Probing Nucleon Spin Structure Using Deep Inelastic Scattering

E12-06-121: Neutron g_2 and d_2

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Jefferson Lab

Outline

- Introduction to DIS
- Existing results and projections
- Hall C layout
- Rate estimates and run plan
- Progress and updates
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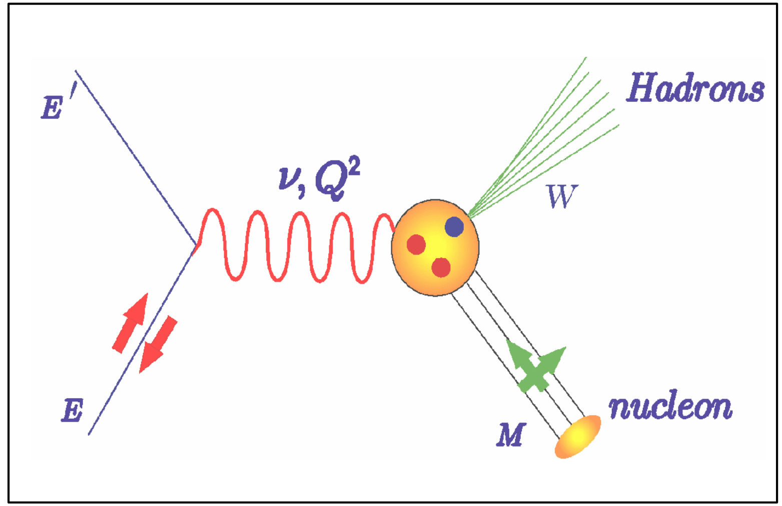
Deep Inelastic Scattering

Unpolarized cross section:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\frac{\theta}{2}} \left(\frac{2}{M} F_1(x,Q^2) \sin^2\frac{\theta}{2} + \frac{1}{\nu} F_2(x,Q^2) \cos^2\frac{\theta}{2} \right)$$

- Unpolarized structure functions F_1 and F_2 contain information about the momentum structure of the target nucleon.



Polarized cross section:

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 E'}{MQ^2\nu E}\left[(E+E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu} g_2(x,Q^2)\right] = \Delta\sigma_{\parallel}$$

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta E'^2}{MQ^2\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right] = \Delta\sigma_{\perp}$$

- Polarized structure functions g_1 and g_2 encode information about the spin structure of the target nucleon.

Q^2 = 4-momentum transfer squared of the virtual photon

ν = E-E' = energy transfer

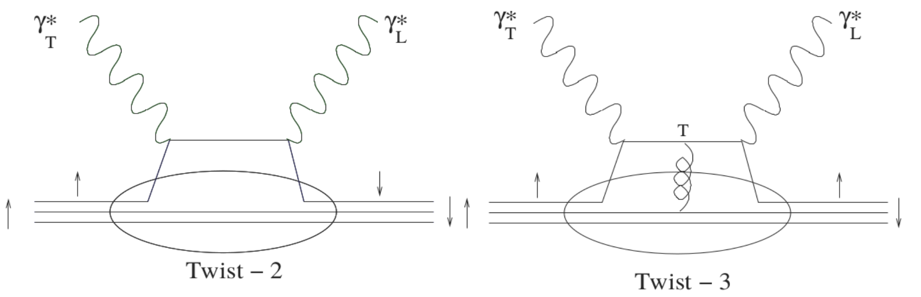
θ = scattering angle

x = Fraction of nucleon momentum carried by the struck quark

g_2 and Quark-Gluon Correlations

- In naive quark parton model, nucleon is viewed as a collection of non interacting, point like constituents.

- g_2 has no interpretation in naive quark parton model, provides information on quark-gluon correlation.



$$\gamma^\star(+1) + N(1/2) \rightarrow \gamma^\star(0) + N(-1/2)$$

- g_2 is among the cleanest higher twist observables – contributes to leading order (twist-2 is leading twist) at the transverse spin asymmetry.

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- Twist-2 term (Wandzura & Wilczek).

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y} dy$$

- Twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston).

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

Transversity

Quark-gluon correlation

d_2: Clean Probe of Quark-Gluon Correlations

- d_2 is a clean probe of quark-gluon correlations / higher twist effects - third moment of the linear combination of the spin structure function.

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

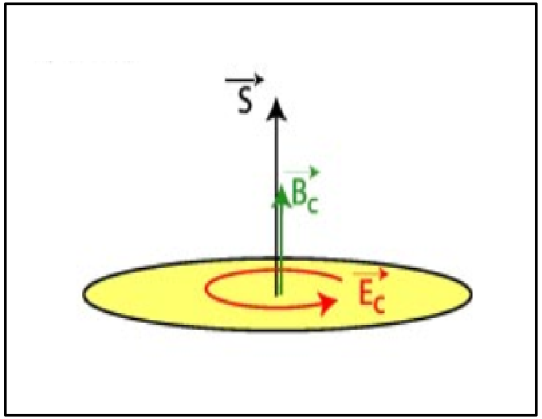
- Related to matrix element in OPE, which represents average color Lorentz force on the struck quark due to the remnant di-quark system and it is cleanly computable using Lattice QCD.

- Connected to "color polarizability".

$$\chi_E=\frac{(4d_2+2f_2)}{3} \qquad \chi_B=\frac{(4d_2-f_2)}{3}$$

- f_2 is a twist-4 contribution can be extracted from the first moment of g_1.

$$\Gamma_1=\int_0^1 g_1\,dx=\mu_2+\frac{M^2}{9Q^2}(a_2+4d_2+4f_2)+O\left(\frac{\mu^6}{Q^4}\right)$$



Response of the color $\vec{B}$ and $\vec{E}$ field to the nucleon polarization

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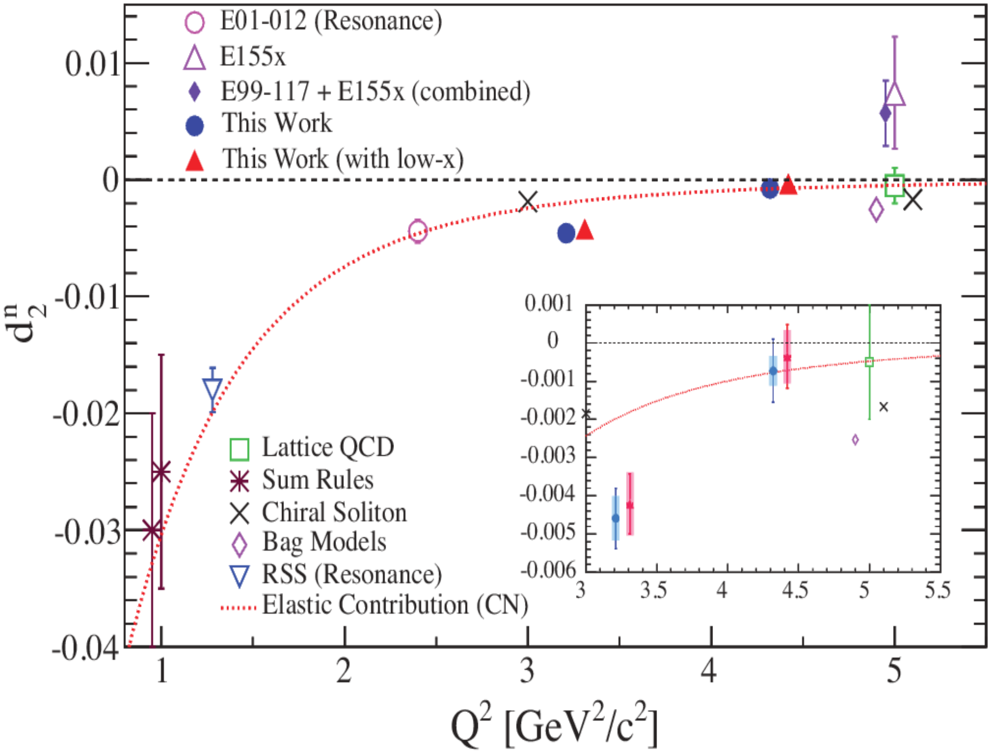
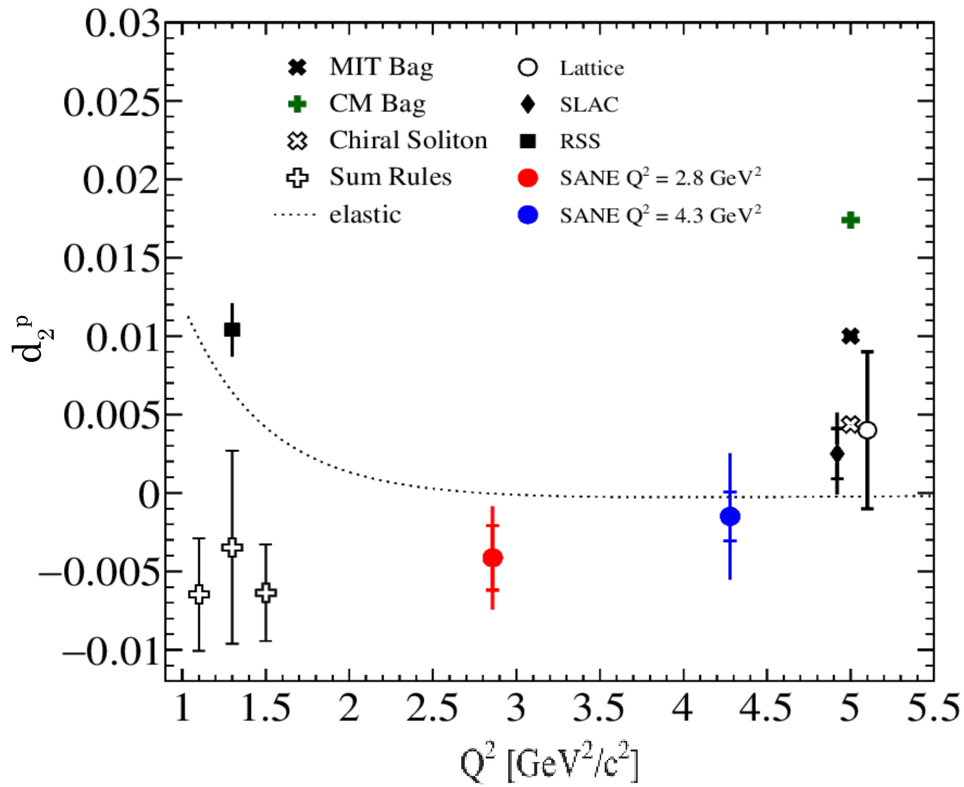
Existing results: d_2 for proton and neutron

Hint of a negative d_2^n, negative twist-3 at moderate $Q^2 \sim 3$ (GeV/c)^2 was noted in E06-014 at JLab .

Posik et al., 10.1103/PhysRevLett.113.022002 (d_2^n, color force extraction)
Flay et al., 10.1103/PhysRevD.94.05200 (Archival paper: g_1^n, g_2^n, d_2^n)
Parno, et al., 10.1016/j.physletb.2015.03.067 (A_1^n)





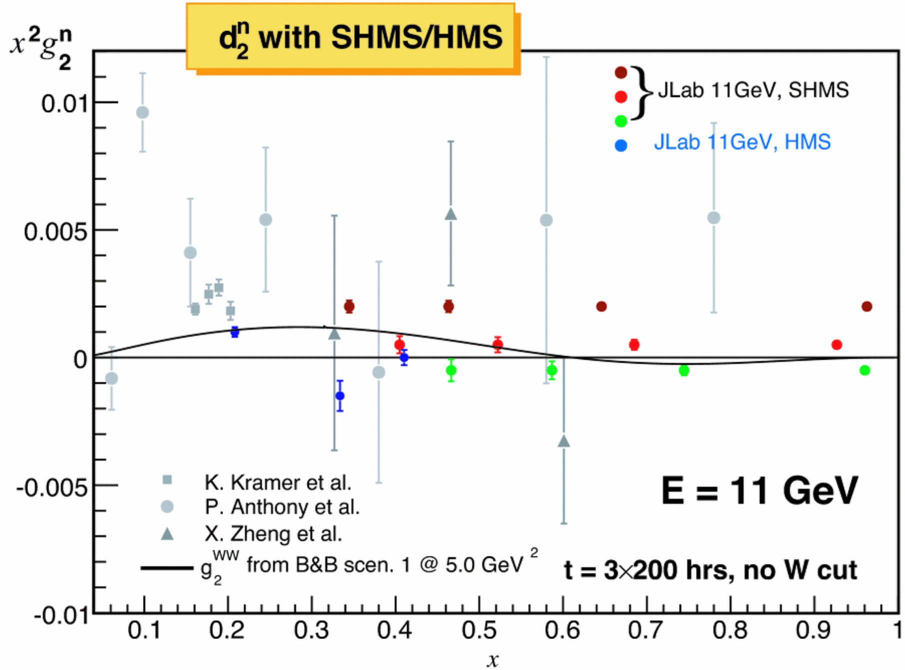
Similar hint of negative twist-3 (dips below CN elastic) in d_2^p data was noted in SANE experiment.

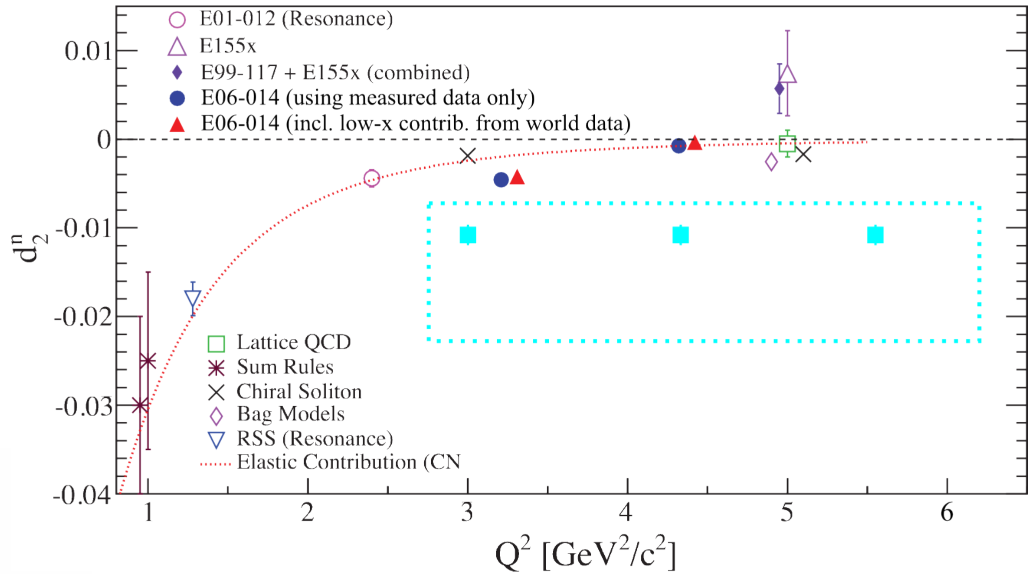
Armstrong et al., PRL 122, 022002 (2019)

E12-06-121: Projected Results

Projection of $x^2 g_2^n$ over broad range of x.

Points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—6 GeV².





Projected results for d_2^n at truly constant Q^2 = 3, 4.3 and 5.6 GeV²/c².

In this region,

- Models are thought to be accurate.
- Direct overlap with 6 GeV Hall A measurements.

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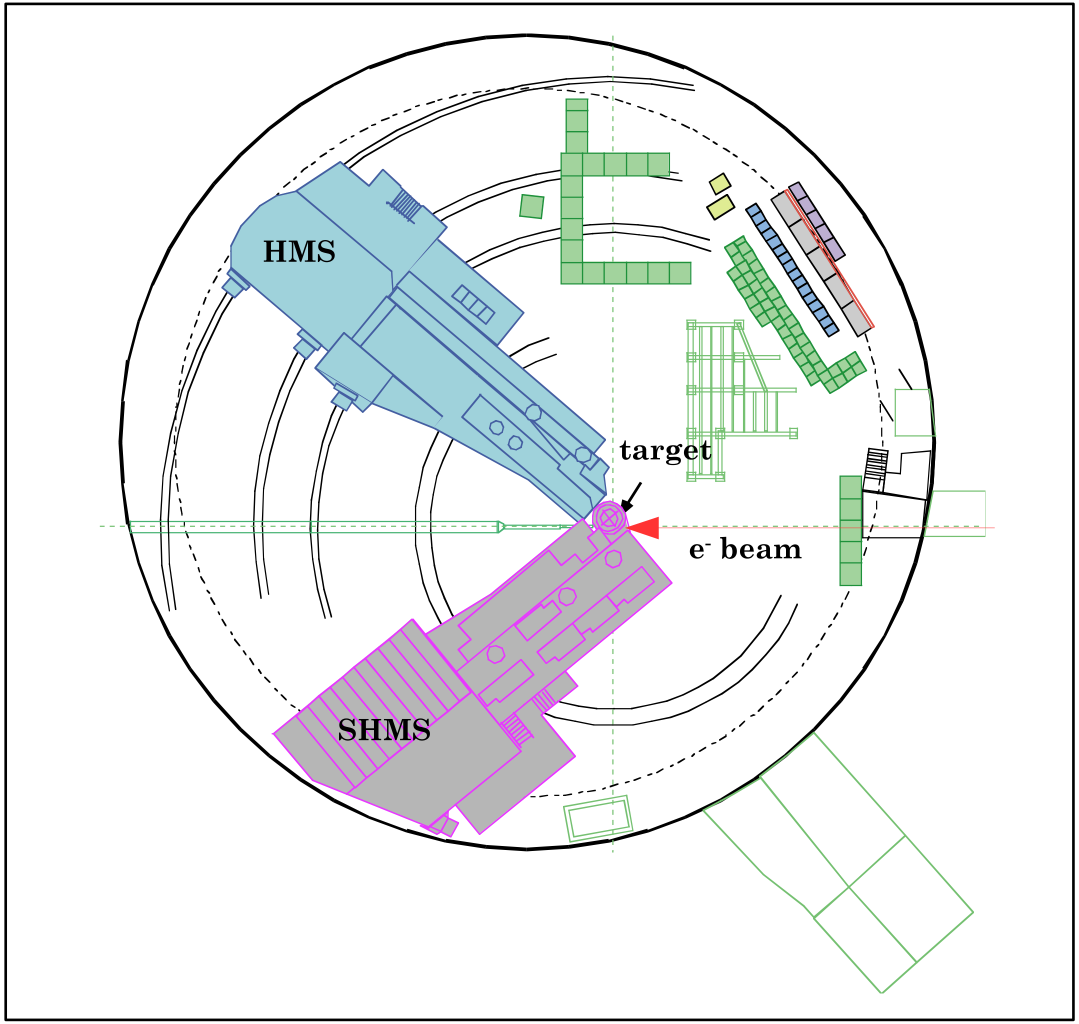
E12-06-121: Hall C Layout



Spectrometers:

- Super High Momentum Spectrometer (SHMS).
- High Momentum Spectrometer (HMS).

Electron Beam :

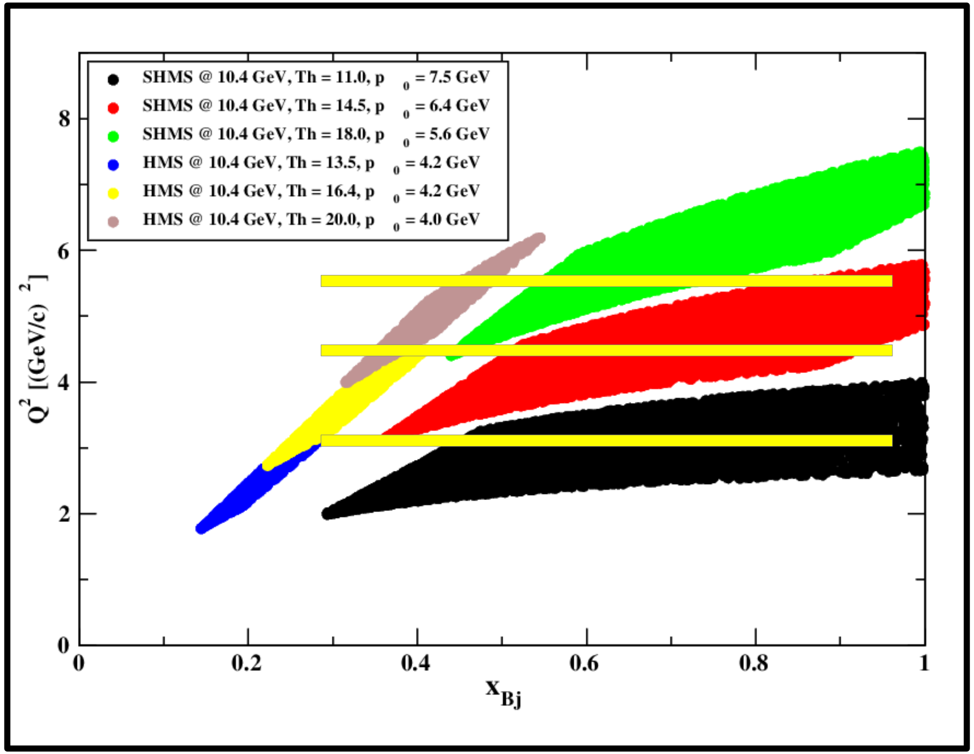
- Beam energies
  - 10.4 GeV/c (production) [5-pass]
  - 2.1 GeV/c (calibration) [1-pass]
- Beam current
  - 30 μA (production)
  - 45 μA (max, calibration)
- Beam polarization ~ 80%
  - Measured to ~3% using Moller polarimetry.

Polarized ^3He target:

- 40 cm long ^3He cell.
- Target polarization
  - 45 - 55% in beam
  - 55 - 60% without beam.

E12-06-121: Kinematic coverage

- Reduced kinematic settings vs. proposal to accommodate run-time reduction and lower electron beam energy.
- SHMS collects data at $\theta = 11°$, $14.5°$ and $18.0°$ for 125 hrs each.
- HMS collects data at $\theta = 13.5°$, $16.4°$, $20.0°$ for 125 hrs each.
- Each arm measures an absolute polarized cross section independent of the other arm to extract g_1, g_2.

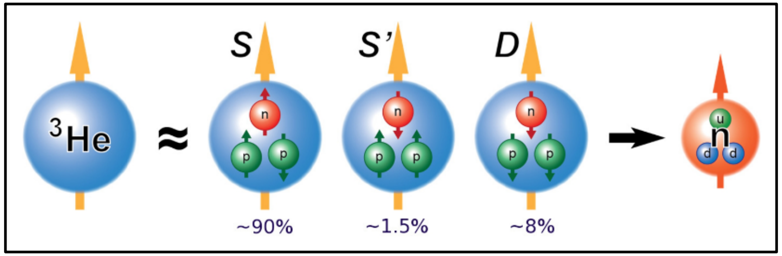


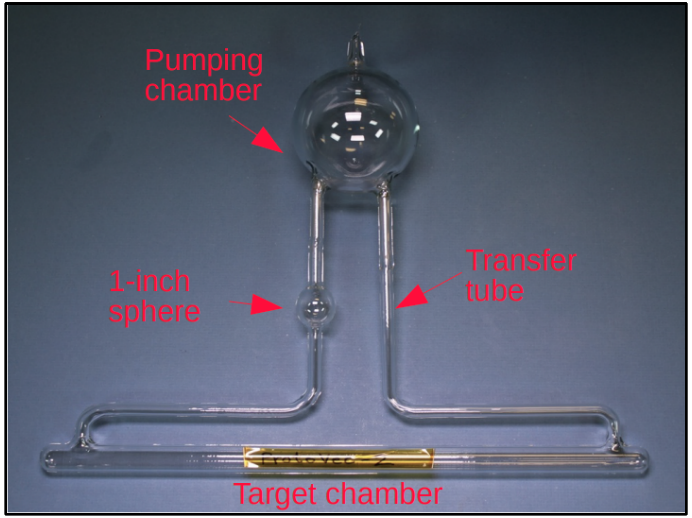
SHMS Production					
Setting	P_o	Angle	x	Q^2 (GeV^2/c^2)	W (GeV)
X	7.5	11.0°	0.527	2.866	1.859
Y	6.4	14.5°	0.565	4.240	2.036
Z	5.6	18.0°	0.633	5.701	2.046

HMS Production					
Setting	P_o	Angle	x	Q^2 (GeV^2/c^2)	W (GeV)
A	4.2	13.5°	0.207	2.414	3.178
B	4.2	16.4°	0.305	3.554	2.993
C	4.0	20.0°	0.418	5.018	2.806

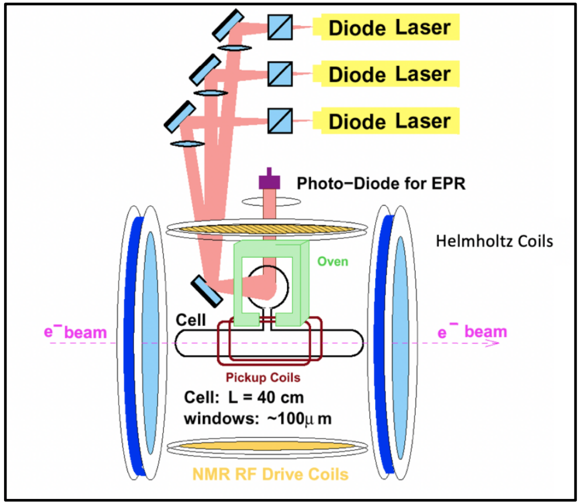
Polarized ³He target

- Short lifetime of neutron (886 s), no dense neutron target.
- Effective neutron target: 90% of ³He spin comes from the neutron spin.





- **Polarization method:** Spin exchange optical pumping (SEOP)
  1. Optical Pumping
  2. Spin exchange
- **Polarization measurements:**
  1. Nuclear Magnetic Resonance (NMR)
  2. Pulse NMR
  3. Electron Paramagnetic Resonance (EPR)



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E12-06-121: Rate estimates

HMS Kin.	theta (deg)	E' (GeV)	Q^2 (GeV^2)	x	W (GeV)	e^- rate (Hz)	π^- rate (Hz)	$t_\parallel$ (Hz)	$t_\perp$ (Hz)	ΔA_{raw} (par) (10^{-4})	ΔA_{raw} (perp) (10^{-4})
A	13.5	4.2	2.474	0.216	3.14	3083	2973	8.06	116.9	2.71	0.7
B	16.4	4.2	3.643	0.318	2.948	179	100.3	9.6	115.4	4.48	1.297
C	20	4	5.018	0.418	2.806	39	13.9	11.2	113.8	8.91	2.8
SHMS Kin.	**theta (deg)**	**E' (GeV)**	**Q^2 (GeV^2)**	**x**	**W (GeV)**	**e^- rate (Hz)**	**π^- rate (Hz)**	**$t_\parallel$ (Hz)**	**$t_\perp$ (Hz)**	**ΔA_{raw} (par) (10^{-4})**	**ΔA_{raw} (perp) (10^{-4})**
X	11	7.5	2.866	0.527	1.859	3153	5.29	9.6	115.4	2.51	0.723
Y	14.5	6.4	4.24	0.565	2.036	528.2	5.62	11.38	113.6	5.63	1.78
Z	18	5.6	5.701	0.633	2.046	80.82	1.06	12.85	112.1	13.5	4.58

- The tables have a first estimate of the expected rates and error in raw asymmetries for the different kinematics (B. Sawatzky, W. Korsch).

Input parameters and assumptions →

E [GeV]	l_{tgt} [cm]	ρ_{tgt} (fill) [amg]	ρ_{tgt} (T-corr.) [amg]	P_{tgt}	P_{beam}	I [μA	Be [mil]	GE180 [μm]	A_{charge} [ppm]
10.4	40	8.26	10.56	0.50	0.80	30	10	280	200

Assumptions:

- SHMS
  - SHMS acceptance: 50 cm, −15%, +25% (relative to p_0)
  - N_2 density of 1.4×10^{19} cm^{-3}
  - $\Delta P_{tgt} = 0$
  - $\Delta P_{beam} = 0$
  - $\Delta A_{charge} = 0$
- HMS
  - HMS acceptance: 10 cm, −10%, +10% (relative to p_0)
  - N_2 density of 1.4×10^{19} cm^{-3}
  - $\Delta P_{tgt} = 0$
  - $\Delta P_{beam} = 0$
  - $\Delta A_{charge} = 0$

E12-06-121: Run Plan

Beam time allocation:

A total of **6 calendar weeks** of electron beam time is expected.

SHMS Production			HMS Production		
Setting	P_o	Angle	Setting	P_o	Angle
X	7.5	11.0°	A	4.2	13.5°
Y	6.4	14.5°	B	4.2	16.4°
Z	5.6	18°	C	4.0	20.0°

Start with 5-pass production: SHMS- Kin X, HMS- Kin C
(~ 1-2 calendar weeks)

↓

Take 1-pass calibration data,
E12-06-121A He-3 Elastic FF Measurements.
(~3 days)

↓

Return to 5-pass production: SHMS- Kin Z, HMS- Kin A
SHMS- Kin Y, HMS- Kin B
(rest of the beam time, ~3-4 calendar weeks)

E12-06-121: Run Plan

5-pass running (Production)

For each kinematic pair

- Reference cell runs: ^{3}He, N_2
- Empty cell run
- ~~8 hrs Optics (C-foil + Sieve)~~
- Positive polarity runs: 4 hrs optics, 4 hrs production
- Target NMR (1–2 / shift), PNMR, EPR measurements
- Production runs

Instrumentation / Calibration runs

- BPM calibration (2 hour)
- BCM calibration (2 hour)
- Beam energy (2 hour)

1-pass running (Calibration)

Nominal to do list :

- 8 hr Moller run
- 4 hr Optics run at p_0 = 2.1 GeV/c
- Pressure curves for current cell
- Hydrogen elastics
- Delta QE measurements
- E12-06-121A ^{3}He Elastic Form Factor Measurements

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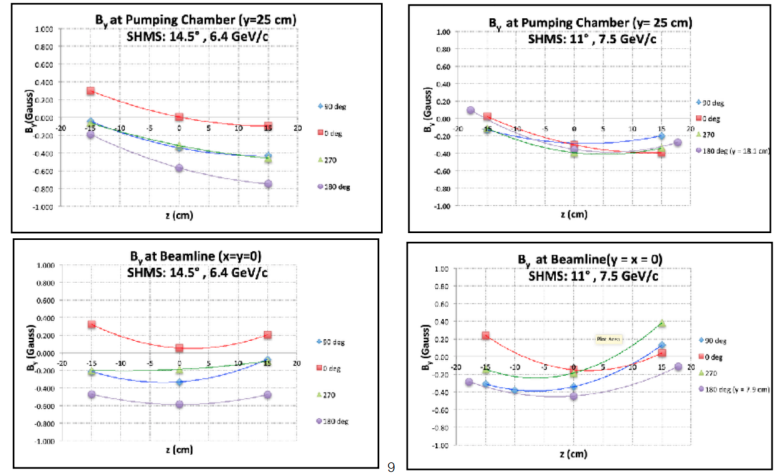
E12-06-121: Progress and Updates

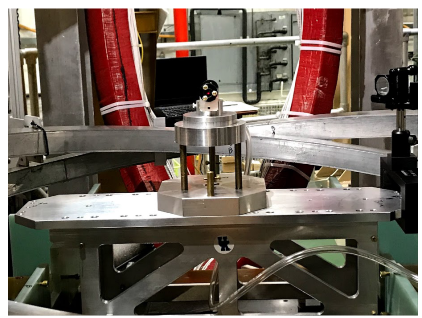
Field mapping and field direction measurements:

- Both the magnetic field mapping and magnetic field direction measurements in target region were completed in March, 2020.
- The vertical correction coil current settings were optimized to eliminate any vertical magnetic field component and to get reduced gradient along the target cell.
- The magnetic field direction was scanned along the target length using an air floated compass. The uncertainty in the direction measurement was limited to ±0.1°.

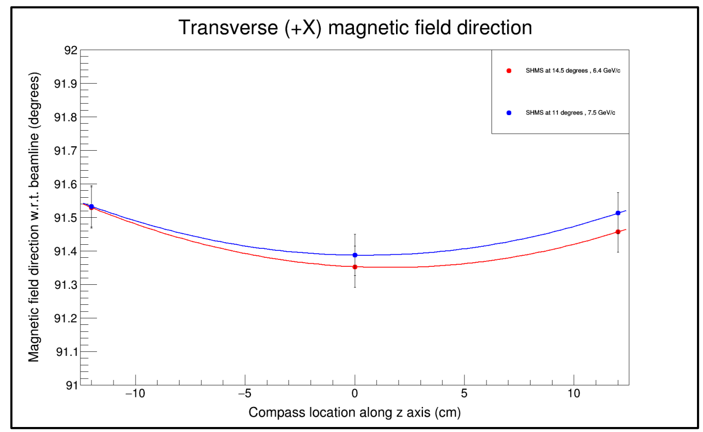
Field mapping setup



Results from Field mapping



Air compass used for field direction measurements

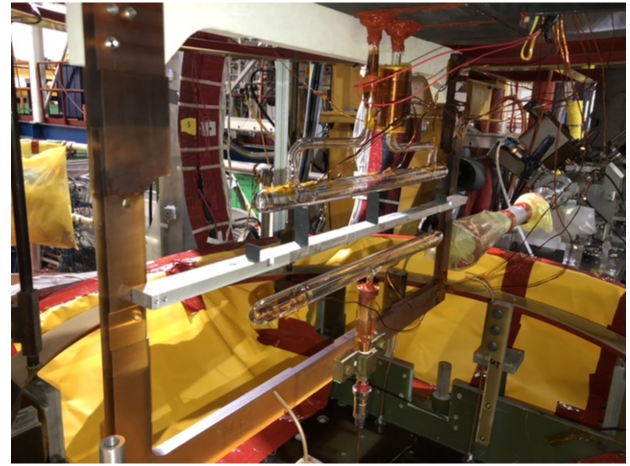


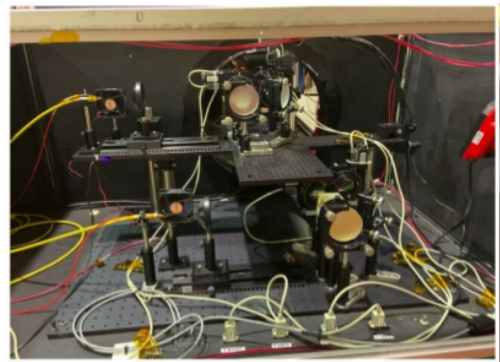
Results from compass measurements

E12-06-121: Progress and Updates

Target preparation and polarimetry:

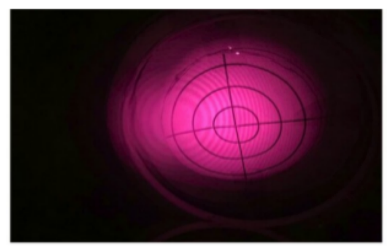
- Polarized ^{3}He cell "Austin" and the reference cell "Christen" were installed in March.
- Target optics were cleaned up.
- Laser software was upgraded.
- Laser alignment in both transverse and longitudinal direction was done.
- Laser polarization optimized, laser spectrum analyzer calibrated.
- New holding field Kepco power supplies were installed and calibrated.
- Quick magnetic field measurement check was done. Results agreed with the field mapping done in March.



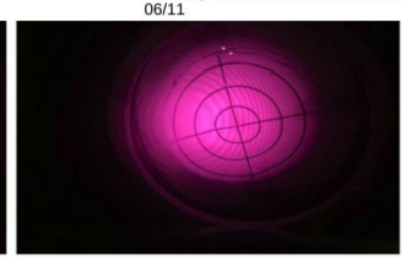


- Laser box status 06/11

- Clean up oven mirrors and windows 06/11



- Longitudinal left line laser spot on oven window (after realignment)

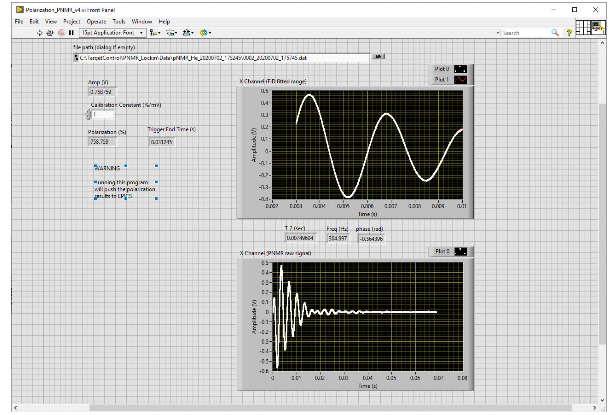


- Longitudinal right line laser spot on oven window (after realignment)

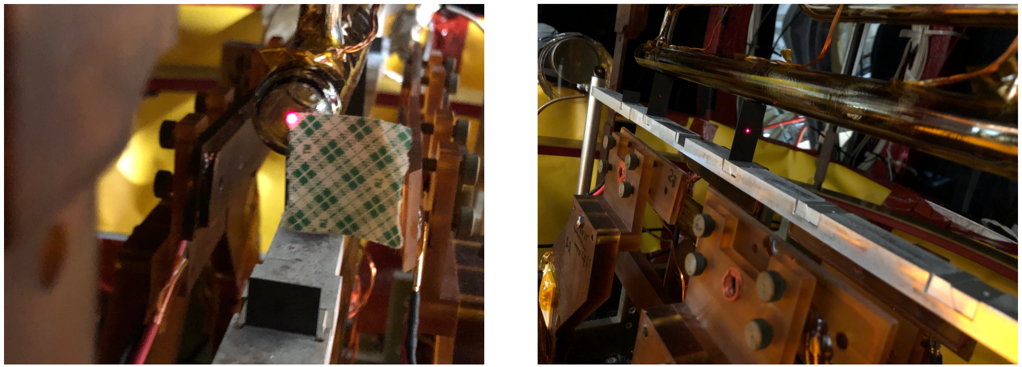
E12-06-121: Progress and Updates

Target preparation and polarimetry:

- Target polarimetry is working perfectly – NMR, PNMR and EPR.
- Target ladder alignment has been completed.

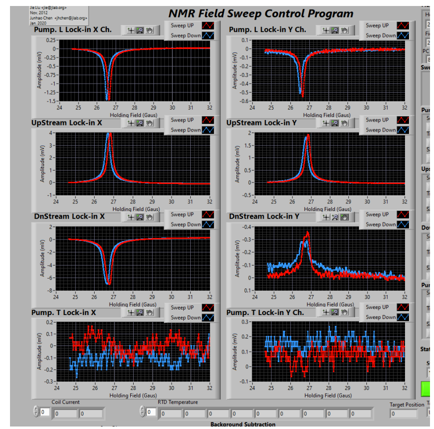


PNMR signal obtained on 07/02/2020

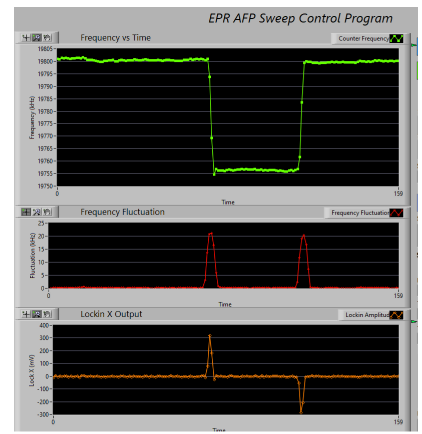


Target ladder alignment

- Cell characterization has been completed for ^{3}He cell "Tommy" (the cell that will be used after "Austin").
- Target spin up and other polarization studies on "Austin" are in progress.



Transverse NMR signal obtained on 07/03/2020



EPR sweep on 07/14/2020

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Summary

- The experiment E12-06-121 (neutron g_2 and d_2) is expected to start production on 27th July, 2020.
- ^{3}He target "Austin" is installed and polarimetry is working.
- Large precision data for g_2 and d_2 over high x and Q^2 will be obtained, d_2^n will be evaluated at truly constant Q^2 values for the first time.
- This experiment will provide insight into quark-gluon correlations.
- Several theoretical predictions (especially Lattice QCD) will be verified.

Thank you!

Supporting Documentations

- Polarized Helium-3 Experiments wiki (2019/2020)
  https://hallcweb.jlab.org/wiki/index.php/Polarized_Helium-3_Experiments

- Proposals
  - ➔ https://hallcweb.jlab.org/wiki/images/c/cb/PR12-06-121.pdf
  - ➔ https://hallcweb.jlab.org/wiki/images/1/1a/D2n_HallC_PAC36-update_v2.pdf

- Polarized ^{3}He Target
  - ➔ https://hallcweb.jlab.org/wiki/index.php/Pol_He-3_Target_Information
  - ➔ https://www.jlab.org/indico/event/351/session/1/contribution/9/material/slides/0.pdf

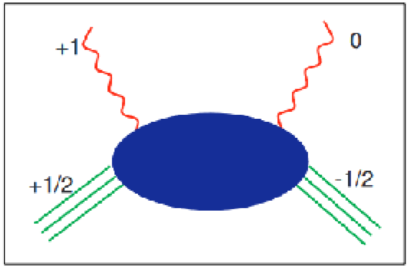
- E06-014 (2009 d_2^n experiment) wiki
  - ➔ https://hallaweb.jlab.org/wiki/index.php/Analysis_resources_for_d2n

Back-up Slides

Twist Expansion

- Quark electromagnetic current in forward Compton amplitude,

$$T_{\mu\nu} = i \int d^4z\, e^{iqz} < N \left| T\left(j_\mu(z) j_\mu(0)\right) \right| N >$$



- Operator product expansion (OPE) : $j_\mu(z) j_\mu(0) = \sum C_{\mu_1 \ldots \mu_n} \mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n}$

$\mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n}$: Local quark gluon operators with mass dimension d and spin dimension n

- Dimension Analysis : $C_{\mu_1 \ldots \mu_n} \mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n} \longrightarrow \frac{q_{\mu_1}}{Q} \ldots \frac{q_{\mu_n}}{Q} Q^{2-d} M^{d-n-2} p^{\mu_1} \ldots p^{\mu_n}$

$$\rightarrow \frac{P.q}{Q^n} Q^{2-d} M^{d-n-2}$$

$$\rightarrow \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2+n-d}$$

$$\rightarrow \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2-t}$$

	Quark	Gluon
d	3/2	2
n	1/2	1
t	1	1

Twist, t = d-n

Systematic Error Table

Item description	Subitem description	Relative uncertainty
Target polarization		1.5 %
Beam polarization		3 %
Asymmetry (raw)		
	• Target spin direction (0.1°)	$< 5 \times 10^{-4}$
	• Beam charge asymmetry	$<$ 50 ppm
Cross section (raw)		
	• PID efficiency	$<$ 1 %
	• Background Rejection efficiency	$\approx$ 1 %
	• Beam charge	$<$ 1 %
	• Beam position	$<$ 1 %
	• Acceptance cut	2-3 %
	• Target density	$<$ 2%
	• Nitrogen dilution	$<$ 1%
	• Dead time	$<$ 1%
	• Finite Acceptance cut	$<$ 1%
Radiative corrections		$\leq$ 5 %
From ^{3}He to Neutron correction		5 %
Total systematic uncertainty (for both $g_2^n(x,Q^2)$ and $d_2(Q^2)$)		$\leq$ 10 %
Estimate of contributions to d_2 from unmeasured region	$\int_{0.003}^{0.23} \tilde{d}_2^n \, dx$	4.8×10^{-4}
Projected absolute statistical uncertainty on d_2		$\Delta d_2 \approx 5 \times 10^{-4}$
Projected absolute systematic uncertainty on d_2 (*assuming* $d_2 = 5 \times 10^{-3}$)		$\Delta d_2 \approx 5 \times 10^{-4}$

Neutron Asymmetries from ^{3}He

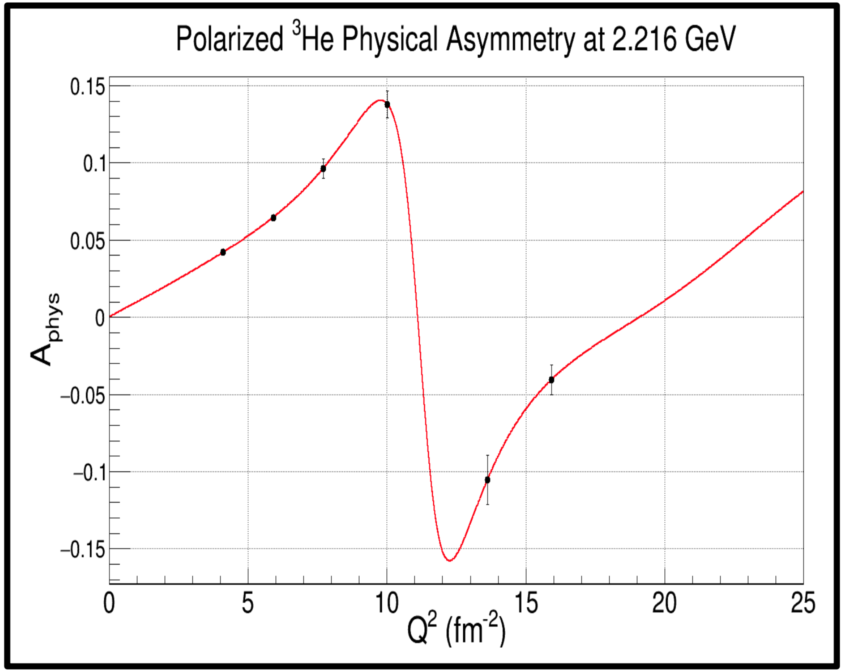
- $A_1^n = \frac{1}{P_n} \frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)} \left(A_1^{3He} - 2P_p\left(1 - \frac{0.014}{2P_p}\right) \frac{F_2^p}{F_2^{3He}} A_1^p\right)$
- $A_2^n = \frac{1}{P_n} \frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)} \left(A_2^{3He} - 2P_p\left(1 - \frac{0.014}{2P_p}\right) \frac{F_2^p}{F_2^{3He}} A_2^p\right)$
- $\frac{g_1^n}{F_1^n} = \frac{1}{P_n} \frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)} \left(\frac{g_1^{3He}}{F_1^{3He}} - 2P_p\left(1 - \frac{0.014}{2P_p}\right) \frac{F_2^p}{F_2^{3He}} \frac{g_1^p}{F_1^p}\right)$
- $\frac{g_2^n}{F_1^n} = \frac{1}{P_n} \frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)} \left(\frac{g_2^{3He}}{F_1^{3He}} - 2P_p\left(1 - \frac{0.014}{2P_p}\right) \frac{F_2^p}{F_2^{3He}} \frac{g_2^p}{F_1^p}\right)$

P_p, P_n : Effective proton and neutron polarizations in ^{3}He

E12-06-121A: Measurement of ³He Elastic Electromagnetic Form Factors

- Significant discrepancies between theoretical and experimental ³He FFs (particularly G_M).

- All higher Q^2 data are from unpolarized electron scattering results.



$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\tau}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)\right]$$

with $\epsilon = \left(1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$ and $\tau = \frac{Q^2}{4M^2}$

- **Double polarization asymmetry:**

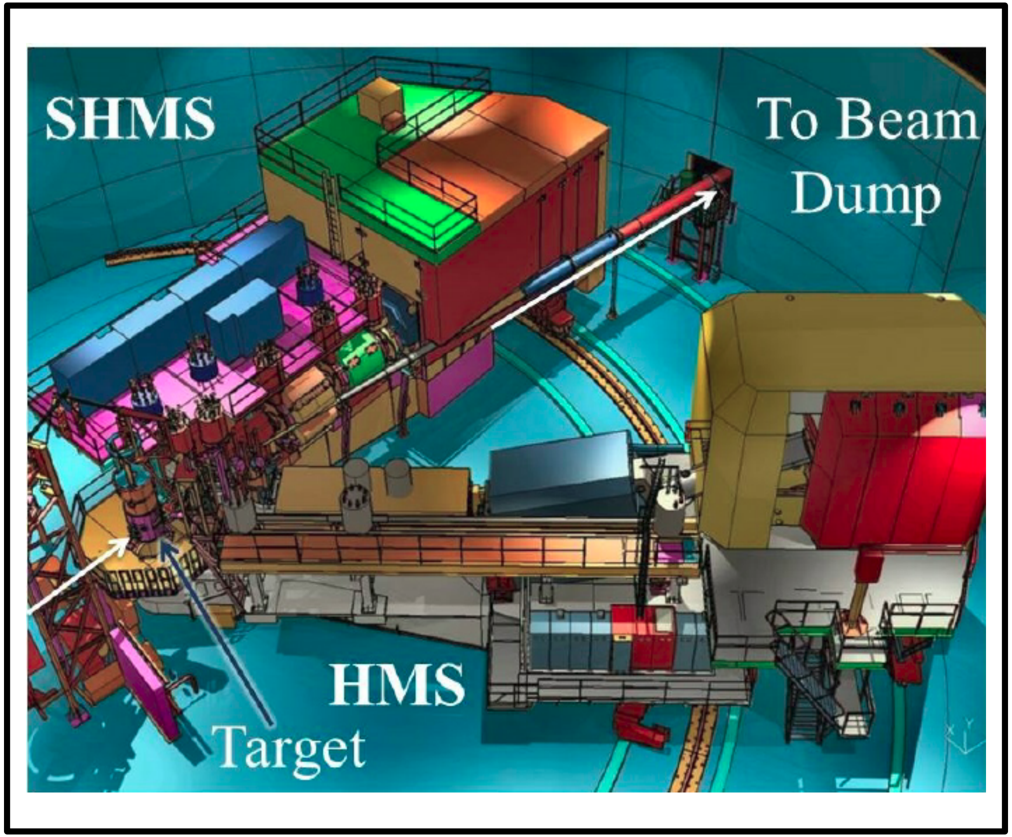
$$A_{phys} = \frac{-2\sqrt{\tau(1+\tau)}\tan\left(\frac{\theta}{2}\right)}{G_E^2 + \frac{\tau}{\epsilon} G_M^2}\left[\sin(\theta')\cos(\varphi') G_E G_M + \sqrt{\tau\left[1 + (1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]}\cos(\theta') G_M^2\right]$$

New independent tool to map FFs without the issues of unpolarized Rosenbluth measurements!

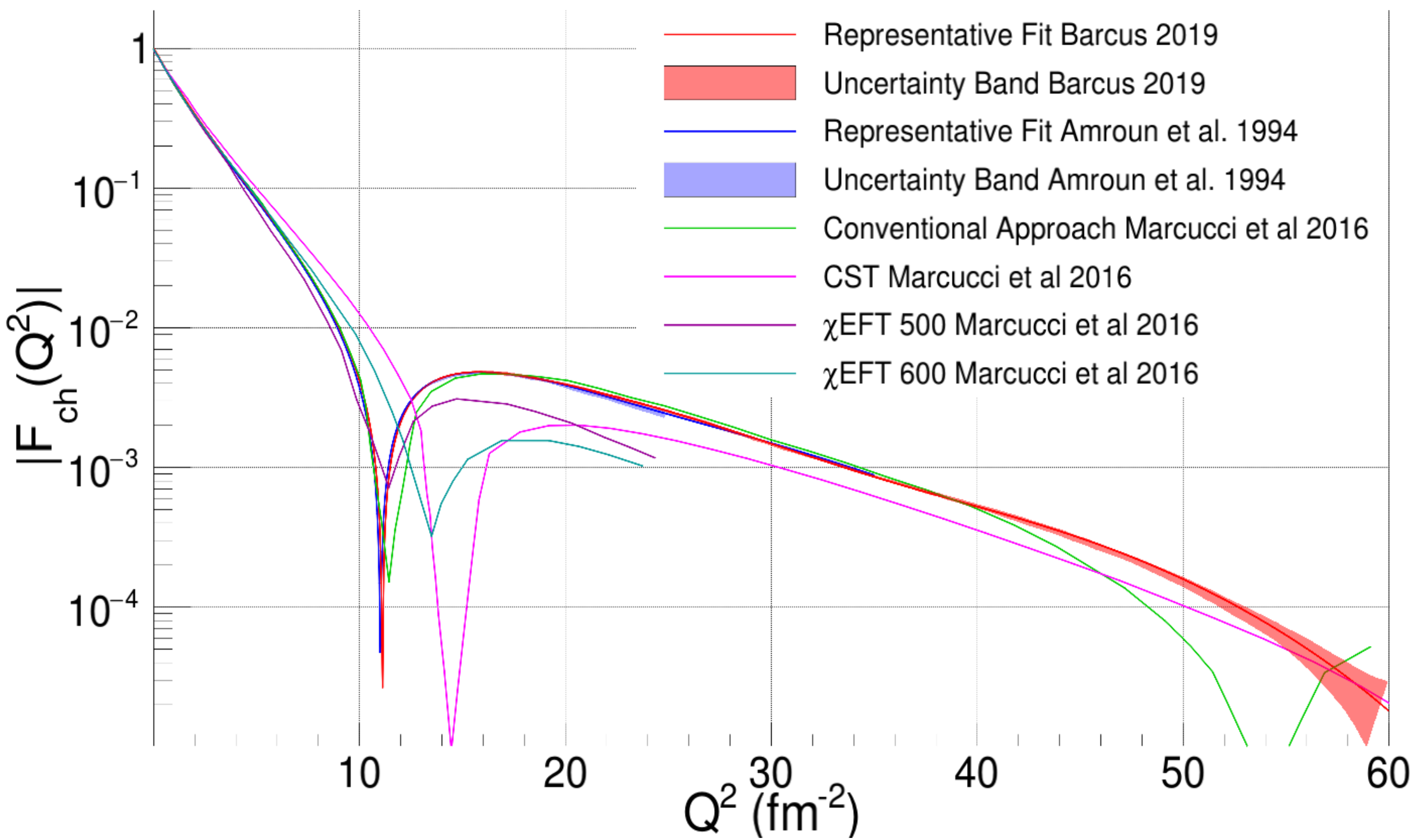
E12-06-121A: Proposed Procedure

Take data during d_2^n 1-pass (~24 PAC hours)

- Polarized ^{3}He target (polarization > 50 %)
- HMS:
  - Positioned at single angle centered on the anticipated FF diffractive minima for the entirety of the run.
- SHMS:
  - Start at small angles and step up in Q^2 passing through the G_E minimum and approaching just below G_M's.
  - Constrains the minima locations while mapping the asymmetry.



^{3}He Charge Form Factor



^{3}He Magnetic Form Factor