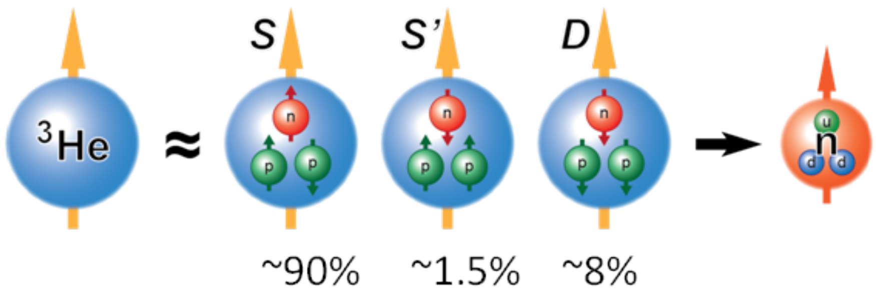
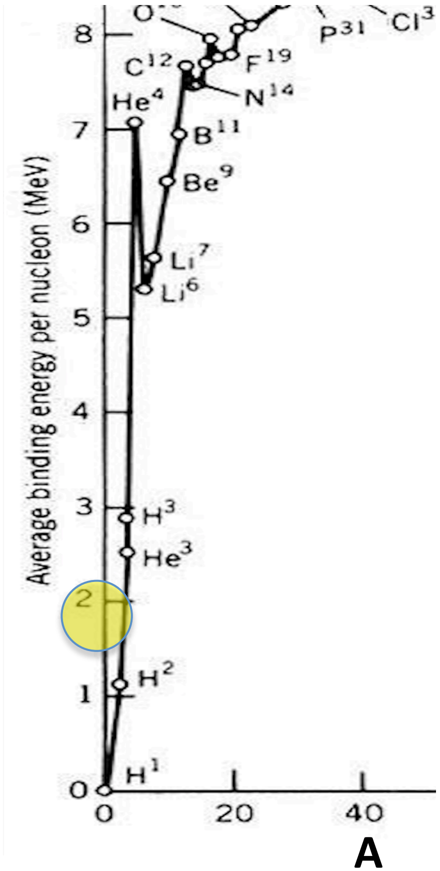
Polarized ^{3}He Target in CLAS12

- Physics Possibilities
- Possible Technical Realization
- 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

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

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

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

When normalized, this becomes

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

Similarly, it follows that

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

- **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

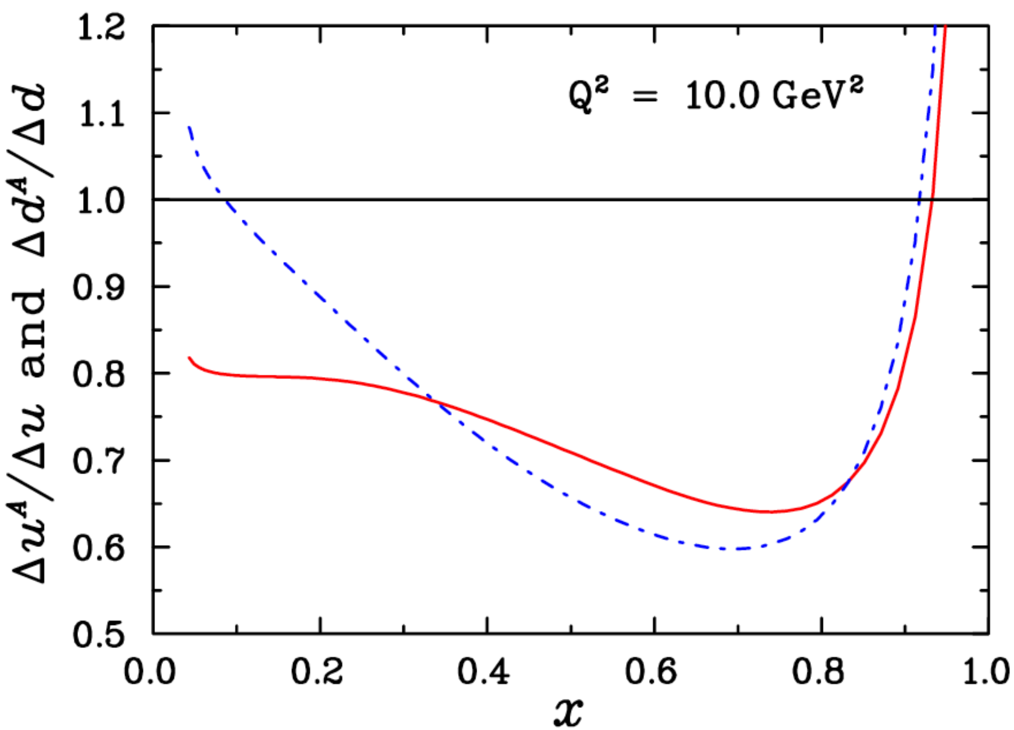
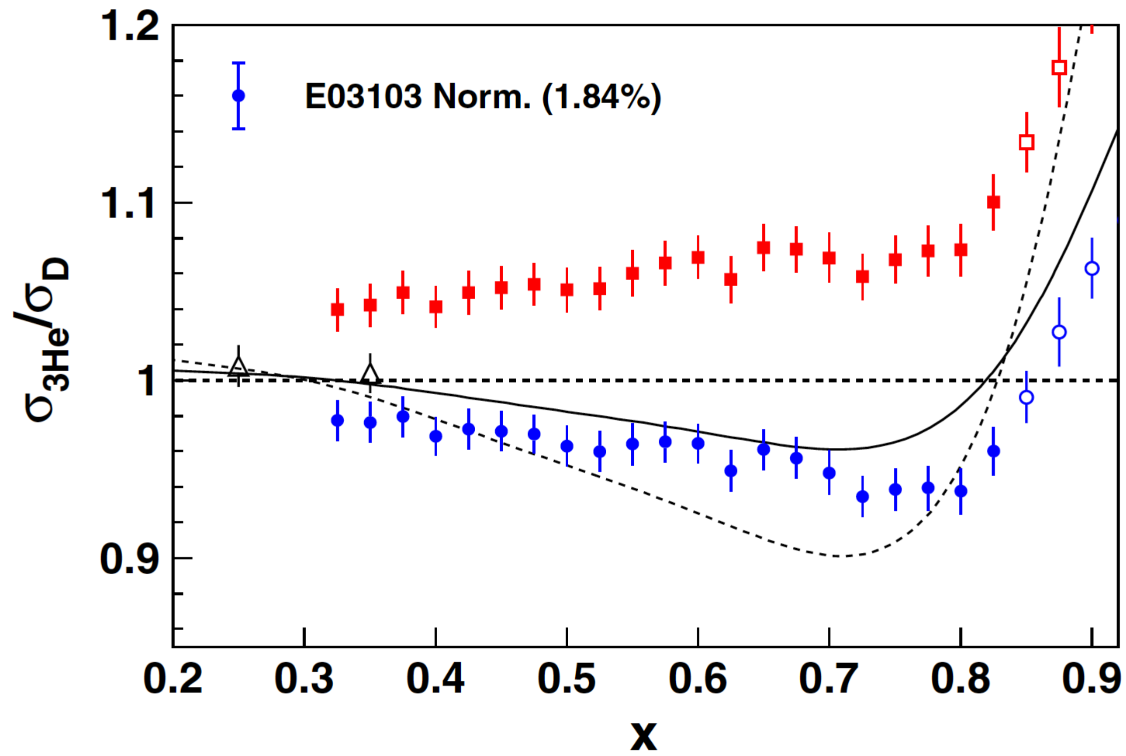


FIG. 4 (color online). Ratio of the quark distributions in nuclear matter to the corresponding free distributions, at a scale of $Q^2 = 10\ \text{GeV}^2$. The solid line represents $\Delta u^A(x)/\Delta u(x)$ and the dot-dashed line $\Delta d^A(x)/\Delta d(x)$. Note, these distributions are the full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

Cloet et al, PRL 95, 052302 (2005)

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)

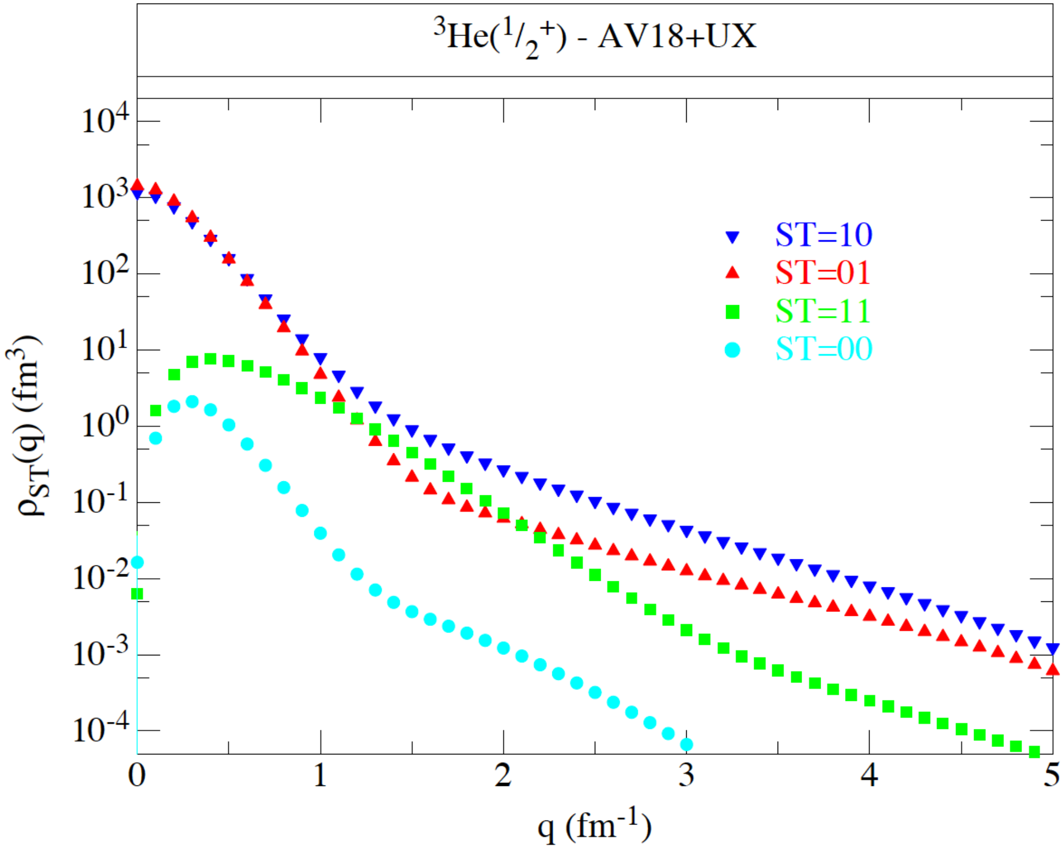


FIG. 8. Momentum distributions of nucleon-nucleon pairs by spin (S) and isospin (T) in ^{3}He in fm^3 calculated using variational Monte-Carlo techniques from [9].

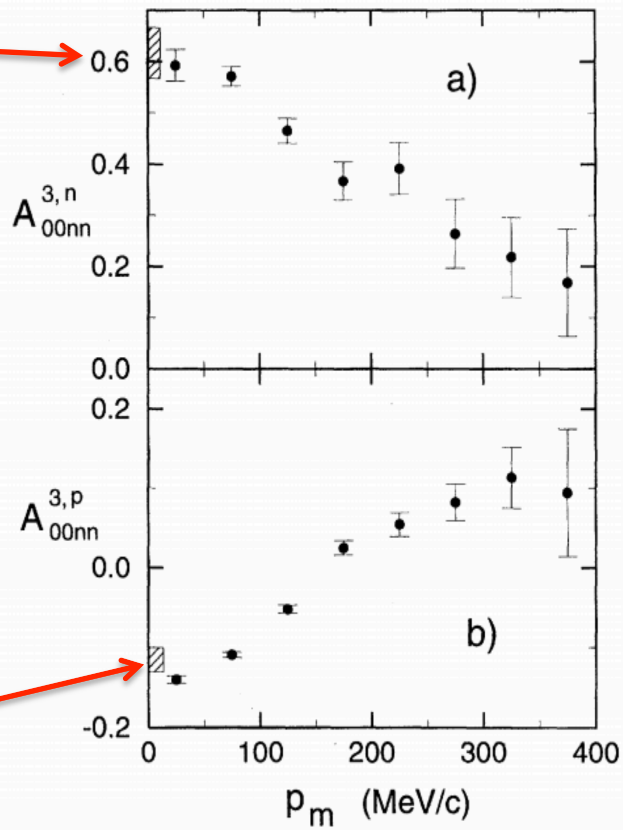
Quasielastic Nucleon Knockout

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

IUCF

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

S-state

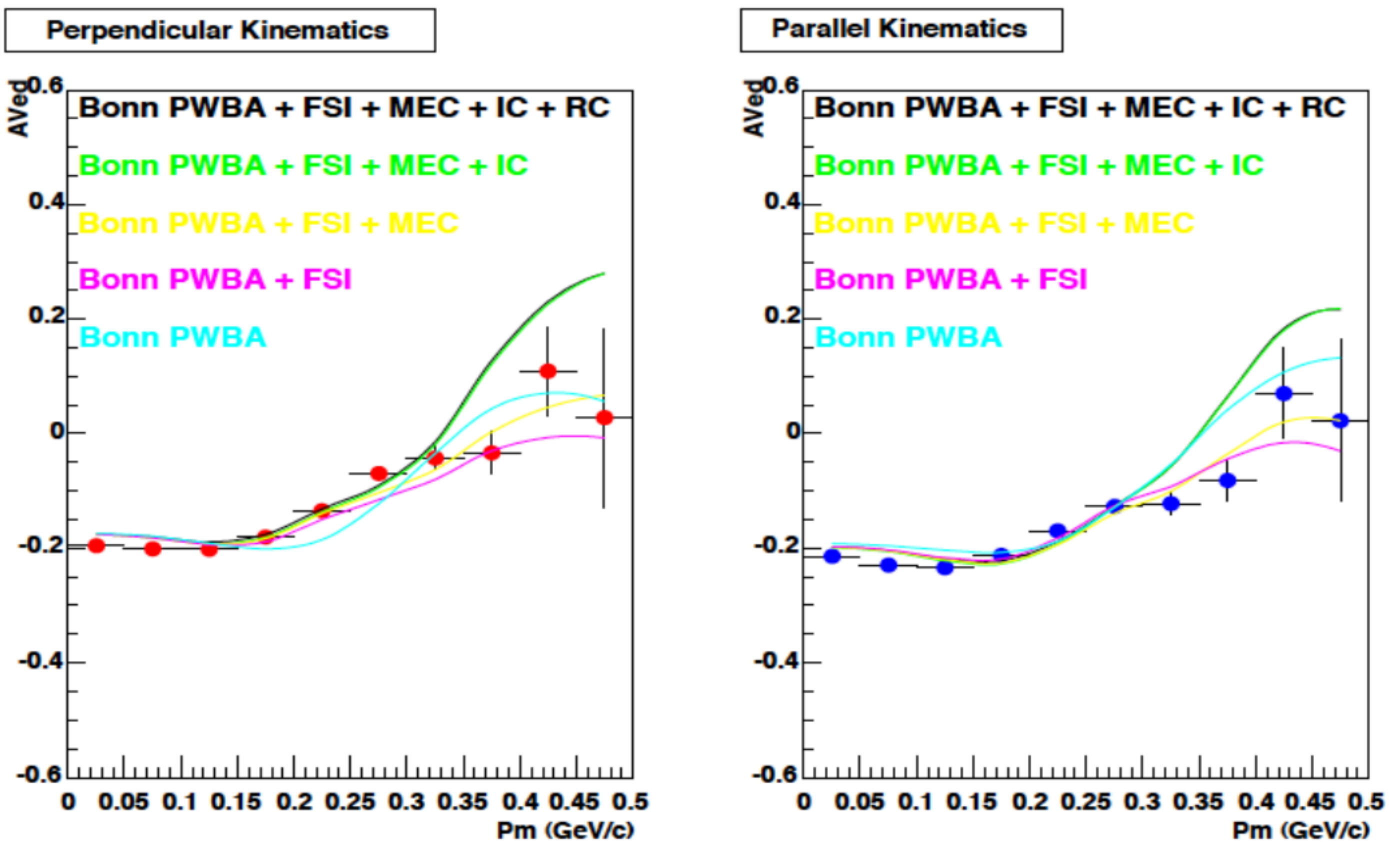


2% S'-state!

FIG. 3. The missing momentum distribution of (a) $A^{3,n}_{00nn}$ in $^{3}\mathrm{He}(p, pn)$ for $|q| > 500$ MeV/c, (b) $A^{3,p}_{00nn}$ 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.

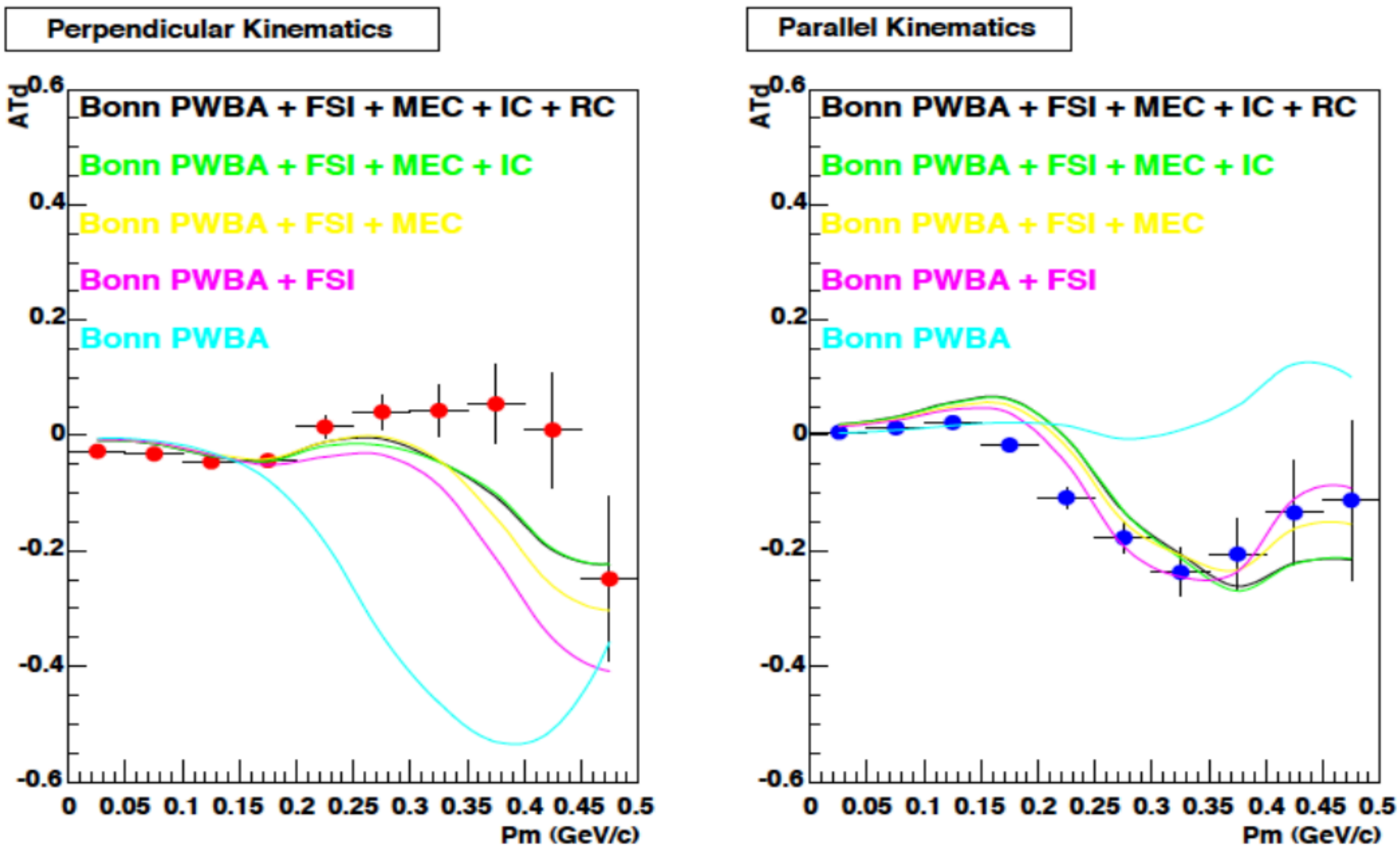
$^2\vec{H}(\vec{e},e'p)$ Vector Asymmetries

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

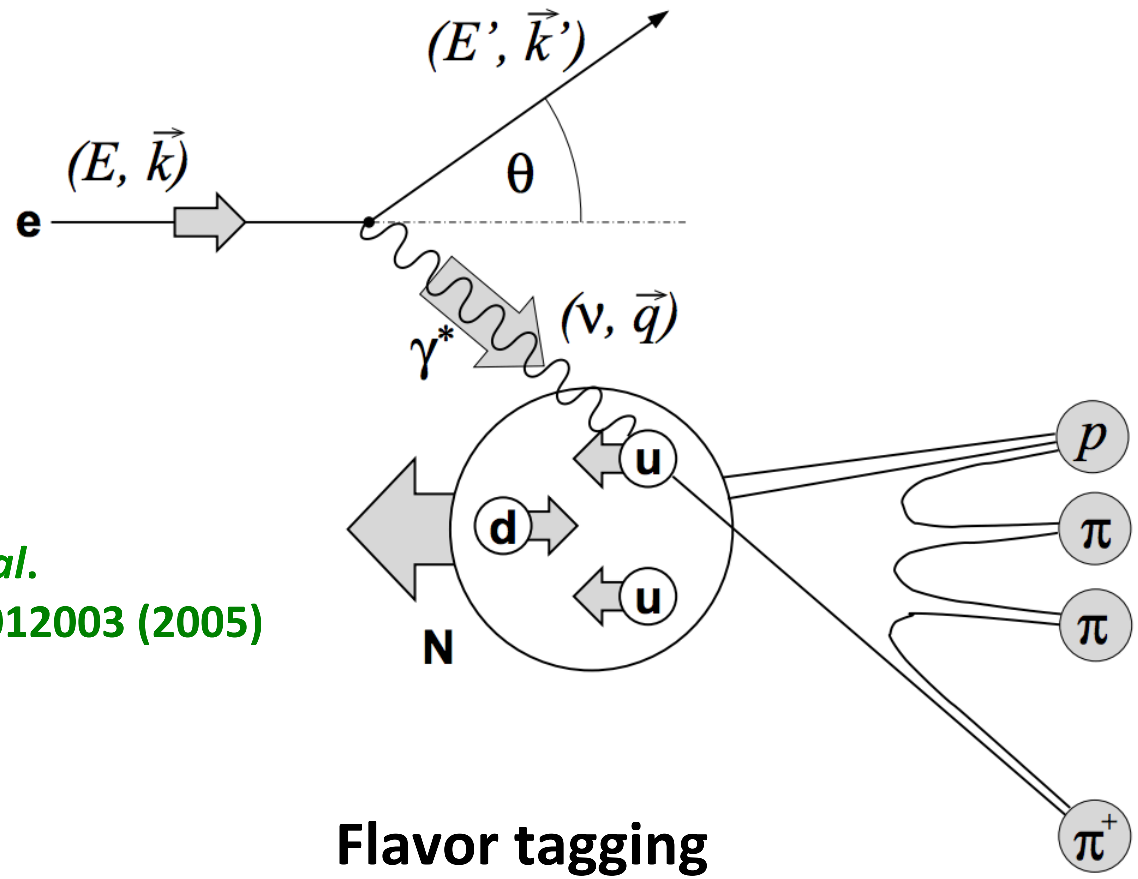


$^{2}\overleftrightarrow{\mathrm{H}}(\vec{e},e'p)$ Tensor Asymmetries

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



Semi-Inclusive DIS

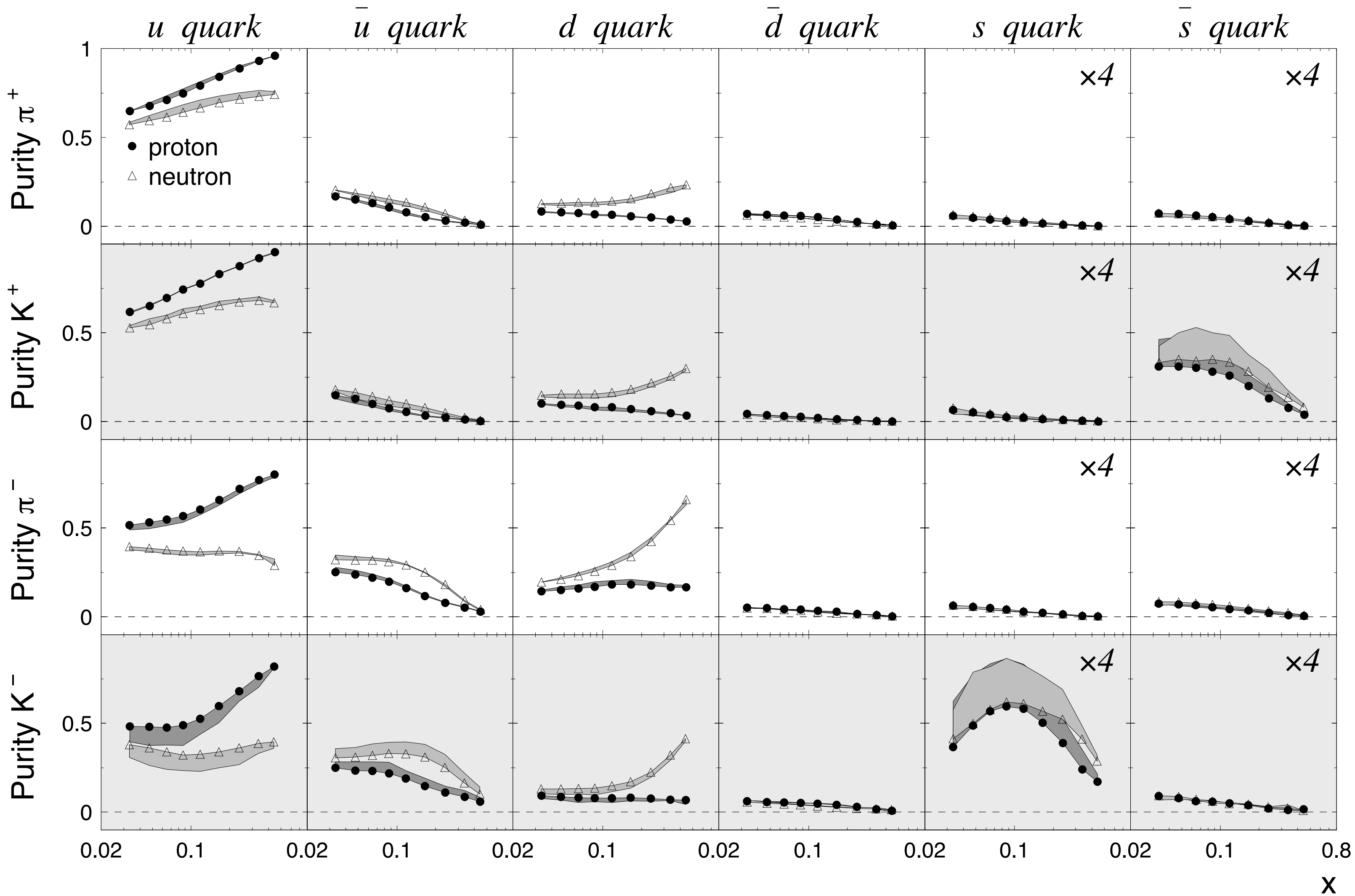


HERMES
A. Airapetian *et al*.
Phys. Rev. D 71, 012003 (2005)

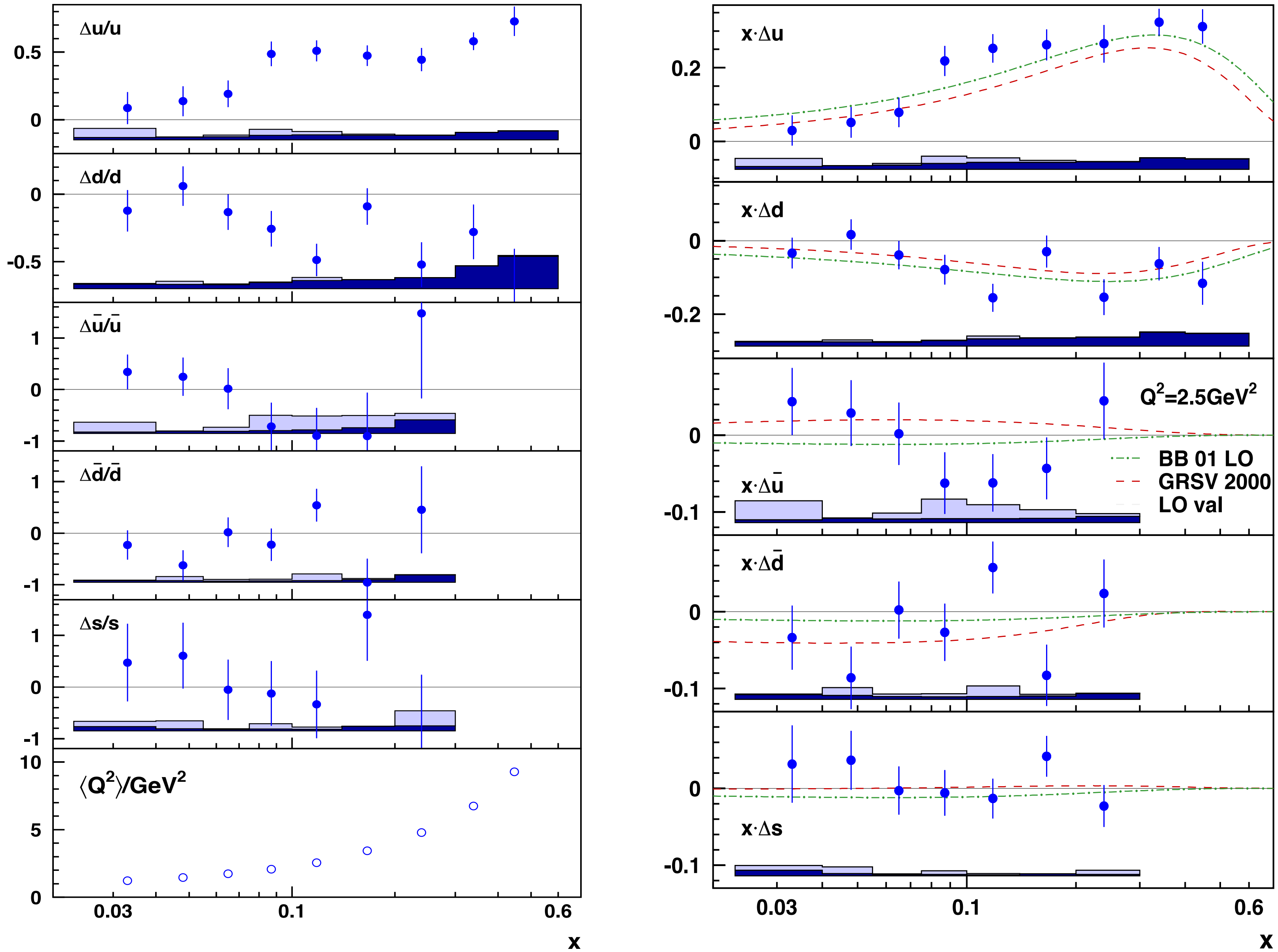
Flavor tagging

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

Purities

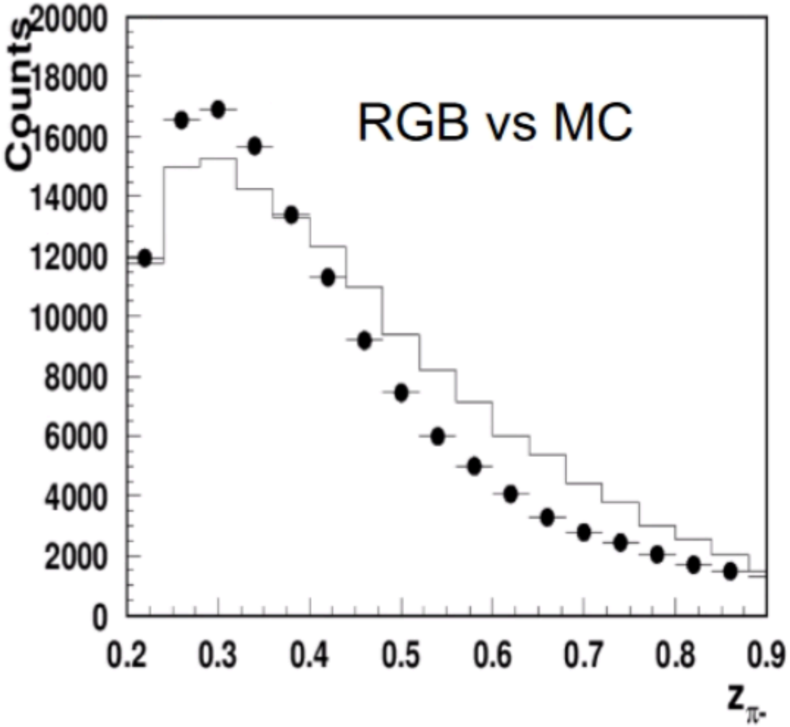


Quark Polarizations

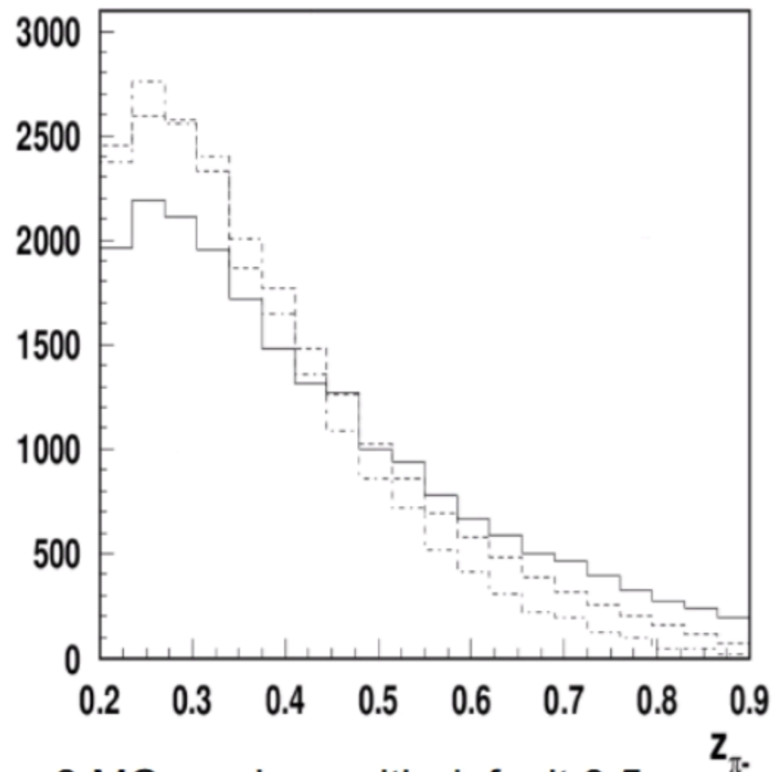


H. Avakian

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

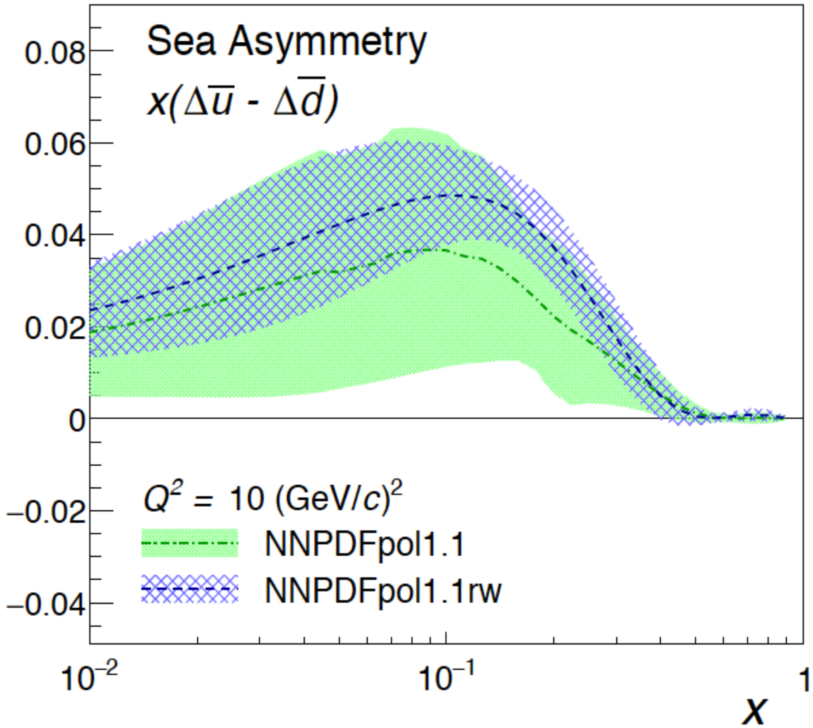


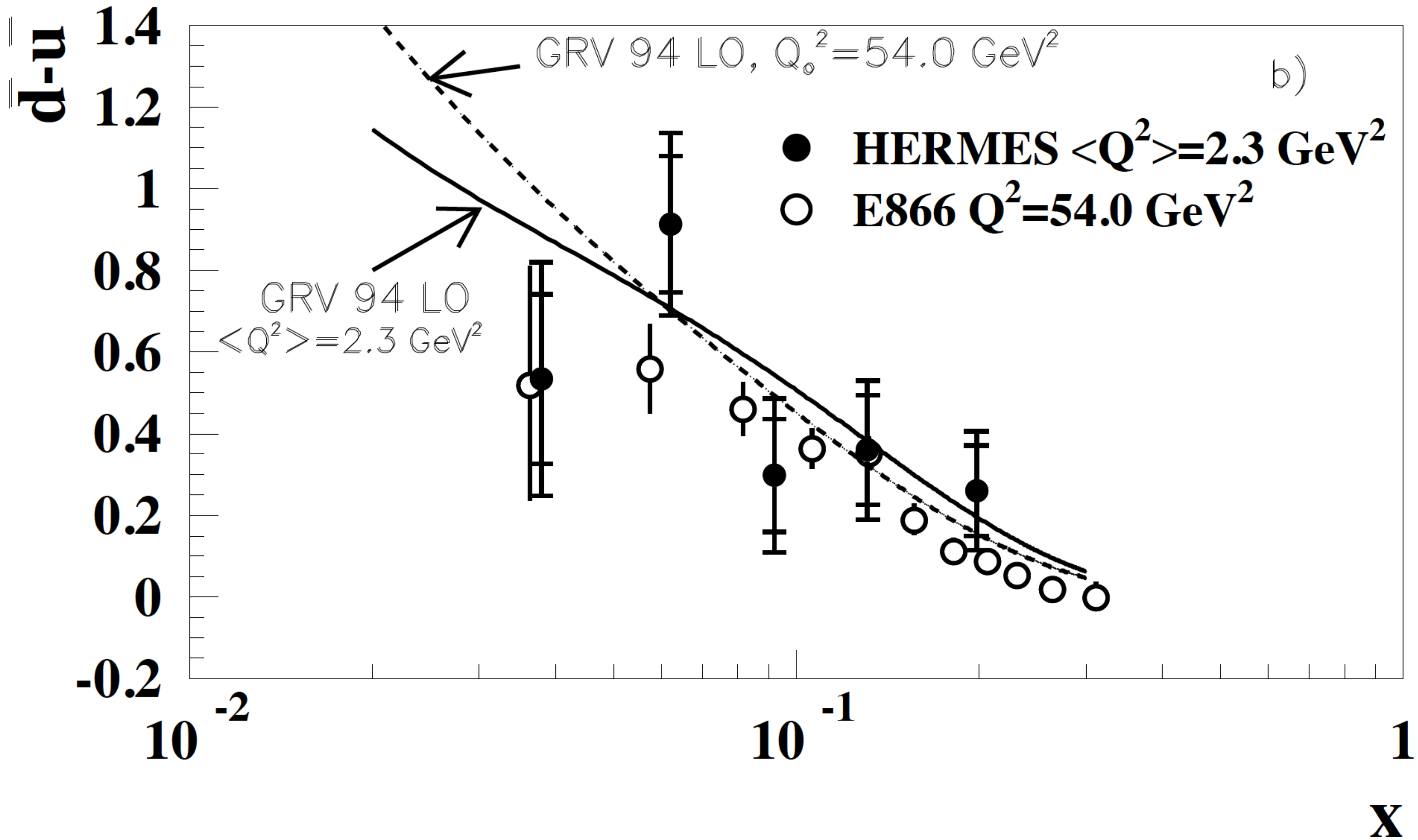
FIG. 6. The difference of the light sea-quark polarizations as a function of x at a scale of $Q^2 = 10\,(\mathrm{GeV}/c)^2$. The green band shows the NNPDFpol1.1 results [1] and the blue hatched band shows the corresponding distribution after the STAR 2013 $W^{\pm}$ data are included by reweighting.

5% asymmetry at $Q^2 = 10\ (\mathrm{GeV}/c)^2$ 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)

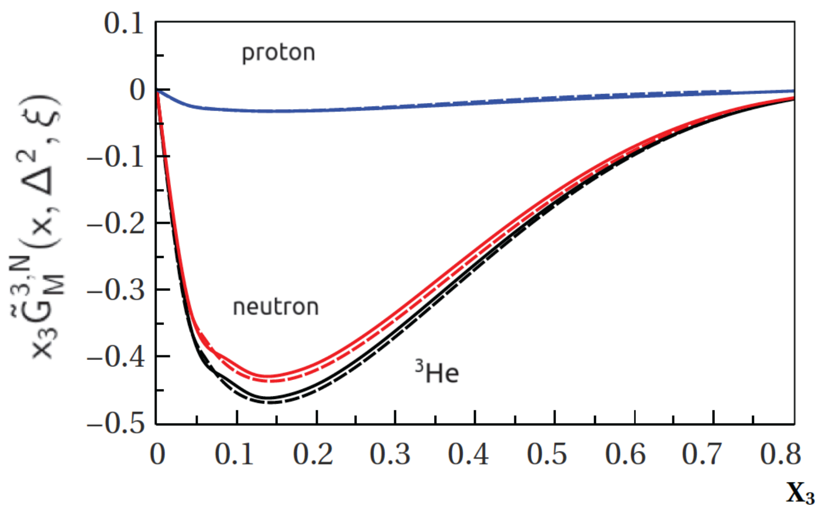


FIG. 6. (Color online) The quantity $x_3\tilde{G}_M^3(x,\Delta^2,\xi)$ of ^{3}He in the forward limit, together with the proton and neutron contribution (solid lines), compared with the approximations to these quantities given by the factorized form of Eq. (21) (dashed lines).

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.

Measurement of Charge Pion Asymmetries

H.J. Lipkin and T.-S. H.Lee, Phys. Lett. B **183**, 22 (1987)

- Pre-existing Δs in ^{3}He
- Assume pure S-state and ignore non-resonant contributions and FSI
- Δ++ must be in an L=2-state
- Then the charged pion ratios are

  for photoproduction Δs $\pi^+:\pi^0:\pi^-$ $\quad \frac{2}{9}:\frac{6}{9}:\frac{1}{9}$

  for knockout Δs $\pi^+:\pi^0:\pi^-$ $\quad \frac{19}{21}:\frac{2}{21}:0$

- Skewness to π^+ for knockout results from large relative probability for Δ^{++} and zero probability for Δ^0 and Δ^-

Polarized ^{3}He Target

RGM and T.W. Donnelly, Phys. Rev. C **37,** 870 (1988)

$$\frac{A(\pi^+)}{A(\pi^-)} = \left[1 + \frac{57}{14} \frac{\Gamma_k}{\Gamma_p} \right]$$

$$\frac{\Gamma_k}{\Gamma_p} = \frac{P_\Delta G_{C0}^{\Delta\Delta} G_{M1}^{\Delta\Delta}}{G_{C2}^{N\Delta} G_{M1}^{N\Delta}} , \qquad (14)$$

where $G_{C2}^{N\Delta}$ and $G_{M1}^{N\Delta}$ are the $C2$ and $M1$ Δ production form factors, respectively, and P_Δ is the probability to find a Δ in the ground state of ^{3}He. Now at low $Q^2 \approx 0.1\ (\mathrm{GeV}/c)^2$, we have

$$G_{C0}^{\Delta\Delta}, G_{M1}^{\Delta\Delta}, G_{M1}^{N\Delta} \sim 1 \text{ and } G_{C2}^{N\Delta} \sim 0.10 , \qquad (15)$$

Use spin to suppress transverse response, i.e. photoproduction.

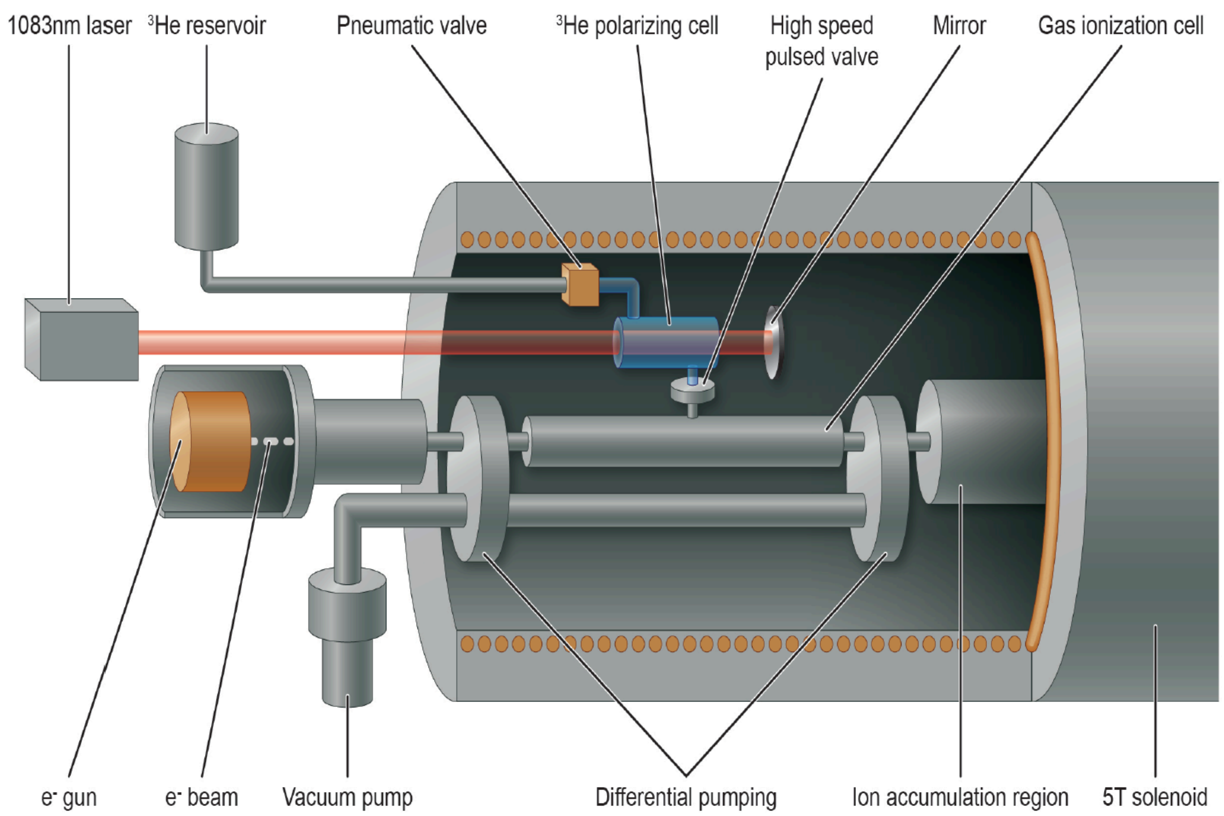
If P_Δ ~ 2%, ratio of charged pion asymmetries changes by a factor of 2.

Summary of Physics Possibilities

- 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
- $(e,e'\pi^{\pm})$: Search for pre-existing Δs.
- +…………………

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 if the central solenoid is removed. **Assume that we do not want to do that.**
- 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.



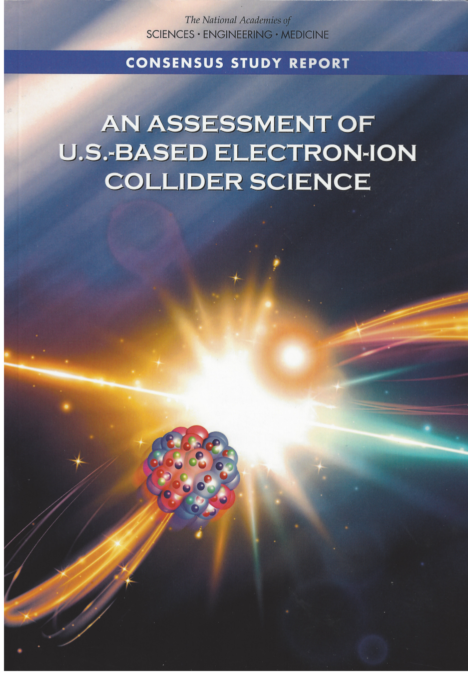


FIG. 5. Schematic layout of polarized ^{3}He ion source under development by a BNL-MIT collaboration using optically pumped polarized ^{3}He atoms directed into the existing Electron Beam Ionization Source.

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

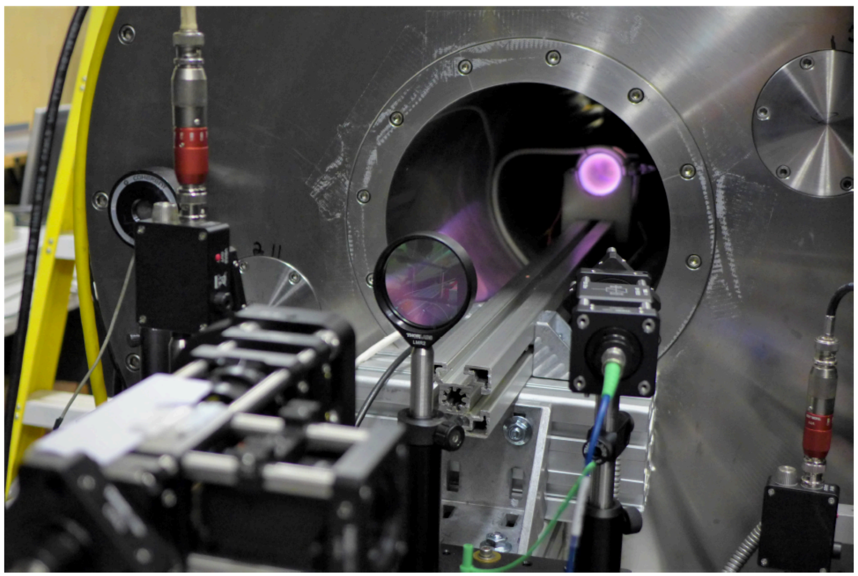


Figure 3: Photograph of the polarizing apparatus and EBIS spare solenoid warm bore. In the foreground are the pumping laser circular polarization optics. The probe laser fiber enters a circular polarizer on the right, and after passing through the cell the probe light is reflected by a mirror back to 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

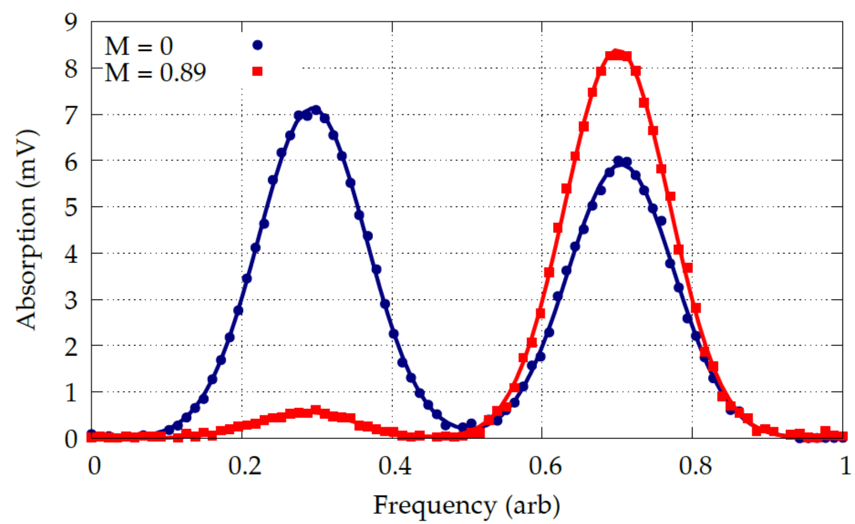


Figure 4: Example probe laser absorption signals with sample nuclear polarization at 0 and 89%, using a 1 torr sealed cell at 3 T. Both probe transition peaks are visible for each signal, as are the side-by-side Gaussian fits used to extract the peak amplitudes for analysis.

Impressive Performance

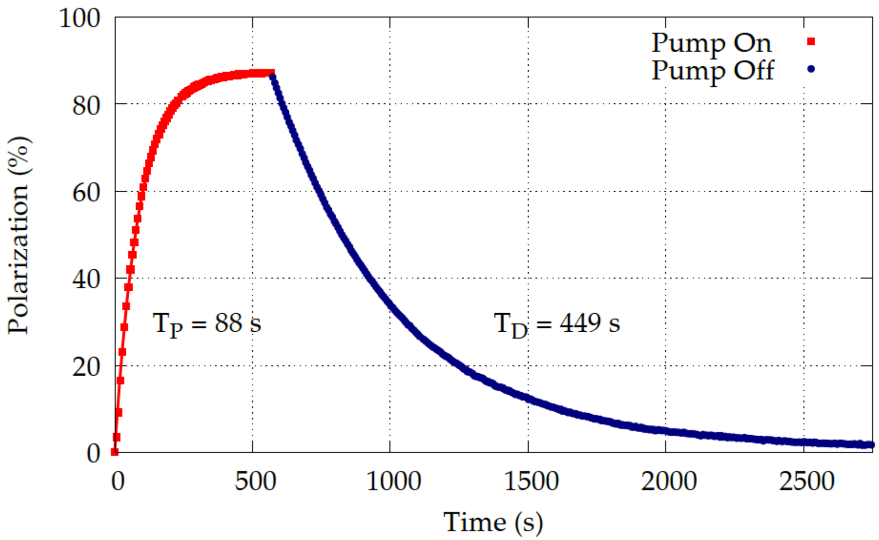


Figure 5: Typical pump and relaxation cycle at 2 T, showing exponential pumping build-up time T_P with the optical pumping active, and the relaxation time T_D after the pumping laser is blocked at 560 s.

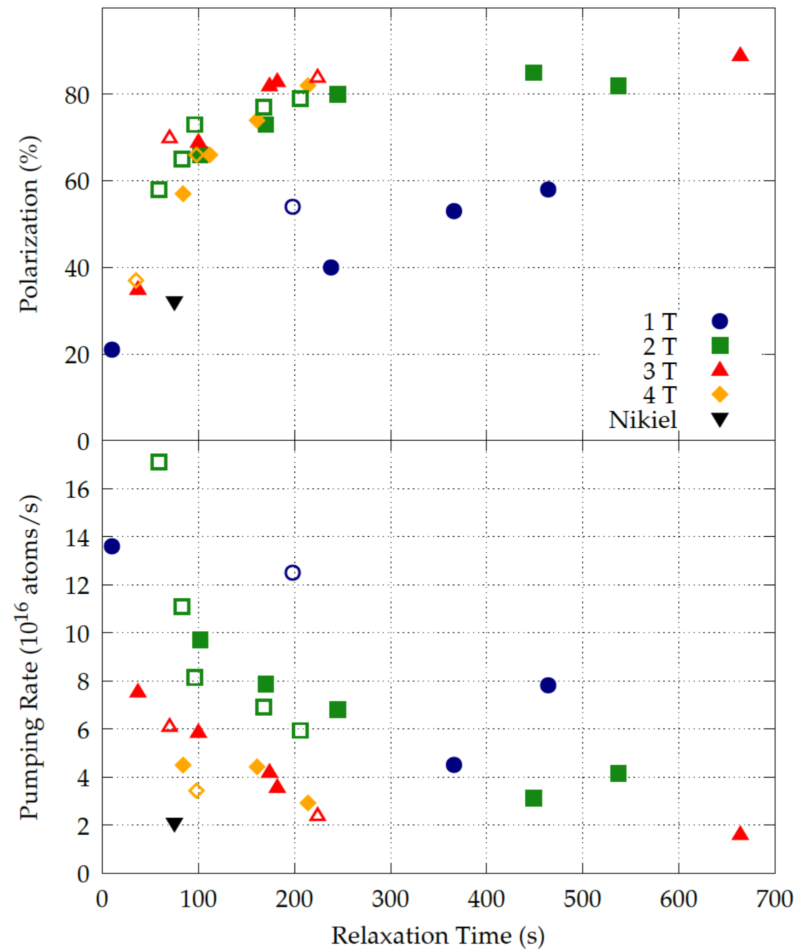


Figure 6: Steady state polarization achieved (top) and corresponding pumping rate (bottom) for a given relaxation time with the plasma discharge. Different shapes represent four magnetic field settings from 1 to 4 T. Filled shapes designate measurements on a 1 torr sealed cell produced a MIT Bates, while 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.

Caltech Target Operated at MIT-Bates 1989

R. McKeown group
at Caltech

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

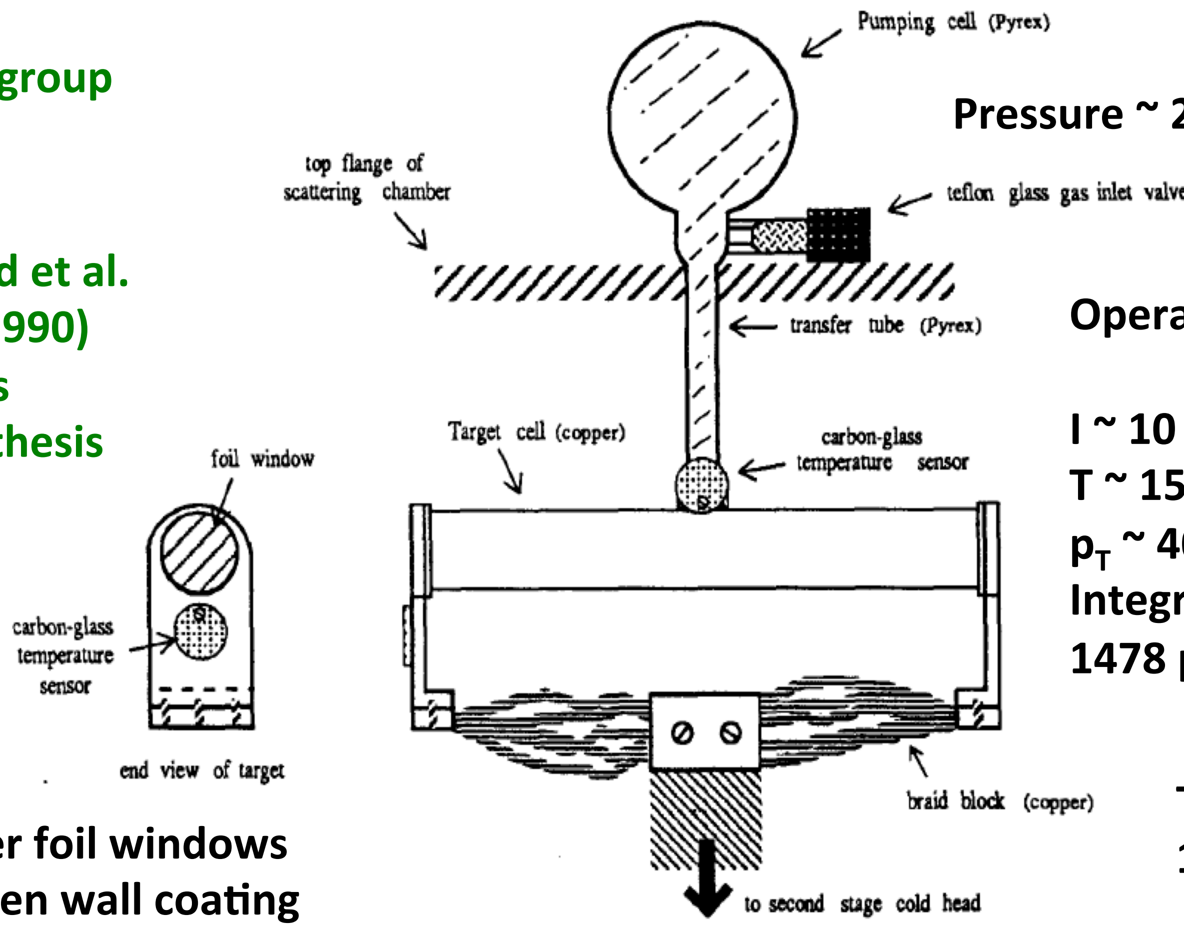


Figure 4.9: Schematic of the polarized ^{3}He target double-cell system. The relative positions of the pumping cell, transfer tube, and target cell are shown, in addition to the braid block, the temperature sensors, and the gas inlet valve.

Pressure ~ 2 Torr

Operating Parameters:

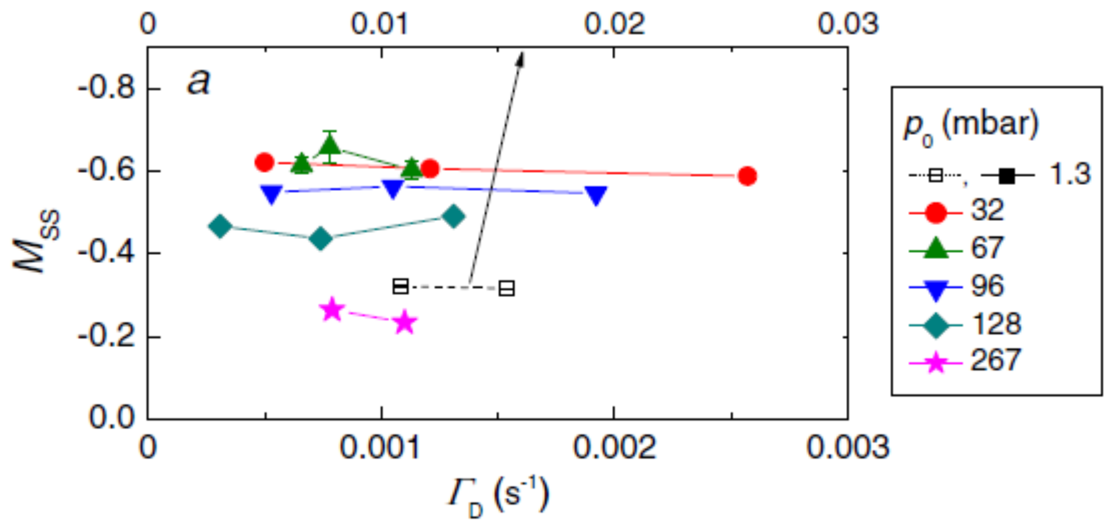
I ~ 10 μA
T ~ 15 K
p_T ~ 40%
Integrated charge:
1478 μA-hour

Target cell:
16 cm X 2.54 cm

4.6 μm copper foil windows
Frozen nitrogen wall coating

Luminosity Estimate

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



- ENS group report ≈60% ^{3}He polarization at 50 Torr
- MEOP at 50 Torr and cool target cell to 15 K
- 10 cm long target
- 10 μA electron beam = 6 X 10^{13} e/sec
- Target thickness = 50 X 3 x 10^{16} X √300/15 X 10 ^{3}He-cm^{-2}

  ≈ 7 X 10^{19} ^{3}He-cm^{-2}

- Luminosity ≈ 4 x 10^{33} ^{3}He cm^{-2} s^{-1}

≈ x 200 increase over HERMES!

Path Forward

- Physics case needs to be developed
  - Use CLAS12 Monte-Carlo and measured rates
  - Engage with theorists

- Target development can be pursued by JLab-MIT collaboration
  - MEOP at high pressure and high field
  - Study beam depolarization effects
  - Build prototype two-cell target system to fit in CLAS12 central detector (10 cm diameter – tight!).

- Assuming that the collaboration is supportive, propose that interested CLAS12 collaborators organize into a working group and that we plan to have a workshop in about 6 months.