From Polarized Targets to Polarized Ion Beams

Opportunities and challenges for EIC spin physics

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October 11, 2019

Argonne NATIONAL LABORATORY

1. Polarized DIS with Longitudinal and Transverse nuclear polarization
   - Recent results from JLab
2. Overview of Fixed Target Technology
3. Comparing polarized fixed targets with polarized ion colliders
4. Polarized Heavy Ions

Introduction

Polarized Deep Inelastic Scattering

$$\sigma_0 = \frac{4\alpha^2 E'^2}{q^4}\left[\frac{2}{M}F_1 \sin^2(\theta/2) + \frac{1}{\nu}F_2 \cos^2(\theta/2)\right]$$

$$2\sigma_0 A_\parallel = -\frac{4\alpha^2}{Q^2}\frac{E'}{E}\left[\frac{E + E'\cos\theta}{M\nu}g_1 - \frac{Q^2}{M\nu^2}g_2\right]$$

$$2\sigma_0 A_\perp = -\frac{4\alpha^2}{MQ^2}\frac{E'^2}{E}\sin\theta\cos\phi\left[\frac{1}{M\nu}g_1 + \frac{2E}{M\nu^2}g_2\right]$$

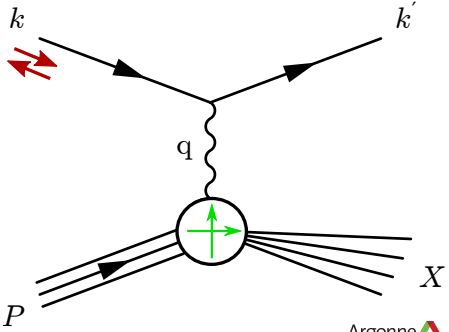
Measured Asymmetries

$$A_\parallel^{\text{raw}} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$

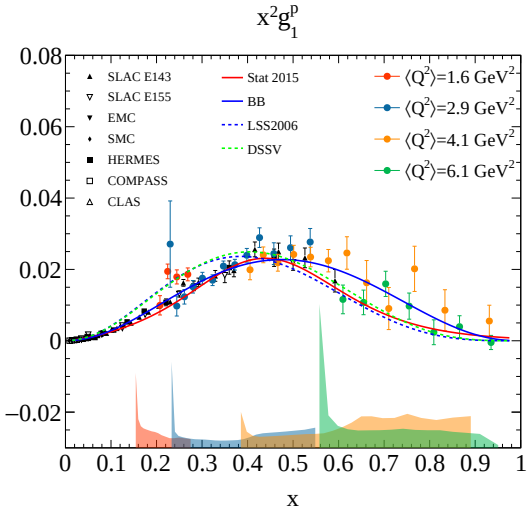
$$A_\perp^{\text{raw}} = \frac{\sigma^{\Leftarrow\downarrow} - \sigma^{\Leftarrow\uparrow}}{\sigma^{\Leftarrow\downarrow} + \sigma^{\Leftarrow\uparrow}}$$

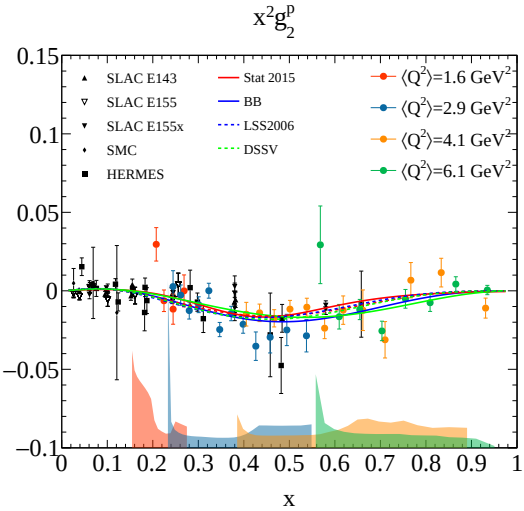
$$A_{\parallel,\perp} = \frac{A_{\parallel,\perp}^{\text{raw}}}{f P_b P_t}$$

Need $\parallel$ and $\perp$ polarizations



SANE results for $x^2 g_1^p$ and $x^2 g_2^p$





The dynamical twist-3 matrix element: d_2

An average color Lorentz force

$$\int_0^1 dx x^{n-1}\{g_1 + \frac{n}{n-1}g_2\} = \frac{1}{2}d_{n-1}E_2^n(Q^2, g)$$

For $n = 3$

$$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2$$

Interpretations of d_2

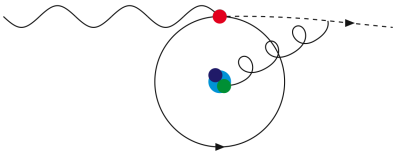
- Color Polarizabilities (X.Ji 95, E. Stein et al. 95)
- **Average Color Lorentz force** (M.Burkardt)

M. Burkardt Phys.Rev.D 88,114502 (2013) and Nucl.Phys.A 735,185 (2004).

$$d_2 = \frac{1}{2MP^{+2}S^x}\langle P, S \mid \bar{q}(0)gG^{+y}(0)\gamma^+ q(0) \mid P, S\rangle$$

but with $\vec{v} = -c\hat{z}$

$$\sqrt{2}G^{+y} = -E^y + B^x = -(\vec{E} + \vec{v} \times \vec{B})^y$$



$d_2 \Rightarrow$ average color Lorentz force acting on quark moving backwards (since we are in inf. mom. frame) the instant after being struck by the virtual photon. $\langle F^y \rangle = -2M^2 d_2$

Quark-gluon Correlations : $g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$

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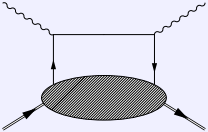
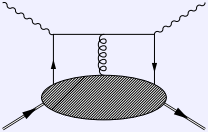
Twist-2 (Wandzura, Wilczek, 1977)



$$g_2^{WW}(x,Q^2) = -g_1^{LT}(x,Q^2) + \int_x^1 g_1^{LT}(y,Q^2)\mathrm{d}y/y$$
$$\equiv g_2^{tw2}(x,Q^2)$$

Twist-3 (Cortes, Pire, Ralston, 1992)

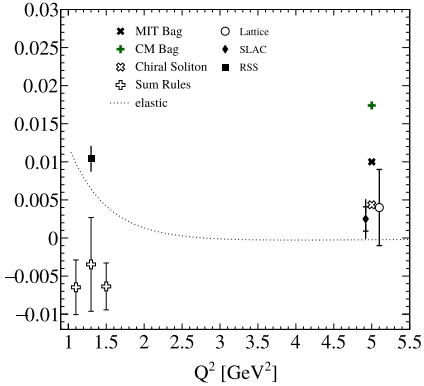


$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$
$$\equiv g_2^{tw3}(x,Q^2)$$

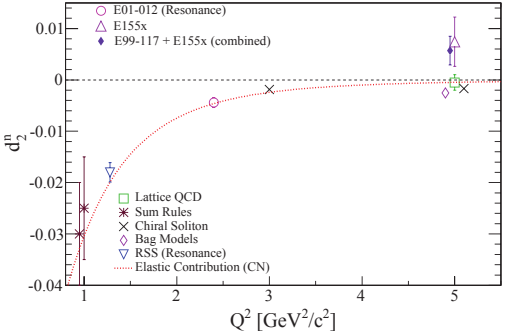
$$d_2(Q^2) = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

As Q^2 decreases,
when do higher twists begin to matter?
When is the color force non-zero?

proton: PRL 122, 022002 (2019)

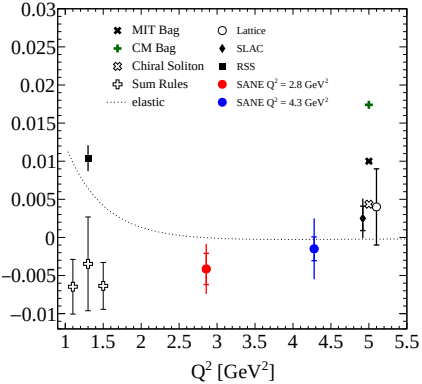


neutron

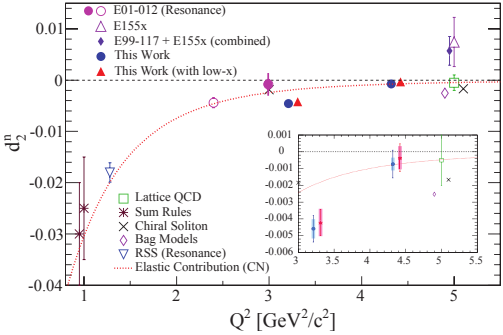


Existing data

proton: PRL 122, 022002 (2019)



neutron

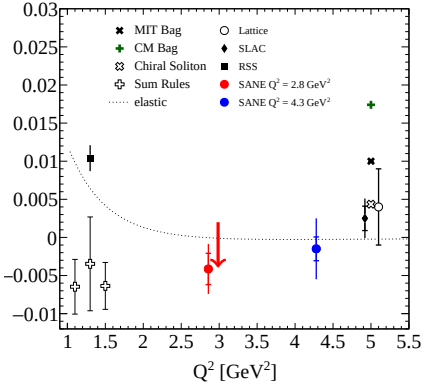


Neutron from d_2^n experiment: D.Flay, et.al. PRD.94(2016)no.5,052003

SANE and d_2^n Result

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron

proton: PRL 122, 022002 (2019)



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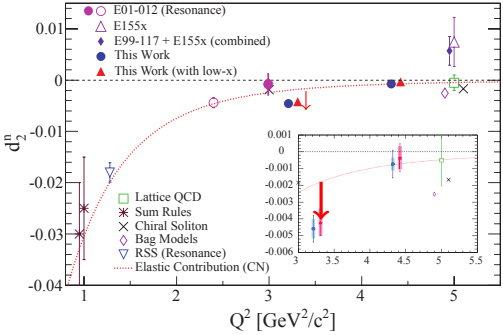

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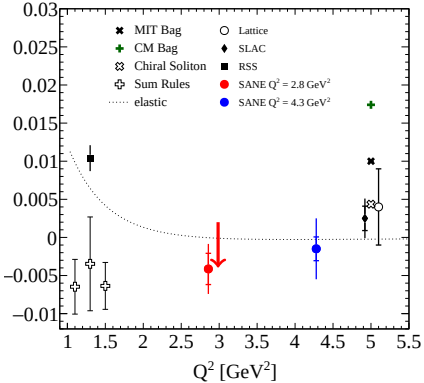
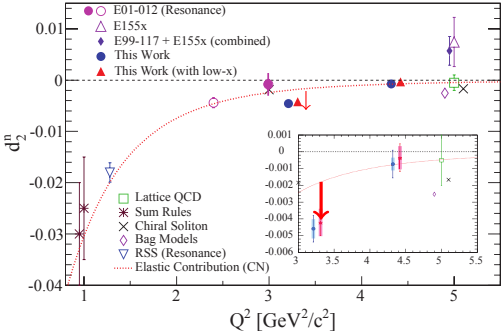


neutron



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SANE and d_2^n Result

- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this an isospin independent average color force?
- Updated Lattice calculations are long over due!

Fixed Target Technology

A quick overview of polarized fixed targets

Dynamic Nuclear Polarization (DNP)	solid
Metastability-exchange optical pumping (MEOP)	gas
Spin exchange optical pumping (SEOP)	gas
Atomic Beam Source (ABS)	internal gas

Polarized nucleon targets

DNP $\vec{p}$	Solid frozen target NH_3, butanol, LiH
ABS $\vec{p}$	Internal target (Hermes)
DNP $\vec{n}$	From $\vec{d}$
SEOP $\vec{n}$	From $^3\vec{\mathrm{He}}$
MEOP $\vec{n}$	From $^3\vec{\mathrm{He}}$

Polarized Target Dilution Factor

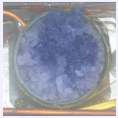
Example: Polarized NH3 Target

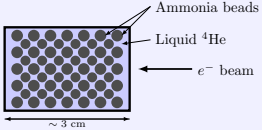
Dilution

- Takes into account scattering from unpolarized material in target.
- Need to know target geometry and material.
- Function of x and W

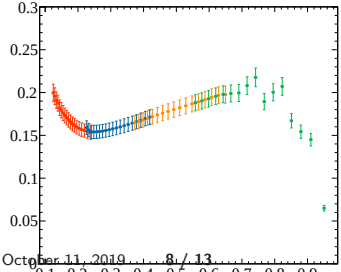
Polarized NH3

- Packing faction of NH_3 about 60%



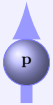


$$f(x,W) = \frac{N_p \sigma_p(x,W)}{N_p \sigma_p + \sum_i N_i \sigma_i(x,W)}$$



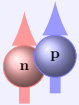
Collider Benefits

Proton



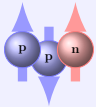
- No dilution from extra material

Deuteron



- Polarized neutron or proton

^{3}He



- Polarized neutron

- No dilution from windows, cryogenics, molecular structure, ...
- Forward spectator tagging to identify struck nucleon.
- Arbitrary ion polarization direction

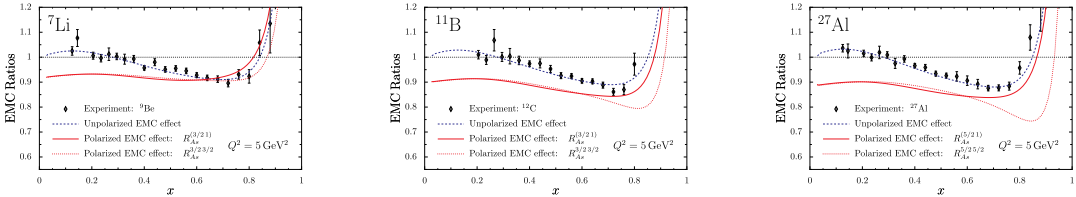
Collider Benefits

	Fixed Target	**Ion Collider**
Dilution	NH_3: $f \simeq 0.12$ ^{3}He: $f \simeq 0.92/3$	proton: no dilution neutron: $f \simeq 1/3$
Spectator Tagging	Very difficult	Possible with forward detectors
Luminosity	NH_3: Beam current limited to 100 nA $\rightarrow \mathcal{L} \simeq 10^{35} s^{-1} cm^{-2}$ ^{3}He: $\mathcal{L} \simeq 10^{37} s^{-1} cm^{-2}$	$\mathcal{L} \simeq 10^{34} s^{-1} cm^{-2}$ better dilution compensates for lower luminosity
$\parallel$,$\perp$ polarization	NH^3: physically rotated 5T magnet leads to different rates/backgrounds in detectors for same kinematics ^{3}He: weak field, dual Helmholtz coils for easy rotation.	Bunch by bunch ion spin rotation?

Polarized Heavy Ions

Polarized EMC Effect

$R \simeq g_1^A / g_1^p$



Cloët, et.al., Phys.Rev.Lett. 95 (2005) 052302

Tagging to identify struck system

- Full tagging of spectator system (A-1)
- Identify struck nucleon to eliminate dilution of nucleus
- Would like many polarized ions beyond ^{3}He

Laser Driven Source

25 Years Ago at Argonne

PROSPECT OF POLARIZED TARGETS IN ELECTRON RINGS*

R. J. Holt

Argonne National Labo

The feasibility of performi
with polarized targets in electro
examples of the physics which wo
method are given. It is noted th
with recent proposals for linac-
A new method for producing a pola
is proposed and some preliminary
summary of laser-driven polarize
produced polarized atomic beams

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Nuclear Instruments and Methods in Physics Research A 364 (1995) 58–69

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Laser-driven source of spin-polarized atomic hydrogen and deuterium

M. Poelker [a,*,1], K.P. Coulter [a,2], R.J. Holt [a,3], C.E. Jones [a], R.S. Kowalczyk [a], L. Young [a], B. Zeidman [a], D.K. Toporkov [b]

[a] Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843, USA
[b] Budker Institute for Nuclear Physics, 630 090 Novosibirsk, Russian Federation

Received 20 January 1995

Nuclear Instruments and Methods in

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An active storage cell for a polarized gas internal target

K.P. Coulter [a,*,1], R. Gilman [a,2], R.J. Holt [a], L.G. Isaeva [b], E.R. Kinney [a,3], R.S. Kowalczyk [a], S.I. Mishnev [b], J. Napolitano [a,4], D.M. Nikolenko [b], S.G. Popov [b], D.H. Potterveld [a], I.A. Rachek [b], A.V. Sukhanov [b], A.B. Temnykh [b], D.K. Toporkov [b], E.P. Tsentalovich [b], B.B. Wojtsekhowski [b], L. Young [a], A. Zghiche [a]

[a] Argonne National Laboratory, Argonne, IL 60439-4843, USA
[b] Budker Institute of Nuclear Physics, Novosibirsk 630090, Russian Federation

Received 8 June 1994

Recent Developments

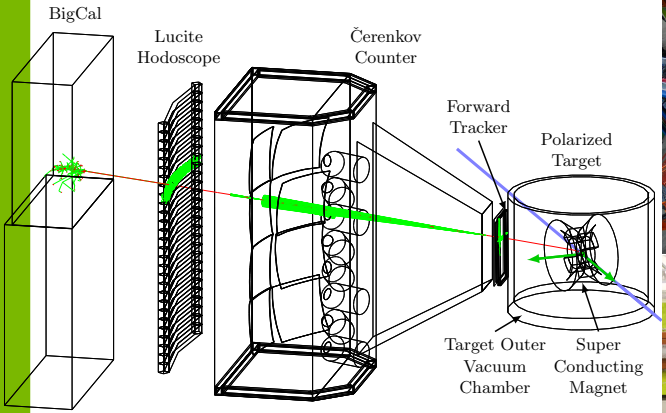
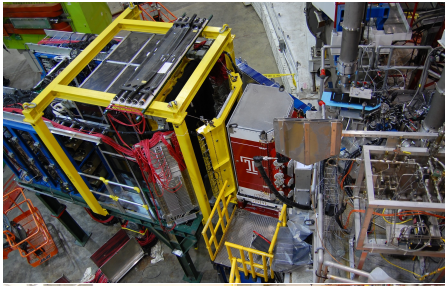
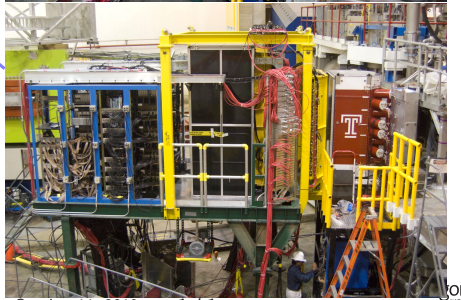
- Hybrid SEOP → K and Rb (M.V. Romalis PRL 105, 243001 (2010))
- Readily available high power diode lasers for pumping Rb (795 nm)
- Successful polarized ^{3}He program at JLab.

Beginning to investigate general purpose hybrid SEOP to polarize heavier ions such as ^{21}Ne.

Summary

- Nuclear polarization is key for unraveling QCD at the EIC
- **All polarization directions equally important**, especially for imaging program
- Extreme forward tagging will **significantly improve the science** extracted with each polarized ion electron collision
- Nuclear polarization is needed to investigate Polarized EMC Effect
- A general purpose laser driven source may provide polarized heavy ions

Thank You!

Backup

E07-003 : **B**ig **E**lectron **T**elescope **A**rray