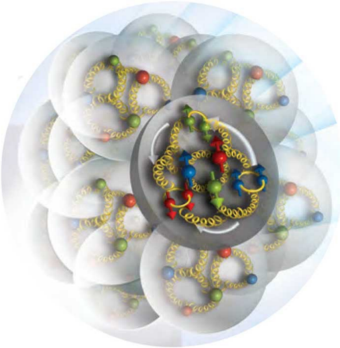
# Search for Exotic Glue in Nuclei

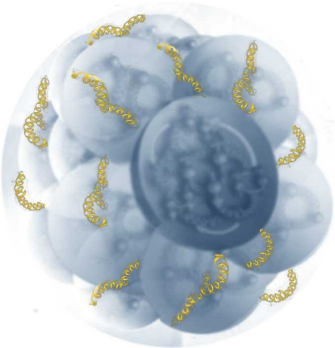
## Gluonic Transversity in Polarized DIS

J. Maxwell

Jefferson Lab

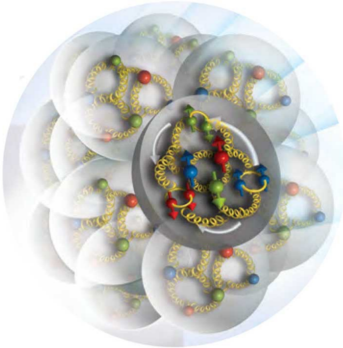
CLAS Collaboration Meeting
June 19th, 2019

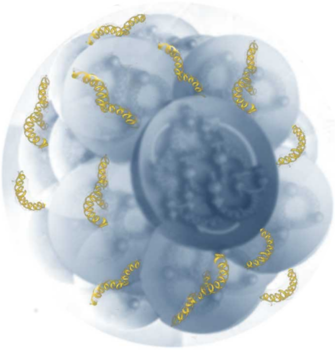




# Outline

1. Double Helicity-Flip Structure Function
   - Lattice Calculations
   - Measurement Approaches
2. Jefferson Lab Measurement
   - JLab Polarized Target
   - Hall B?
3. Gluonometry at the EIC





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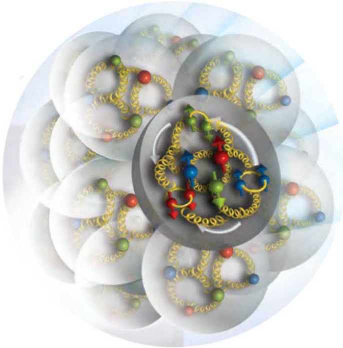
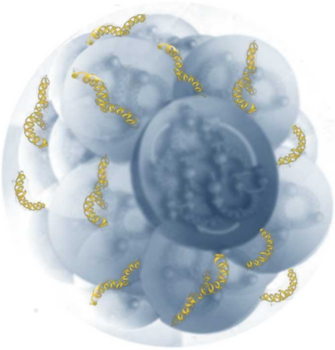
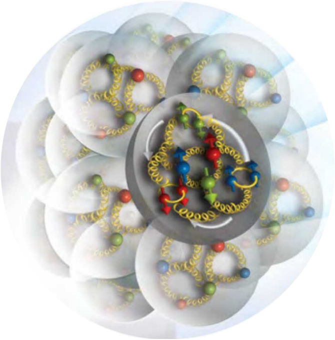




# Gluon Structure of Nuclei

- Understanding glue is a key challenge of NP and central goal of EIC



**Studying gluons is tricky**

- Gluon does not couple to photon
- Probed indirectly by electron scattering from nuclei

- A nuclear glue effect, free from contributions of any nucleon, could offer invaluable view of nuclear structure
- "Nuclear Gluonometry" (Jaffe, Manohar, 1989) offers a probe sensitive **only** to gluonic states in the nucleus: $\Delta(x, Q^2)$

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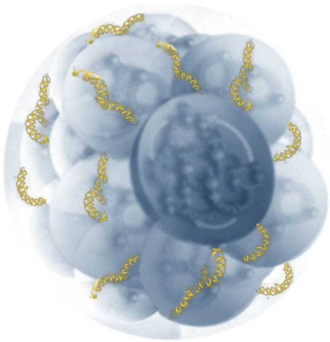

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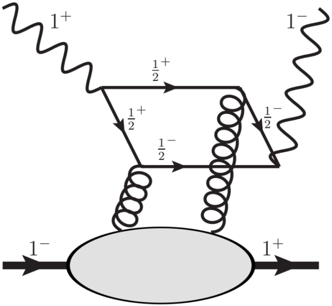
- $\Delta(x, Q^2)$ corresponds to helicity amplitude $A_{+-,-+}$
  - Photon helicity flip of two
  - Unavailable to bound nucleons or pions
  - Purely gluonic observable
- Hadrons: Gluonic Transversity
- Nuclei: Exotic Glue
  - Gluons not associated with an individual nucleon
- Unpolarized $e$ beam on transversely polarized nuclei, spin $\geq 1$
  - Primary challenge of measurement is polarized target or source
- Moments calculable in Lattice QCD



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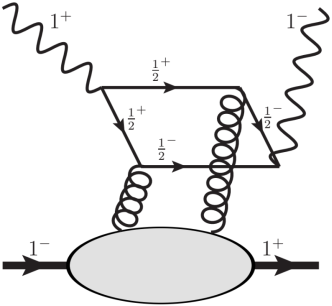


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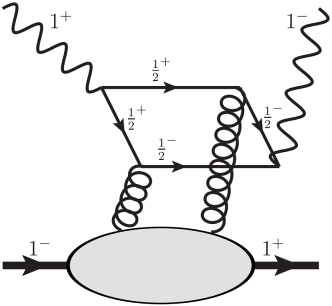


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# Lattice QCD Guidance for $\Delta$

- Initial calculations for first moment of $\Delta$ on spin-1 $\phi$ $(s\bar{s})$
  - $m_\pi = 405$ MeV
  - Gave definitive signal[1]
- Following year, first moment of $\Delta$ calculated on non-physical $d$
  - $m_\pi = 806$ MeV
  - Again definitive signal was seen[2]
- Results have generated significant interest in an observable mostly ignored since 1989
- Calculation with physical $d$ underway

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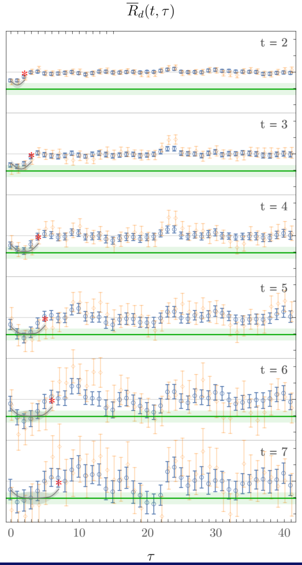


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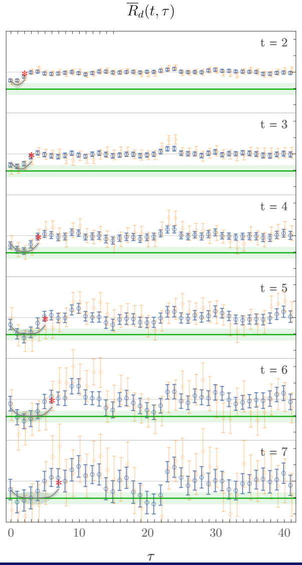


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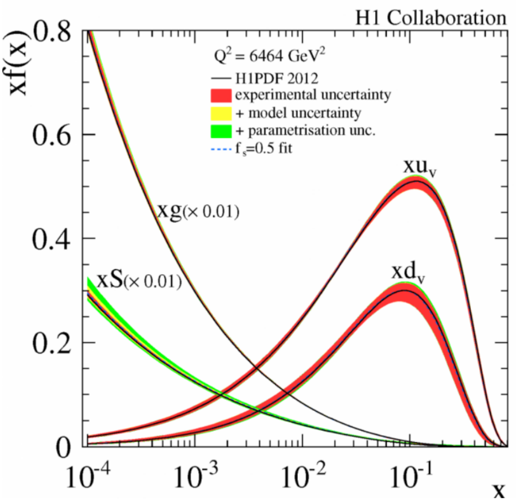
# Where do we start looking?



# Measuring $\Delta(x, Q^2)$ via DIS

- Transversely aligned, spin-1 target and unpolarized electron incident from $-z$
- In the Bjorken limit, double helicity component of the hadronic tensor $W^{\Delta=2}_{\mu\nu,\alpha\beta}(E, E')$ becomes (dropping higher twist structure functions)[1]:

$$\lim_{Q^2\to\infty} \frac{d\sigma}{dx\,dy\,d\phi} = \frac{e^4 M E}{4\pi^2 Q^4}\left( xy^2 F_1(x, Q^2) + (1-y) F_2(x, Q^2) - \frac{x(1-y)}{2}\Delta(x, Q^2)\cos 2\phi \right)$$

[1] Jaffe, Manohar, Phys Letters B 223 (2) (1989).

For a spin−1 target polarized at angle $\theta_m$ from the $z$-axis and electron incident from $-z$, target spin $\lambda_m = (1, 0, -1)$:

$$\frac{d\sigma}{dx\,dy\,d\phi}(\lambda_m) = \frac{2y\alpha^2}{Q^2}\left(F_1 + \frac{2}{3}a_m b_1 + \frac{1-y}{xy^2}\left(F_2 + \frac{2}{3}a_m b_2\right)\right.$$
$$\left. - \frac{1-y}{y^2} c_m \sin^2\theta_m \Delta(x, Q^2) \cos(2\phi)\right)$$

with

$$a_m = \frac{1}{4}c_m(3\cos^2\theta_m - 1)$$
$$c_m = 3|\lambda_m| - 2$$

Differences of cross sections: $N_+, N_0, N_-$ for $\lambda_m = (1, 0, -1)$

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Differences of cross sections: $N_+, N_0, N_-$ for $\lambda_m = (1, 0, -1)$

## Average over Polarization: $N_+ + N_- + N_0 \Rightarrow \bar{\sigma}$

- $c_+ + c_0 + c_- = 0$

$$\frac{d\bar{\sigma}}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left(F_1 + \frac{1-y}{xy^2}F_2\right)$$

- Of course, no $\Delta$ dependence
- $\Delta$ also cancels out of vector polarization difference $(N_+ - N_0) + (N_0 - N_-) = N_+ - N_-$
  - $c_+ - c_- = 0$

## Tensor Polarization: $(N_+ - N_0) - (N_0 - N_-) \Rightarrow \Delta\sigma$

- $c_+ - 2c_0 + c_- = 6$

$$\frac{d\Delta\sigma}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left((3\cos^2\theta_m - 1)(b_1 + \frac{1-y}{xy^2}b_2) - \frac{1-y}{y^2}6\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)\right)$$

- Tensor structure functions $b_1$, $b_2$ contribute significantly
- Unless! $(3\cos^2\theta_m - 1) = 0 \quad \Rightarrow \quad \theta_m = 54.7^\circ$

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**Difference of Polarized and Unpolarized:**
$N_+ - \bar{N} = N_+ - \frac{1}{3}(N_+ + N_- + N_0) = \frac{1}{3}(N_+ - N_0) \Rightarrow \hat{\sigma}$

- $c_+ - c_0 = 1$

$$\frac{d\hat{\sigma}}{dx\,dy\,d\phi} = \frac{2y\alpha^2}{Q^2}\left(\frac{1}{6}(3\cos^2\theta_m - 1)(b_1 + \frac{1-y}{xy^2}b_2) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)\right)$$

- Again tensor structure functions $b_1$, $b_2$ contribute significantly unless $\theta_m = 54.7°$

# 3 ways to measure $\Delta(x, Q^2)$

$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x, Q^2)\cos(2\phi)$$

1. Leverage $\cos(2\phi)$ to isolate $\Delta(x, Q^2)$ dependence
   - Need azimuthal detector acceptance
2. Form tensor asymmetry: $\mathcal{A} = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$
   - $\theta_m = 54.7°$ to cancel $b_1$, $b_2$ dependence
   - Change polarization to produce $N_+$, $N_-$ and $N_0$ yields
3. Form difference of vector polarized and unpolarized cross sections
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# Transverse Polarized Target Nuclei

- Need a spin$\geq$1 nucleus, but this is a **multi-nucleonic** effect
  - Expected larger in compact nuclei (like EMC effect?)
  - Perhaps explains enhanced LQCD signal with larger $m_\pi$, more compact $d$?
- Deuteron? Should be investigated, but may not offer best chance for discovery.
  - Expect two nucleons to good approximation
- Something heavier: Li? $\alpha + d$
- Practical limitations from available polarized targets
  - Long history of polarized $p$ and $d$ in solid targets
  - Lithium Hydride and Deuteride: $^6$LiH,$^6$LiD, also $^7$LiH
  - Ammonia: $^{14}NH_3$,$^{14}ND_3$, also $^{15}NH_3$
- Or, for $eA$ collider, polarized ion sources
  - $D$. Alkalis? $^6$Li, $^7$Li, $^{23}$Na attractive options

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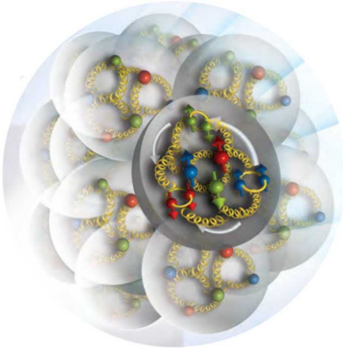

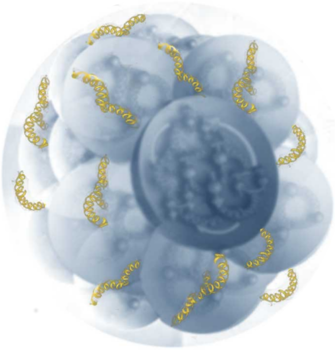

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$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)$$

1. Not easy: need out of plane detectors for $\cos(2\phi)$
   - Not standard in Halls A, C. SoLID?
   - No transverse target in Hall B
2. Form tensor asymmetry: $A = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$
   - Set target field at $\theta_m = 54.7°$
   - Yields at $N_+$, $N_-$ and $N_0$ separated in time: systematic headaches
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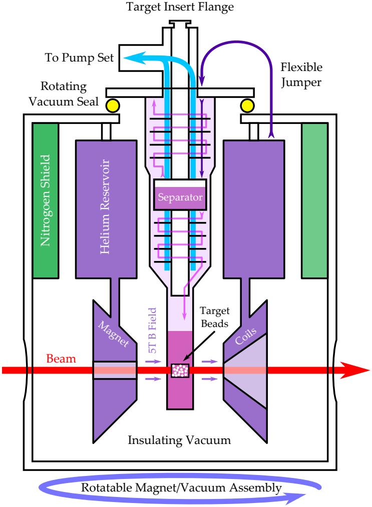
# Kinematic Reach with 12 GeV CEBAF in Hall C

- 11 GeV, unpolarized $e^-$ on fixed, polarized $^{14}NH_3$
- Preliminary SHMS Monte Carlo (Gaskell, Arrington)
  - Transverse (not 54.7°!) UVa magnet (M. Jones)

| $\theta$ | E (GeV) | E' (GeV) | $Q^2$ (GeV/c$^2$) | $x$ | Rate (Hz) |
|---|---|---|---|---|---|
| 10.5 | 11 | 5 | 1.842 | 0.164 | 170 |
| 10.5 | 11 | 4 | 1.474 | 0.112 | 152 |
| 10.5 | 11 | 3 | 1.105 | 0.074 | 138 |
| 10.5 | 11 | 2 | 0.737 | 0.044 | 100 |
| 15 | 11 | 5 | 3.748 | 0.333 | 28 |
| 15 | 11 | 4 | 2.999 | 0.228 | 30 |
| 15 | 11 | 3 | 2.249 | 0.15 | 32 |
| 15 | 11 | 2 | 1.499 | 0.089 | 34 |

# JLab Solid Polarized Target

- Dynamic Nuclear Polarization
  - 5 T field, 1 K $^4$He evap. fridge
  - Dope material with paramagnetic radicals ($NH_3$: $NH_2$ or H)
  - Leverage $e - p$ spin coupling
  - $\mu$-waves drive polarizing transitions
  - $e$ relaxes to flip–flop with new $p$
- Irradiated Ammonia: 95% $p$, 40% $d$
  - Beam current <100 nA
  - P decay: anneals and replacement
- Workhorse DIS technique at SLAC, JLab; 2012's $g_p^2$ most recently[2], CLAS12 polarized target under testing




[2] Pierce, Maxwell, NIM A 738 (2014).

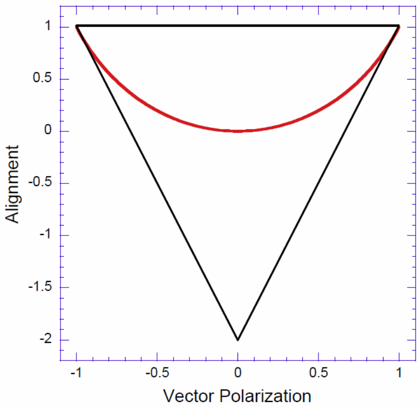
# Polarization, Tensor *Alignment* and DNP

$$
\begin{aligned}
P &= (N_+ - N_0) + (N_0 - N_-) \\
&= N_+ - N_- \\
A &= (N_+ - N_0) - (N_0 - N_-) \\
&= 1 - 3N_0
\end{aligned}
$$

- Polarization and alignment can be anywhere in the black triangle
- At *equal spin temperature*, can be only on red curve:

$$A = 2 - \sqrt{4 - 3P^2}.$$

- For $P = 40\% \;\Rightarrow\; A = 13\%$

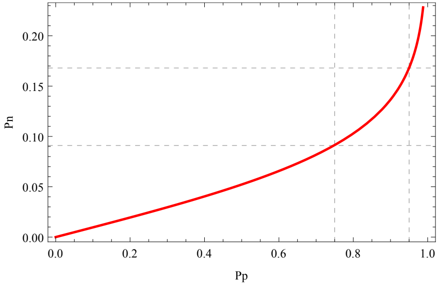


# Nitrogen Polarization in Ammonia: Not Easy

- We can also relate polarization of N to $p$ at EST:

$$P_N = \frac{4\tanh((\omega_N/\omega_p)\,\text{arctanh}(P_p))}{3+\tanh^2((\omega_N/\omega_p)\,\text{arctanh}(P_p))}$$

- At 95% $p$: 17% N
  - $P_N = 17\% \Rightarrow A_N = 2\%$
- NMR measurement is difficult
  - Peaks too far apart for one NMR scan (2.4 MHz)
  - Overcome at SMC with 2 sweeps, changing B field[3]




[3] B. Adeva, NIM A 419 (1998).

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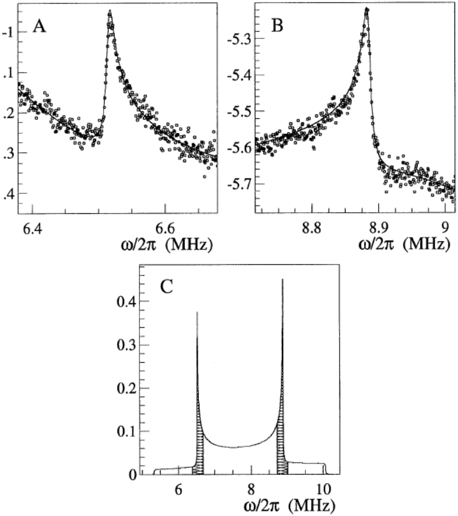


[3] B. Adeva, NIM A 419 (1998).

# Techniques to Improve $P_N, A_N$

- "RF Hole Burning"[4]
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  - Vast separation of NMR peaks in N will help.
- Cross Spin Transfer
  - Drop magnetic field (56mT) for cross relaxation of $p$ Zeeman, N quadrupolar systems
  - SMC: 40% $P_N \Rightarrow$ 12% $A_N$
- RF Spin Transfer
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  - RF to drive $p - N$ flip-flops
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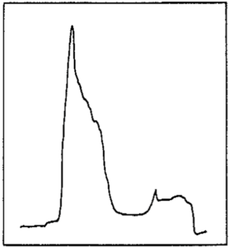

Starting polarization = 37%
RF-induced alignment "up to 20%"

W. Meyer and E. Schiling, Proceedings of 4th Int'l Workshop on Polarized Target Materials and Techniques, Bonn (1984) 165.

[4] P. Delheij, NIM A 251 (1986).

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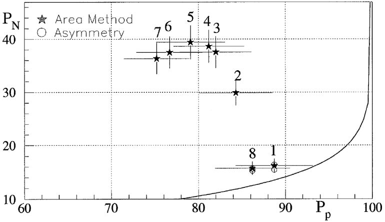


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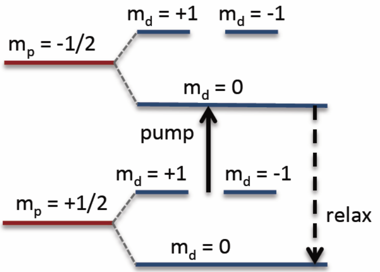


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# Jefferson Lab Letter of Intent 12-16-006 (Hall C)

- $\sim$30 PAC days with solid polarized target[5]
  - Run with approved measurement of $b_1$ in Hall C
  - Ballpark 1% statistical error
  - Heavily dependent on achieved polarization
  - Systematic uncertainty on target polarization 4-5%
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  - Encouragement with charges
  - Guidance on size of $\Delta$ from Lattice QCD
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[5] arXiv:1803.11206 [nucl-ex]

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# Nuclear Gluonometry in Hall B?

$$(3\cos^2\theta_m - 1)\left(b_1 + \frac{1-y}{xy^2}b_2\right) - \frac{1-y}{y^2}\sin^2\theta_m \Delta(x,Q^2)\cos(2\phi)$$

1. $\cos(2\phi)$ offers $\Delta(x,Q^2)$ sensitivity
   - Need to produce polarizing field transverse to beam
   - Actually, only need to rotate out to 54.7°
2. ~~Form tensor asymmetry:~~ $\cancel{A = \frac{1}{A}\frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}}$
   - Set target at $\theta_m = 54.7°$
   - ~~Yields at~~ $\cancel{N_+}$, $\cancel{N_-}$ ~~and~~ $\cancel{N_0}$ ~~separated in time: systematic headaches~~
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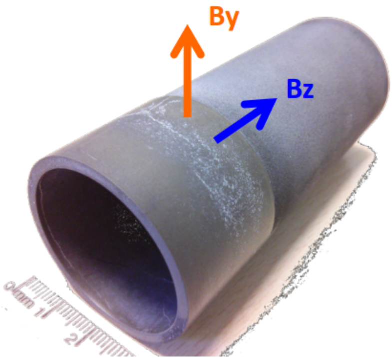
# Transverse Targets in CLAS12

- HD-Ice: transverse polarized target with bulk superconductor[6]
  - Lock in field at desired angle, then introduce into CLAS12
  - Bulk superconductor both shields longtudinal field and holds transverse
- For a DNP target, field uniformity requirement is more restrictive
  - Reduce target cell size?
- Second, transverse magnet inside CLAS12 5 T solenoid?
  - 3.5 T would rotate to 54.7°
  - BUT, need to keep $\int B \cdot dl$ low




[6] Statera, NIM A 882 (2018)

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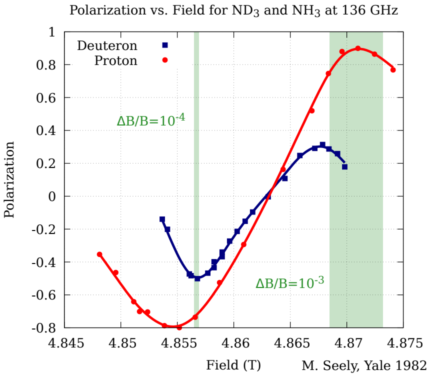
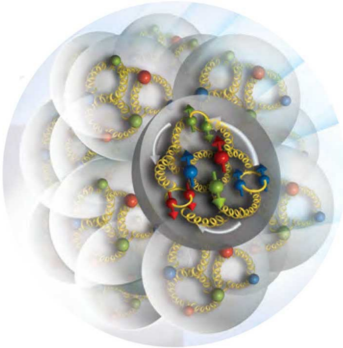
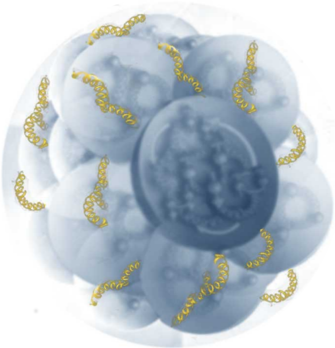



[6] Statera, NIM A 882 (2018)

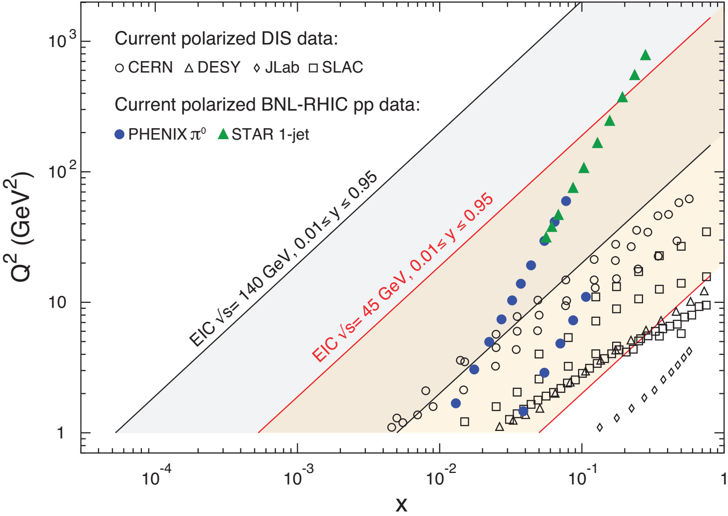
# Outline

1. Double Helicity-Flip Structure Function
   - Lattice Calculations
   - Measurement Approaches
2. Jefferson Lab Measurement
   - JLab Polarized Target
   - Hall B?
3. Gluonometry at the EIC





# Kinematic Reach at Electron–Ion Collider




EIC white paper

# Polarized Ion Beam Possibilities

At EIC, $\Delta(x, Q^2)$ search becomes a problem of available ion sources and their corresponding depolarizing resonances.

| Nucleus | Spin | Technique | Pol. | Flux | G |
|---|---|---|---|---|---|
| $^{2}$H | 1 | OP, ABS | 100% | 1$\mu$A | -0.14 |
| $^{6}$Li | 1 | OP, ABS | 88% | 2.4$\mu$A | -0.18 |
| $^{7}$Li | $\frac{3}{2}$ | OP, ABS | | | 1.53 |
| $^{8}$Li | 2 | TFM | $\sim 1\%$ | | |
| $^{10}$B | 3 | Not known | | | |
| $^{23}$Na | $\frac{3}{2}$ | OP, ABS | 77% | 6.5 $\mu$A | 0.55 |

# Towards Design of an Optimized EIC Experiment

- Exploration of $\Delta$ in $x$, $Q^2$, S, & A
  - How does effect change for different nuclear spin $\geq 1$?
  - Spin-1/2 species important cross-check
  - How does effect change for different atomic masses?
  - Spin-1 $^6$Li vs. Spin-3/2 $^7$Li
- Simulate measurement for Inclusive DIS on Nuclei
- Estimate running time for given statistical uncertainties
  - Species choice informed by simulation
  - Loss of luminosity compared to JLab made up for by lack of dilution, kinematic coverage
- Fixed target experiment at JLab would be a crucial first exploration, provide high-$x$ data for the production of moments

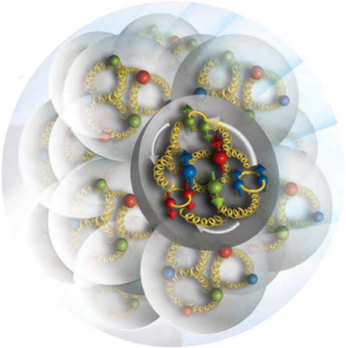
# Summary

- $\Delta(x, Q^2)$ offers a rare look at gluonic components in the nucleus
  - Significant Lattice QCD result drives interest
  - Need spin $\geq 1$, polarized, nuclear target
  - Low $x$, where glue dominates, region of interest
- Jefferson Lab experiment still in pre-proposal stage
  - Polarized $^{14}$N target fertile for development
  - Transverse target in Hall B worth investigating
  - SoLID also a possibility
- EIC capable of thorough search
  - Vast low $x$ exploration
  - Polarized ion sources needed, Li and Na most attractive
  - Spin manipulation of polarized, "heavy" ions crucial
  - Initial investigations towards measurements at eRHIC (R.Milner) and JLEIC (JDM) begun

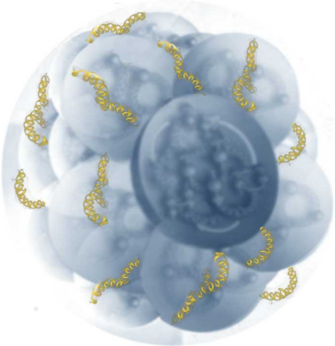
JLab Nuclear Gluonometry Collab:

- JLab: M. Jones, C. Keith, J. Maxwell, D. Meekins
- MIT: W. Detmold, R. Jaffe, R. Milner, P. Shanahan
- Univ. of Virginia: D. Crabb, D. Day, D. Keller, O. Rondon
- Oak Ridge: J. Pierce

Thanks to A. Zelenski, V. Morozov, Y. Furletova



Thank you for your attention!



# 5 T Split-Pair Target Magnet

- Can we get $\theta_m = 54.7°$
- Old Hall C Magnet, with largest opening angles, retired in 2012
  - Better than $10^{-4}$ uniformity in 3x3x3 cm$^3$ volume
- $g_2^p$ ran with modified Hall B magnet
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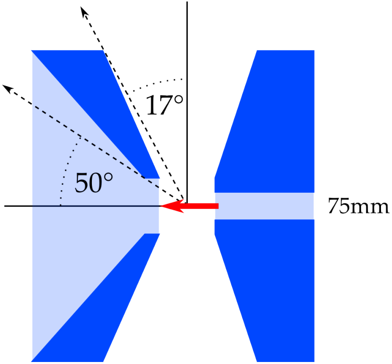
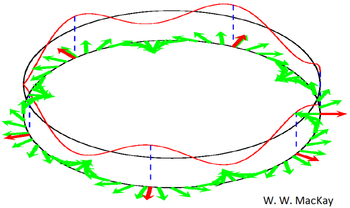


# Spin Manipulation in Ring

- Depolarizing resonances when spin precession frequency = frequency of perturbing B field[7]
- Imperfection: $\nu_s = G\gamma = n$
- Intrinsic: $\nu_s = G\gamma = Pn + \nu_y$
- Anomalous $g$-factor $G$

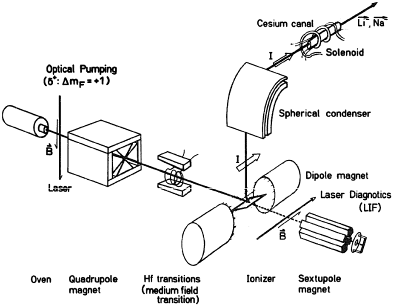



  - $^7$Li: G of 1.53 (like proton's 1.79) $\Rightarrow$ easy
  - $^6$Li: G of -0.18 (like deuteron's -0.14) $\Rightarrow$ hard
  - $^{23}$Na: G of 0.55 could work at RHIC with more snakes
  - Figure–8 makes for easier manipulation at lower $G$

[7] Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

# Spin Polarized Alkali Sources

- Improved Heidelberg Source adds OP (1986)[8]
  - Laser pumped, modulated to pump both multiplets
  - $^6$Li: $A = 85\%$, $^{23}$Na: $A = 77\%$
  - Polarization limited due to lack of full ionization




[8] H. Reich, NIM A288 (1989)

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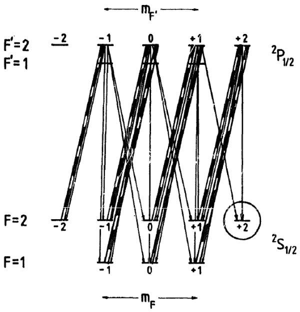


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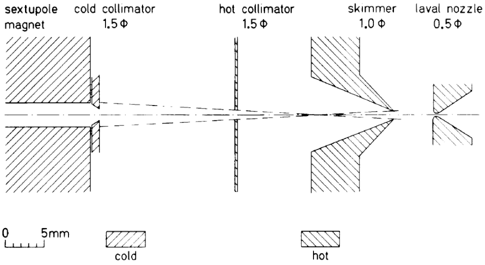
# Spin Polarized Alkali Sources

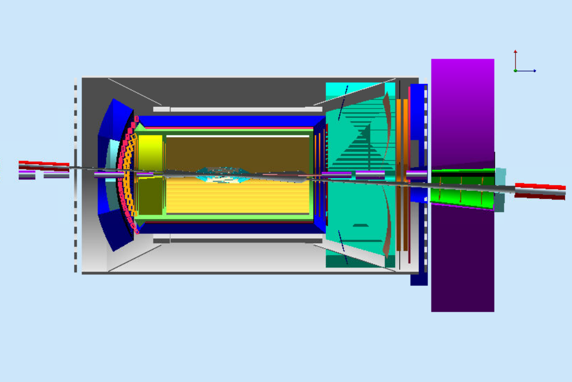
- Heidelberg Atomic Beam Polarized Source (1975)[9]
  - Laval nozzle, Sextupole Stern–Gerlach give $m = +1/2$
  - RF used for adiabatic transitions to fill other states
  - Surface ionization, heated tungsten strip
  - $^{6,7}$Li: $0.57 < |P| < 0.65$, 200 nA
  - $^{23}$Na: 50% losses to $P$ and current in ionization




[9] E. Steffens, NIM 143 (1977)

# Starting JLEIC Modeling

- First work with JLEIC detector geometry, *eA* kinematics
- BeAGLE generator for *eD*, *eLi*, *eNa* (thanks to V. Morozov, M.Baker), GEMC geometry (thanks to Y.Furletova)



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