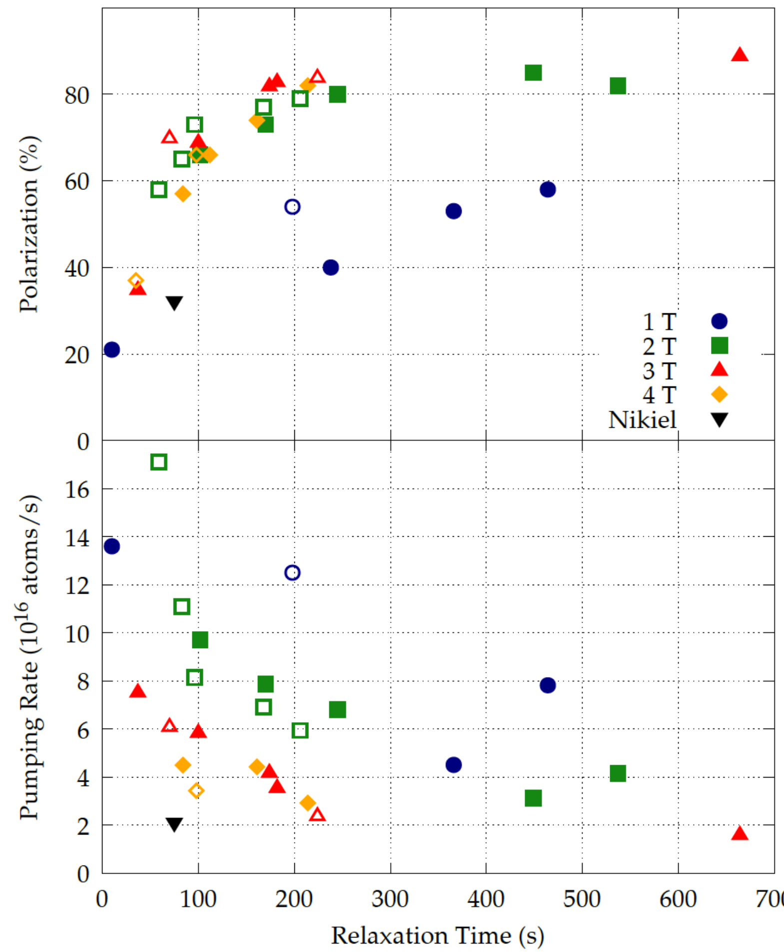


Figure 6: Steady state polarization achieved (top) and corresponding pumping rate (bottom) for a given relaxation time with the plasma discharge. Different shapes represent four magnetic field settings from 1 to 4 T. Filled shapes designate measurements on a 1 torr sealed cell produced a MIT Bates, while open shapes designate those taken on a 1/,torr sealed cell on loan from T. Gentile of NIST. The single 1 torr, 4.7 T result from Nikiel [10] is shown for reference.

Target Operated for Experiment 88-02 at MIT-Bates in 1989

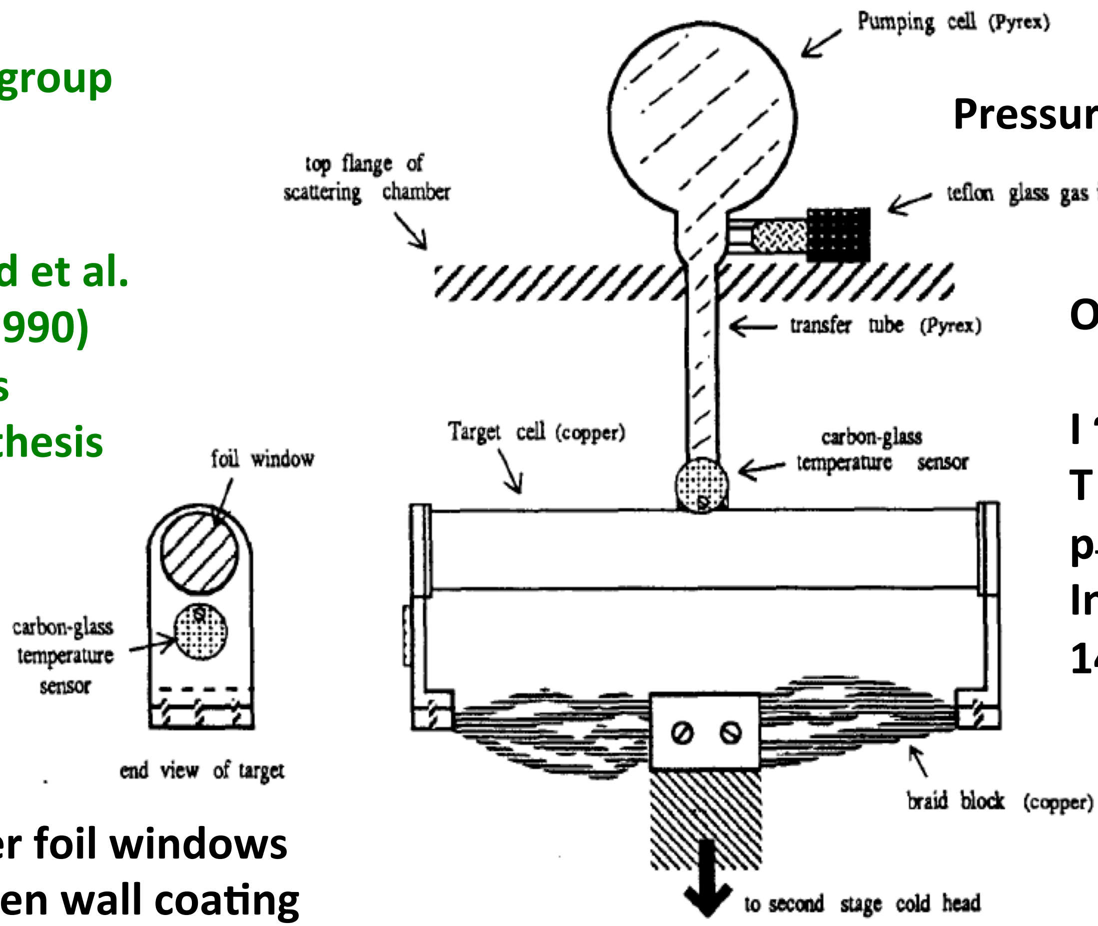
R. McKeown group at Caltech

C.E. Woodward et al.
PRL, 65, 698 (1990)
Cathleen Jones
Caltech Ph.D. thesis
1992

Pressure ~ 2 Torr

Operating Parameters:

I ~ 10 μA
T ~ 15 K
p_T ~ 40%
Integrated charge:
1478 μA-hour



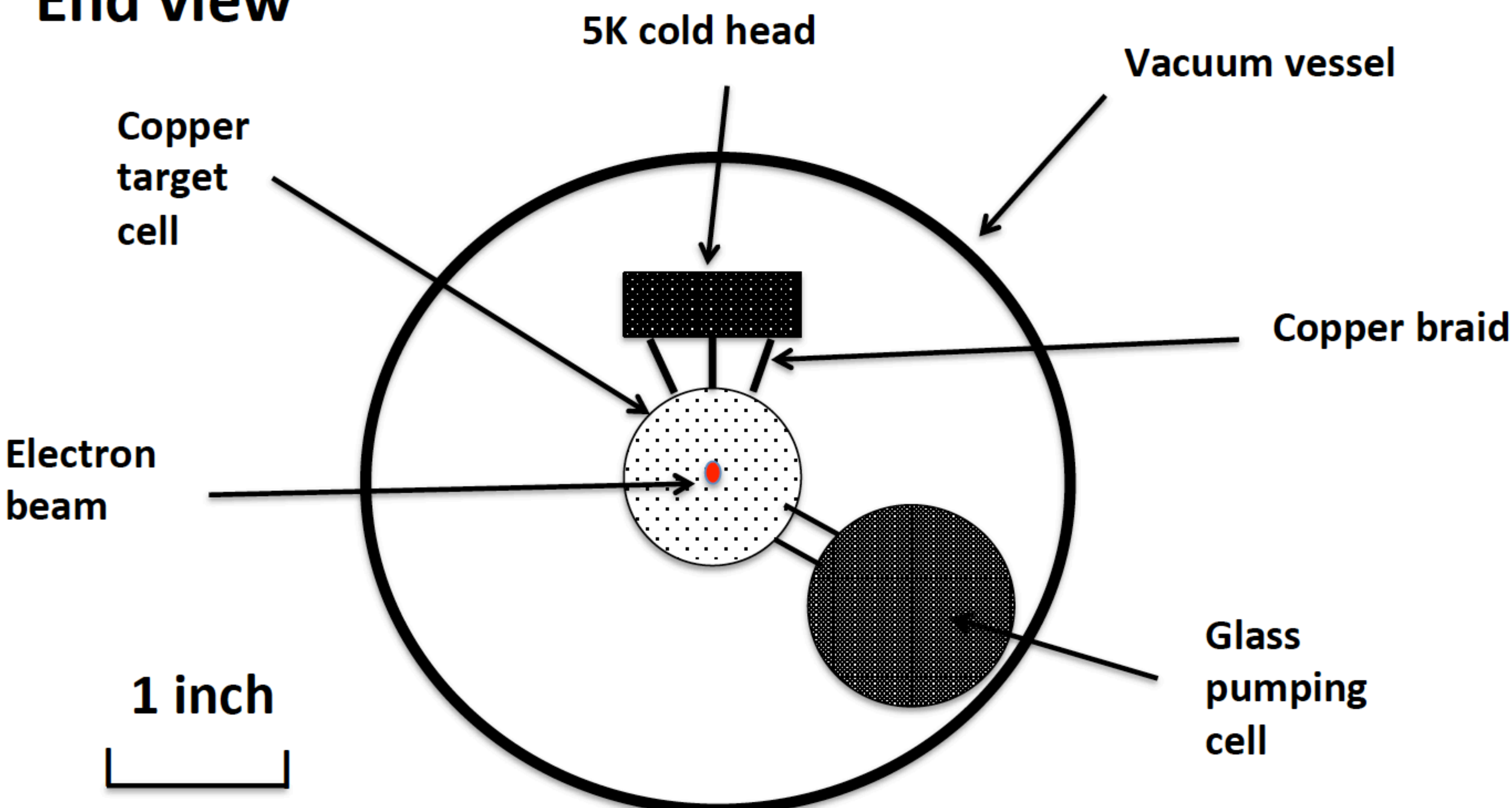
Target cell:
16 cm X 2.54 cm

4.6 μm copper foil windows
Frozen nitrogen wall coating

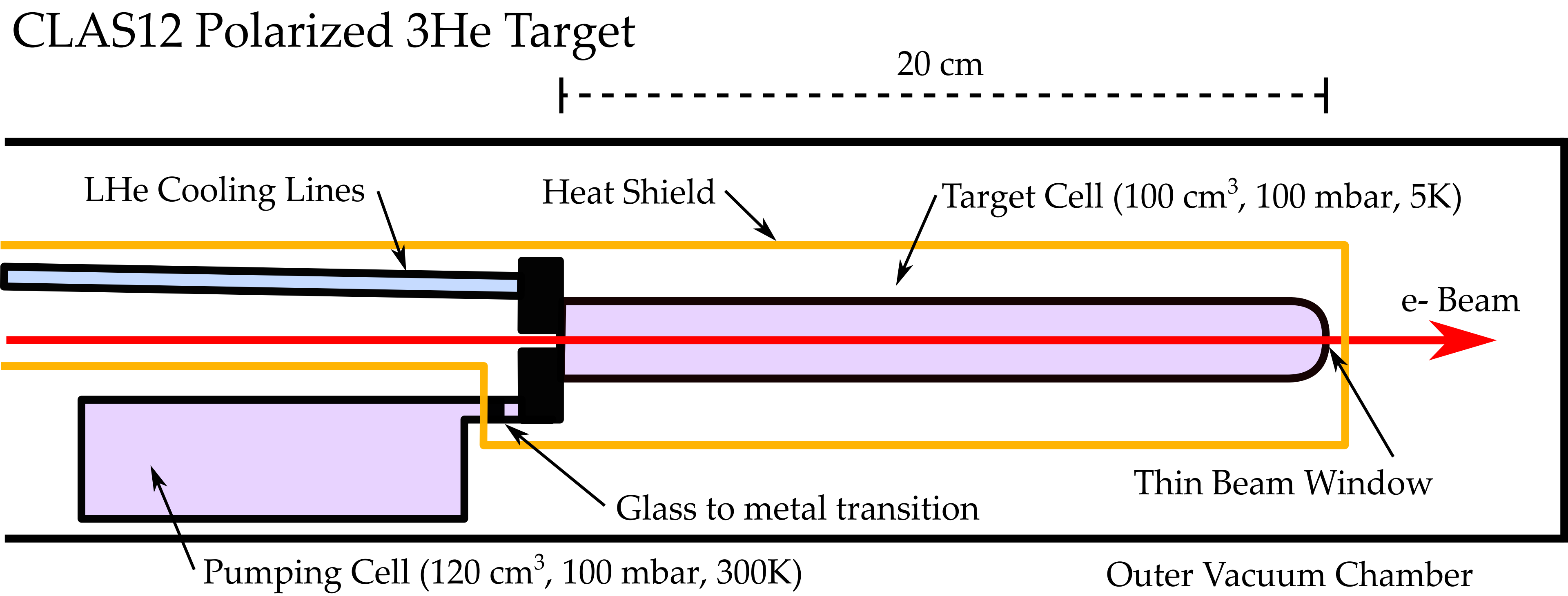
Figure 4.9: Schematic of the polarized ^{3}He target double-cell system. The relative positions of the pumping cell, transfer tube, and target cell are shown, in addition to the braid block, the temperature sensors, and the gas inlet valve.

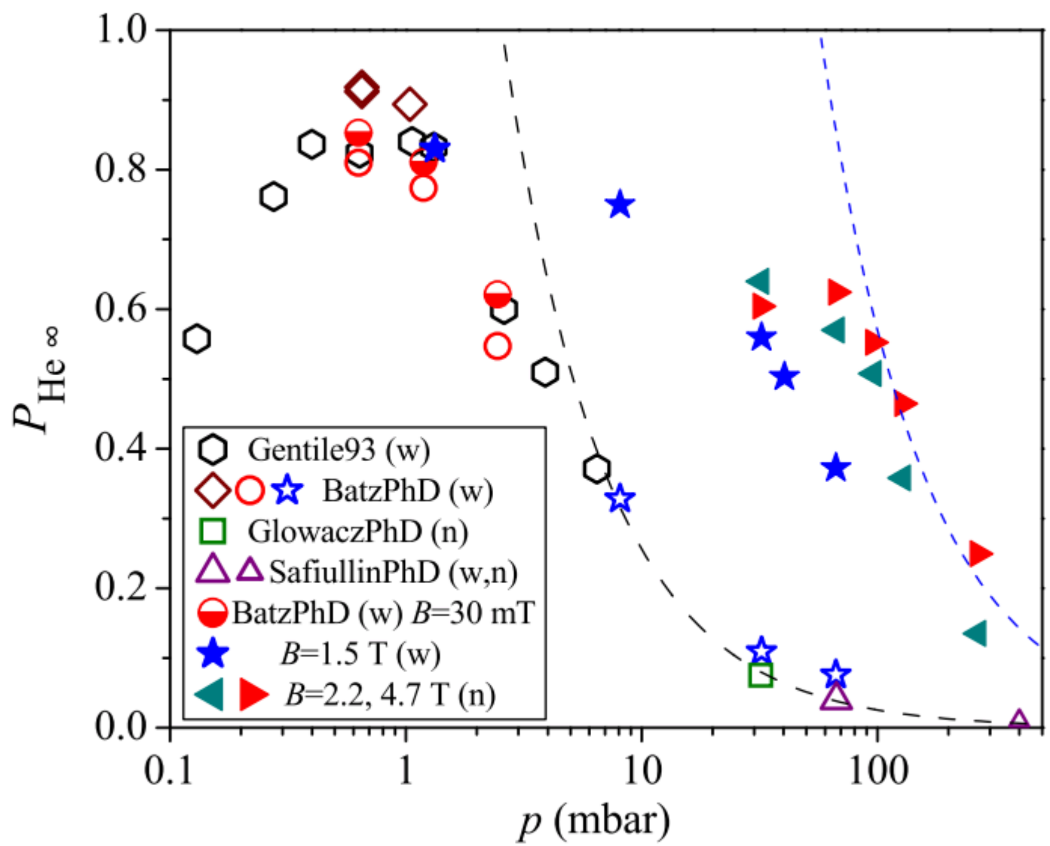
Polarized ^{3}He target in CLAS12 End view

- 2.5 cm dia. X 20 cm long copper target cell
- 4 cm dia. X 10 cm long glass pumping cell



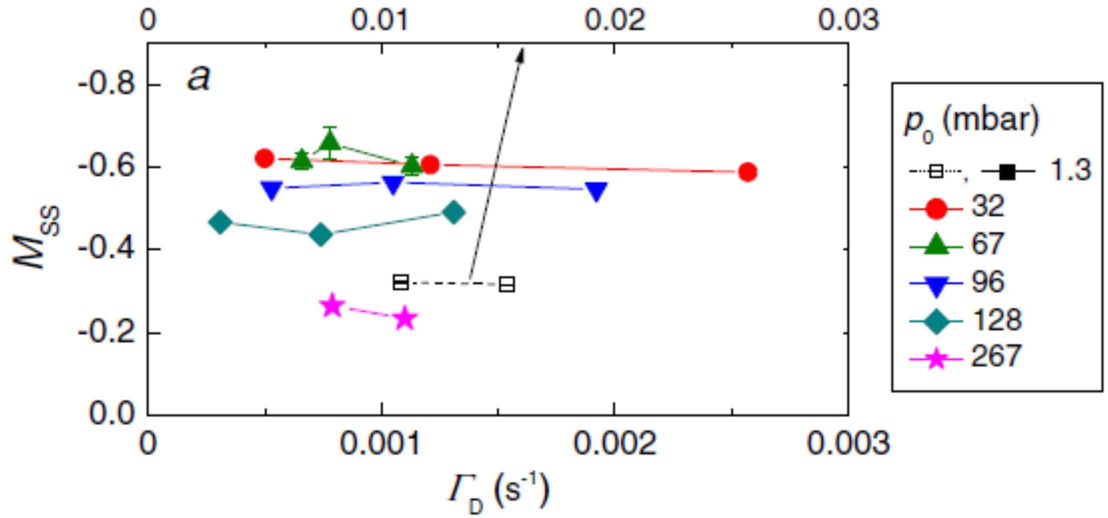
Side view


CLAS12 Polarized 3He Target
20 cm
LHe Cooling Lines
Heat Shield
Target Cell (100 cm3, 100 mbar, 5K)
e- Beam
Thin Beam Window
Glass to metal transition
Pumping Cell (120 cm3, 100 mbar, 300K)
Outer Vacuum Chamber


1.0
0.8
0.6
0.4
0.2
0.0
$P_{He\,\infty}$
0.1
1
10
100
p (mbar)
Gentile93 (w)
BatzPhD (w)
GlowaczPhD (n)
SafiullinPhD (w,n)
BatzPhD (w) B=30 mT
B=1.5 T (w)
B=2.2, 4.7 T (n)

Luminosity Estimate

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



- ENS group report ≈60% ^{3}He polarization at 100 mbar at 4.7 T field
- MEOP at 100 mbar and cool target cell to 5 K
- 20 cm long target
- 2.5 μA electron beam = 6 X 10^{13} e/sec
- Target thickness = 100 X 3 x 10^{16} X 300/5 X 20 ^{3}He-cm^{-2}

  ≈ 3 X 10^{21} ^{3}He-cm^{-2}
- Luminosity ≈ 4.5 x 10^{34} ^{3}He cm^{-2} s^{-1}

≈ x 200 increase over HERMES!

Table 1: Comparison of specifications for the Bates 88-02 target [10] and the CLAS12 target.

Parameter	Bates 88-02 Target Achieved	CLAS12 Target Proposed
Pumping cell pressure (mbar)	2.6	100
Pumping cell volume (cm^3)	200	120
Target cell volume (cm^3)	79	100
Target cell length (cm)	16	20
Number of atoms in pumping cell	1.2×10^{19}	3×10^{20}
Number of atoms in target cell	6×10^{19}	1.5×10^{22}
Holding field (T)	0.003	5
Polarization	40%	60%
Incident electron beam energy (GeV)	0.574	10
Cell temperature (K)	17	5
Target thickness ($^3He/cm^2$)	1.2×10^{19}	3×10^{21}
Beam current (μA)	10	2.5
Luminosity ($^3He/cm^2/s$)	7.2×10^{32}	4.5×10^{34}

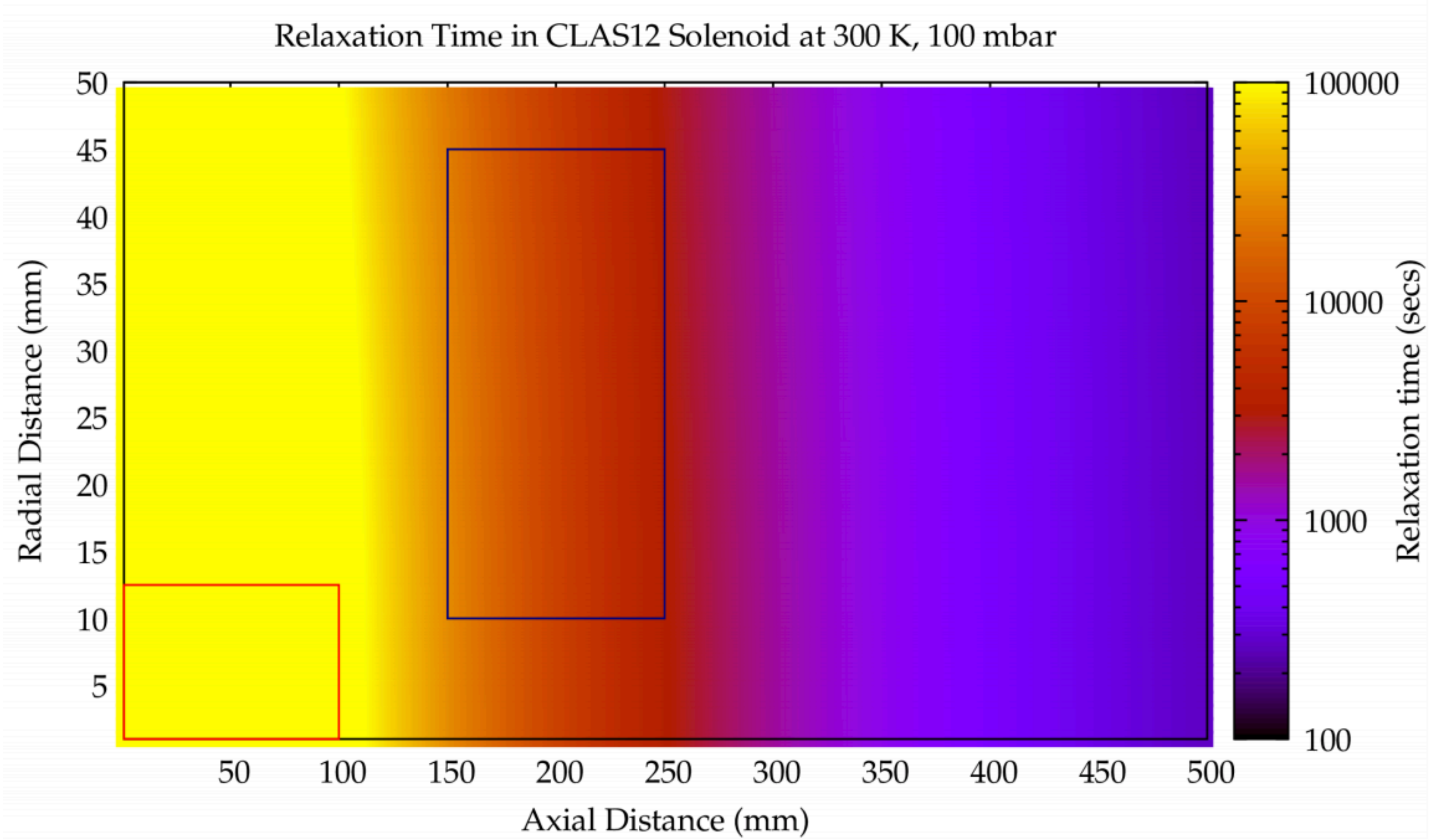


Figure 13: Preliminary map of ^{3}He relaxation time due to transverse field gradients in the CLAS12 solenoid, showing distance from the center of the solenoid. This map assumes gas at 100 mbar and 300 K, and shows candidate locations for a pumping cell (blue box) and target cell (red box).

Issues

- Target cell design
- Heat load
- Beam depolarization
- Solenoidal field gradients
- Beam control and beam dumping
- Transversely polarized target

My Conclusion:

Basic technique sound: based on proven technology

Maximum luminosity attainable in CLAS12 has to be determined via prototype development and testing. Requirements from physics essential here.

Physics with a 10 GeV Polarized Electron Beam on a Polarized ^{3}He Target in the CLAS12 Spectrometer

Assumptions:

Incident beam energy: E_0 = 10 GeV
Beam polarization = 90%
Target polarization = 50% in 5T field of central detector, longitudinal to the direction of the incident beam
Incident beam current: I = 2.5 μA = 1.5×10^{13} e/sec
Target thickness: t = 3×10^{21} ^{3}He/cm^2
Luminosity (I•t) = 4.5×10^{34} ^{3}He/cm^2/s = 1.4×10^{35} nucleon/cm^2/s

Process	**Reaction**	**Physics Focus**	**Issues**
Inclusive DIS	$e+^3He \to e'$	$g_1^n(x,Q^2)$	
Tagged Structure Functions	$e+^3He \to e' + p$ $\to e' + d$	$g_1^p(x,Q^2)$ $g_1^d(x,Q^2)$ for p,d in ^3He Spin-dependent EMC effect	Detecting spectator p/d Coexistence of tagger and polarized target in central detector
Semi-Inclusive DIS	$e+^3He \to e' + \pi^{+/0/-}$ $e+^3He \to e' + K^{+/0/-}$	Flavor dependence of quark polarizations in neutron	Good particle ID
Deeply Virtual Processes	$e+^3He \to$ $e' + {}^3He +$ $\pi^0/\gamma/\phi$.....	Neutron GPDs	Detection of recoil ^3He

Path Forward

- High priority: develop in detail most compelling physics measurements
  - Use CLAS12 Monte-Carlo and measured rates
  - Engage with theorists
- In parallel, target development can be pursued by JLab-MIT collaboration
  - MEOP at high pressure and high field
  - Build prototype two-cell target system to fit in CLAS12 central detector
  - Study beam depolarization effects with low-energy beam
- Organize interested CLAS12 collaborators into a polarized ^{3}He target working group and work on studying quantitatively the physics measurements.
- Plan to have a workshop in about 6 months to prepare LOI for summer 2020 PAC.