Probing Nucleon Spin Structure Using Deep Inelastic Scattering

E12-06-121: Neutron g_2 and d_2

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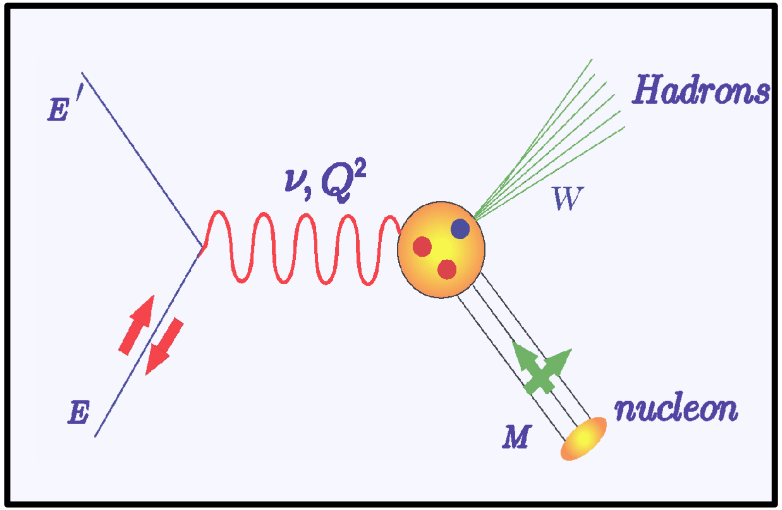
Deep Inelastic Scattering

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

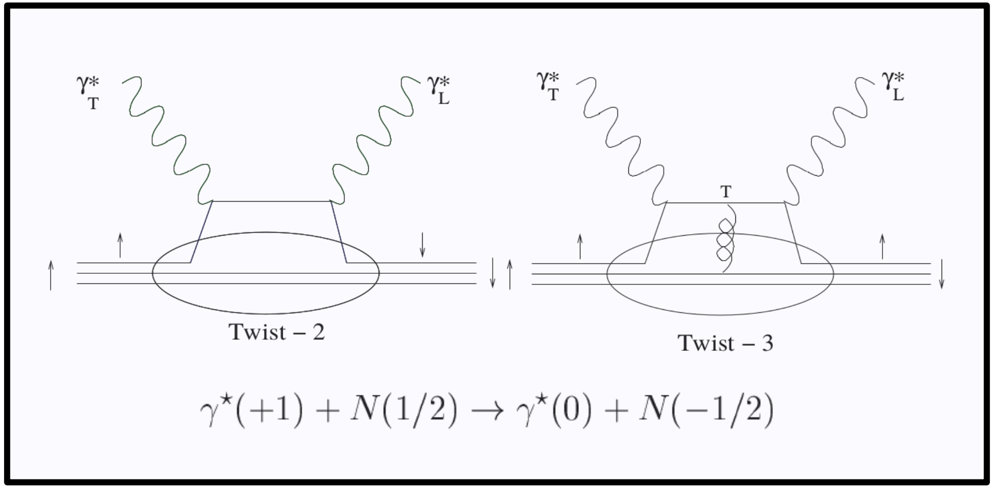
θ = scattering angle

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.



- 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.

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

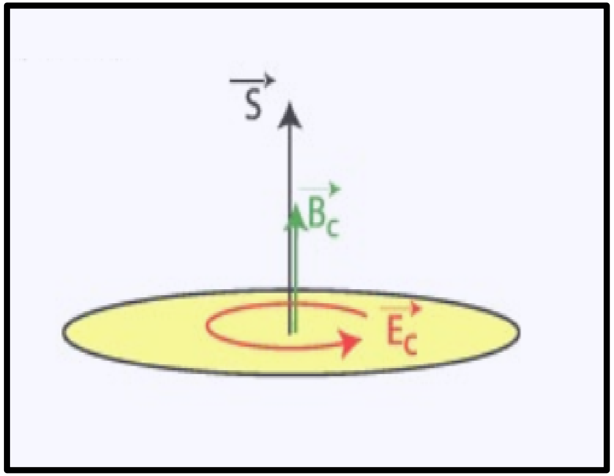
- Related to matrix element in OPE, which represents average color Lorentz force on the struck quark due to the remnant di-quark system and it is cleanly computable using Lattice QCD.

- 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.

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

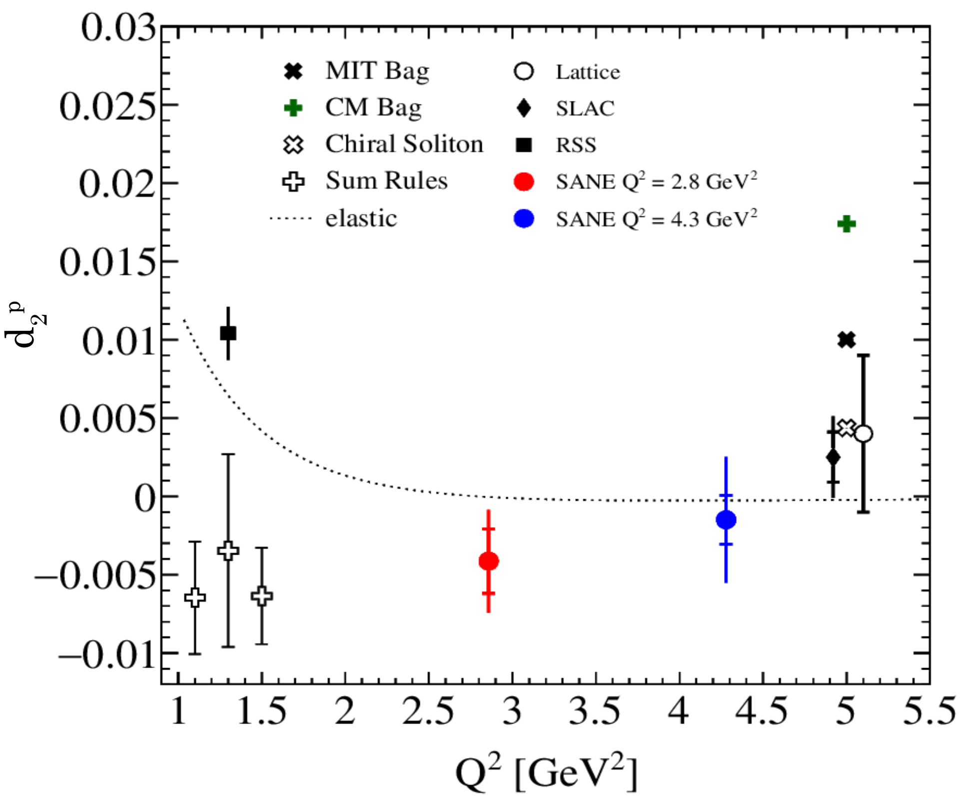


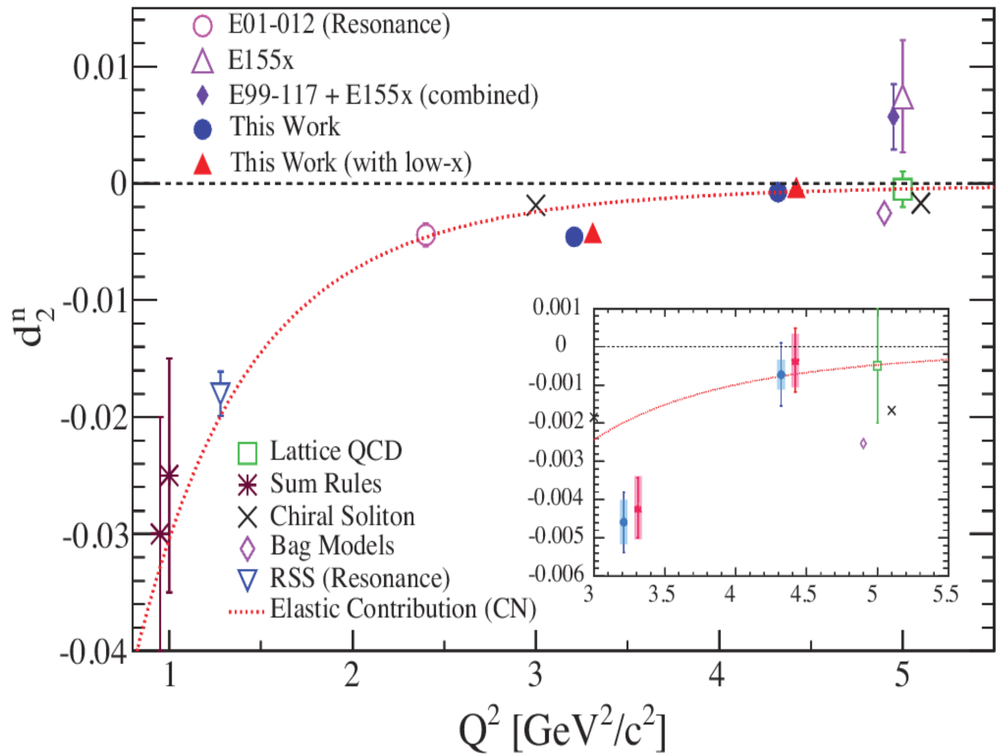
Response of the color $\vec{B}$ and $\vec{E}$ field to the nucleon polarization

d_2 for Proton and Neutron

Hint of a negative d_2^p, negative twist-3 at moderate $Q^2 \sim 3$ GeV^2.

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

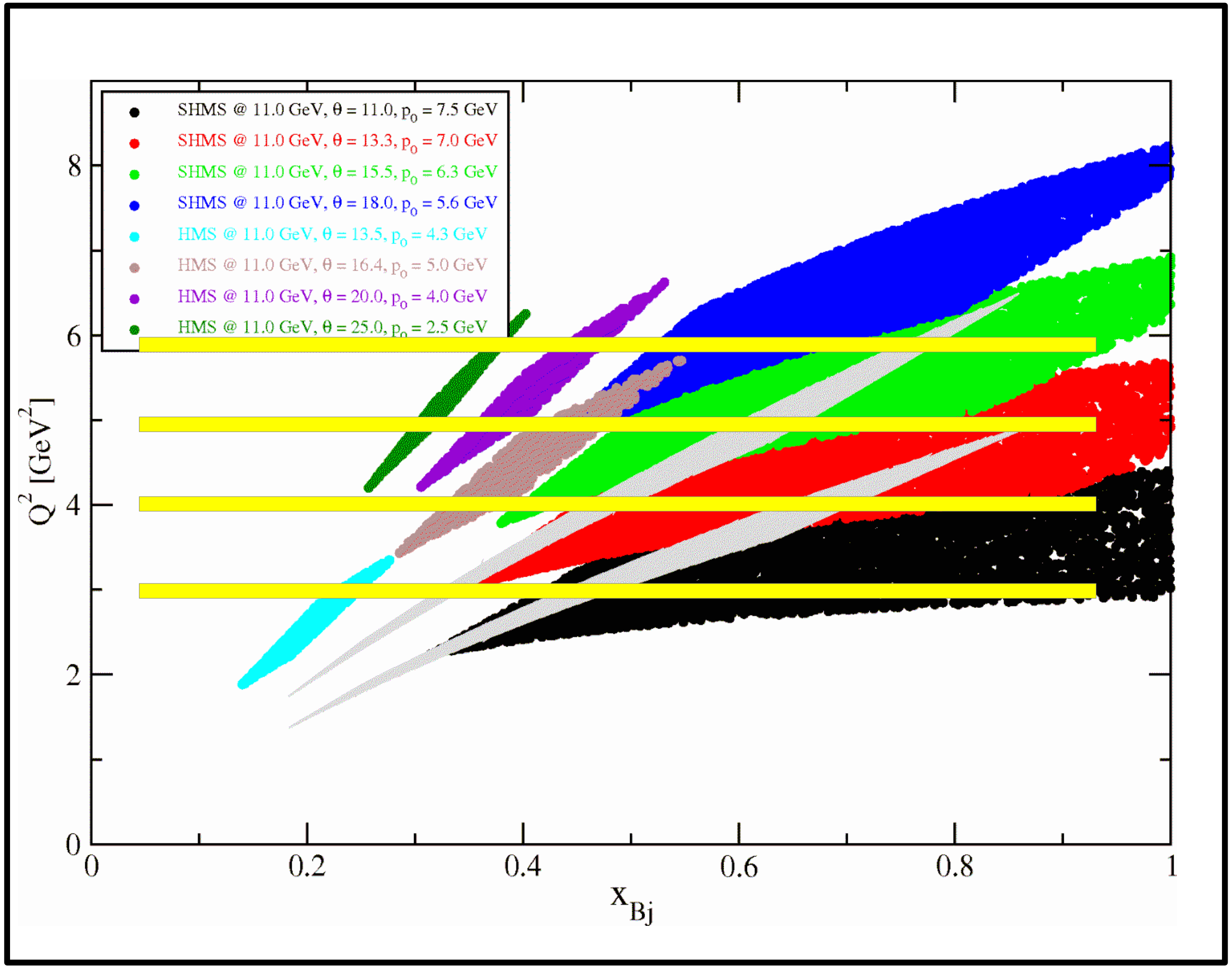




Similar hint of negative twist-3 (dips below CN elastic) in d_2^p data was noted in SANE experiment.

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)

E12-06-121 : Kinematic coverage

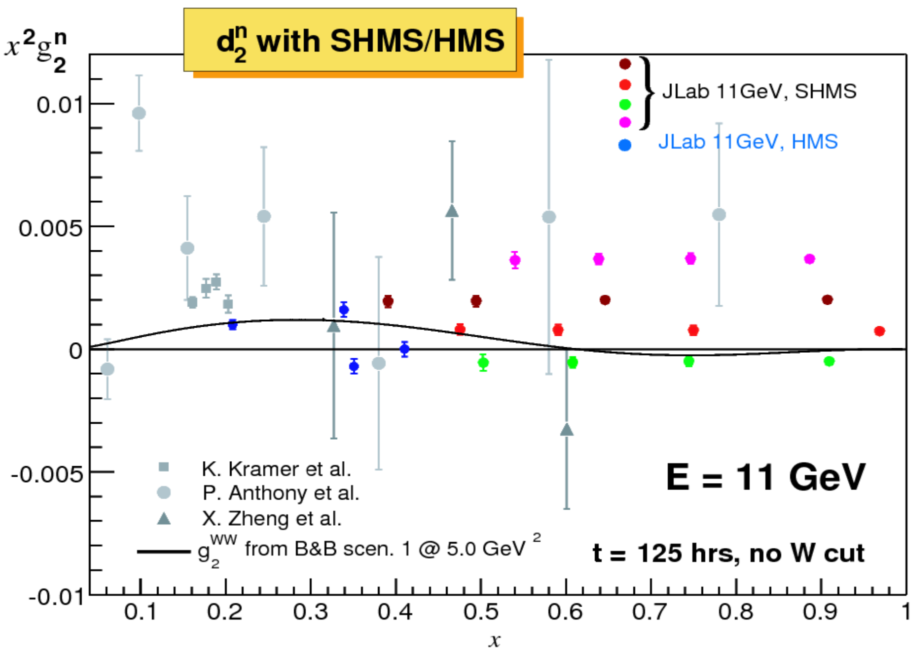


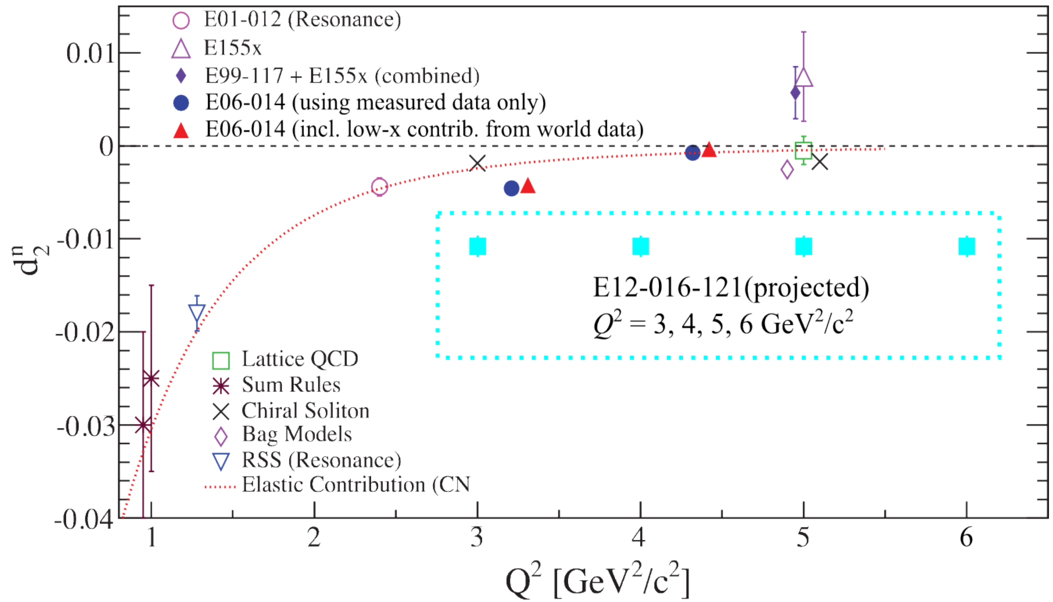
- x and Q^2 evolution of g_2 in the wide kinematic range ($0.23 < x < 0.85$) will give us knowledge about g_2 at higher x.
- Doubles number of precision data points for $g_2^n(x,Q^2)$ in DIS region.
- d_2 will be measured for the constant Q^2= 3,4,5,6 $(GeV/c)^2$ for the very first time.

E12-06-121: Projected Results

Precision g_2^n data set over broad range of x and Q^2.

Points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—7 GeV^2.

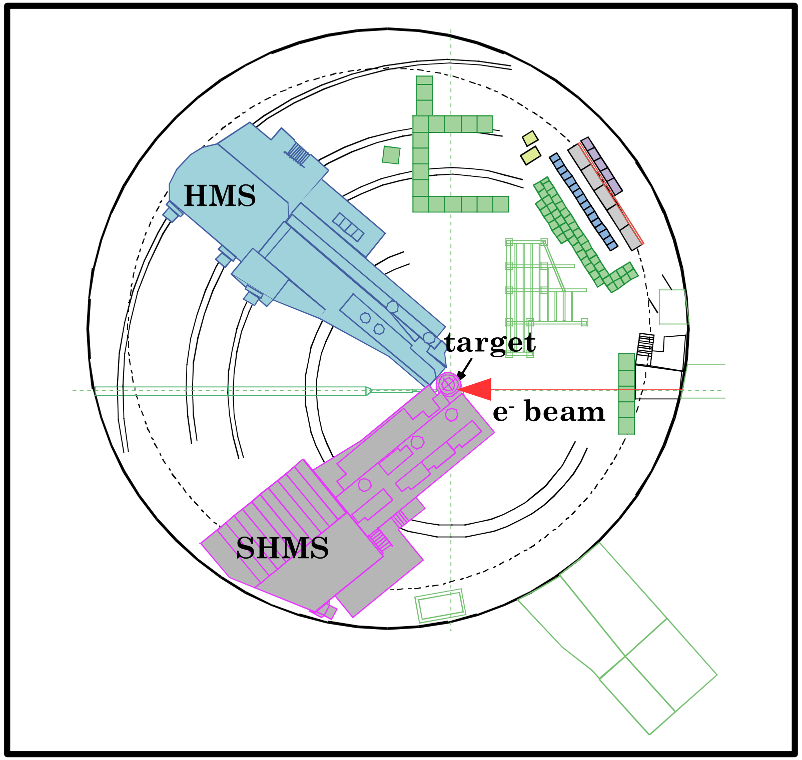




Projected results for d_2^n at truly constant Q^2 = 3,4,5,6 GeV^2/c^2.

E12-06-121 : Hall C Layout

- Hall C: Polarized ^{3}He target, SHMS + HMS
- Beam energies:
  11 GeV (production), 2.2 GeV (calib.).
- Beam currents:
  30 μA (production), 40 μA (max., calib.).
- Each arm measures an absolute polarized cross section independent of the other arm (g_1, g_2).



SHMS Production			HMS Production		
Setting	P_o	Angle	Setting	P_o	Angle
A	7.5	11.0°	A'	4.3	13.5°
B	7.0	13.3°	B'	5.1	16.4°
C	6.3	15.5°	C'	4.0	20.0°
D	5.6	18.0°	D'	2.5	*25.0°

- SHMS collects data at θ = 11°, 13.3°, 15.5° and 18.0° for 125 hrs each.
- HMS collects data at θ = 13.5°, 16.4°, 20.0° and *25.0° for 125 hrs each.

E12-06-121: Run Plan

Nominal beam time allocation:

PAC 36 approved E12-06-121 for requested 700 PAC hours (29 PAC days)

- 5-pass beam (nominal 11.0 GeV/c) for ~ 676 PAC hours.
- 1-pass beam (nominal 2.2 GeV/c) for ~ 20 PAC hours + pass change → 5-pass.

1-pass running (calibration):

1-pass beam allocation : 3 calendar days

Nominal to do list :

- 8 hr Moller run
- 4 hr Optics at p_0 = 2.2 GeV/c
- Pressure curves for current cell
- Hydrogen elastics, delta QE meas
- **^{3}He elastic data (E12-06-121A)** (See Table)

*

	E_{beam} [GeV]		θ [°]	Q^2 [fm^{-2}]	Estimated Cross Section [mb/sr]	Rate [Hz]	Time [hr]
SHMS	2.216	k1	11	4.57	4.39×10^{-4}	723.69	1
		k2	13	6.34	5.14×10^{-5}	84.89	1
		k3	15	8.38	4.37×10^{-6}	7.21	1
		k4	17	10.66	2.22×10^{-7}	0.37	10
		k5	19	13.18	5.97×10^{-8}	0.10	11
HMS	2.216	k6	21	15.93	3.99×10^{-8}	0.12	24

Projection from E12-06-121A

E12-06-121: Run Plan

5-pass running (Production):

5-pass beam allocation : 54 calendar days (162 shifts)

For each kinematic pair (X, X')

- Reference cell runs: ^3He, N_2
- Empty cell run
- 8 hrs Optics (C-foil + Sieve)
- Positive polarity runs: 4 hrs optics, 4 hrs production
- Target NMR sweep (1–2 / shift)
- Production runs (~31 shifts)

Instrumentation / Calibration runs

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

Summing Up:

Total 160 shifts (~40 shifts/setting)

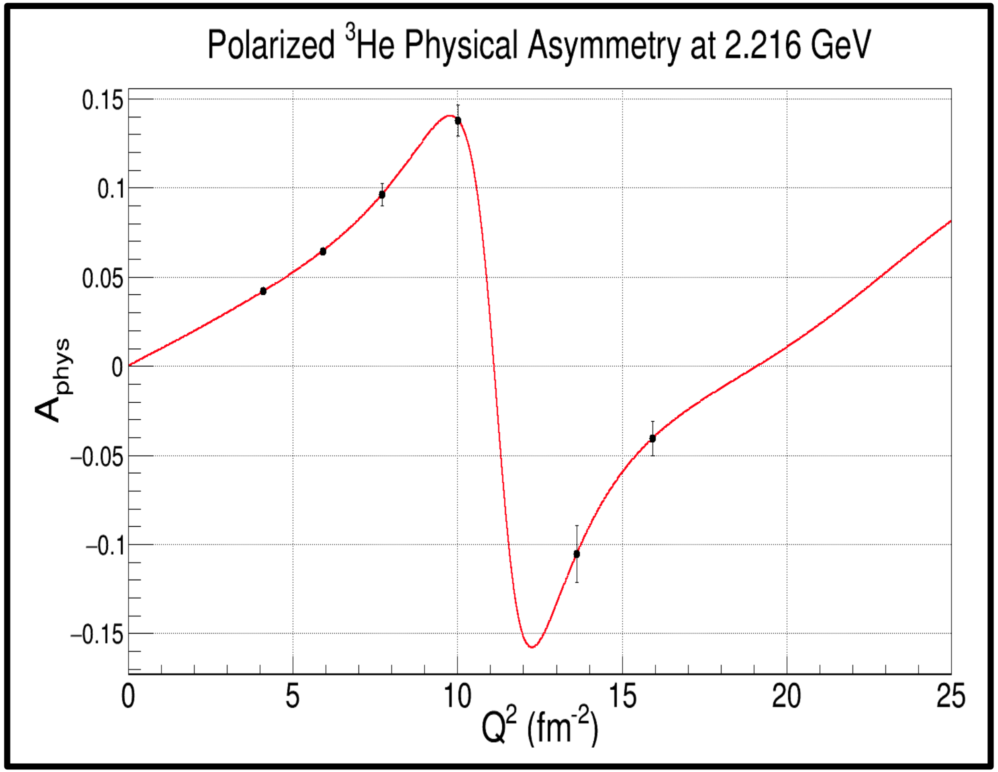
- production + optics + pos. pol. Running - 35 shifts/setting
- Moller Runs (1/week) - 2 shifts/setting
- Allow ~10% overhead = ~3-4 shifts/setting

2 shifts for instrumentation and calibration runs.

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

Spokesperson: Scott Barcus

- Significant discrepancies between theoretical and experimental ^{3}He FFs (particularly G_M).
- All higher Q^2 data are from unpolarized electron scattering results.
  - Rosenbluth separations are impossible in diffractive minima and global fits require FF parametrizations.
- **Double polarization asymmetry:**
  - Zeros of asymmetry are FF diffractive minima.
  - Constrain minima locations.
  - Hypothesis test theoretical models.



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

Summary

- The experiment E12-06-121 (neutron g_2 and d_2) will run in 2020 right after E12-06-110 in Hall C.
- High x and Q^2 evolution of g_2 and d_2 will be explored (large precision data).
- It will be the first evaluation of d_2^n at truly constant Q^2 values.
- This will give insight into quark-gluon correlations.
- Several theoretical predictions (especially Lattice QCD) will be verified.

Thank you!

Supporting Documentations

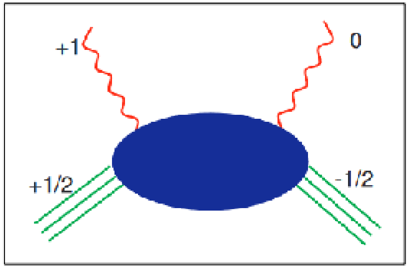
- Proposals
  - ➔ https://hallcweb.jlab.org/wiki/images/c/cb/PR12-06-121.pdf
  - ➔ https://hallcweb.jlab.org/wiki/images/1/1a/D2n_HallC_PAC36-update_v2.pdf
- Polarized ^{3}He Target
  - ➔ https://hallcweb.jlab.org/wiki/index.php/Pol_He-3_Target_Information
  - ➔ https://www.jlab.org/indico/event/351/session/1/contribution/9/material/slides/0.pdf
- 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,

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



- 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

Expected rates for HMS

θ_0 [$\circ$]	E'_{cent} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_\parallel$ [hrs]	$t_\perp$ [hrs]	$\Delta A_\parallel$ [$\cdot 10^{-4}$]	$\Delta A_\perp$ [$\cdot 10^{-4}$]
13.5	4.305	2.617	0.208	3.293	954	765	8	117	2.0	0.6
16.4	5.088	4.555	0.410	2.727	218	15	12	113	3.9	1.2
20.0	4.000	5.31	0.404	2.951	76	66	10	115	6.0	1.8
25.0	2.500	5.15	0.323	3.417	20	84	13	112	10.7	3.1

- The rate table is taken from PAC-30 proposal.
- The uncertainties for $A_\parallel$ and $A_\perp$ are statistical only.

Kinematic bins and expected rates for SHMS

SHMS Setting	E'_{bin} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_\parallel$ [hrs]	$t_\perp$ [hrs]	$\Delta A_\parallel$ [$\cdot 10^{-4}$]	$\Delta A_\perp$ [$\cdot 10^{-4}$]
$\theta_0 = 11^\circ$	7.112	2.875	0.394	2.305	1058	11	12	113	2.0	0.5
	7.709	3.116	0.504	1.988	708	3.1	12	113	2.3	0.7
$E'_{cent} = 7.5$	8.304	3.357	0.663	1.610	259	0.83	12	113	3.7	0.1
GeV	8.900	3.597	0.912	1.109	2.7	0.21	12	113	36	10
$\theta_0 = 13.3^\circ$	6.647	3.922	0.480	2.267	268	3.1	12	113	3.5	1.0
	7.203	4.250	0.596	1.941	139	0.8	12	113	4.8	1.5
$E'_{cent} = 7.0$	7.758	4.578	0.752	1.548	31.6	0.16	12	113	10	3.1
GeV	8.314	4.906	0.972	1.012	0.10	0.033	12	113	173	55
$\theta_0 = 15.5^\circ$	5.997	4.798	0.511	2.342	96	1.9	12	113	5.7	1.8
	6.496	5.197	0.614	2.037	49	0.47	12	113	7.8	2.5
$E'_{cent} = 6.3$	6.995	5.597	0.744	1.677	13.5	0.11	12	113	15	4.7
GeV	7.494	5.996	0.911	1.215	0.29	0.025	12	113	98	33
$\theta_0 = 18.0^\circ$	5.348	5.756	0.542	2.397	35	1.1	12	113	9.5	3.1
	5.790	6.235	0.637	2.106	17	0.25	12	113	13	4.4
$E'_{cent} = 5.6$	6.233	6.711	0.749	1.769	5.1	0.05	12	113	24	8.1
GeV	6.675	7.187	0.885	1.350	0.38	0.01	12	113	87	30

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 ^{3}He Elastic Electromagnetic Form Factors

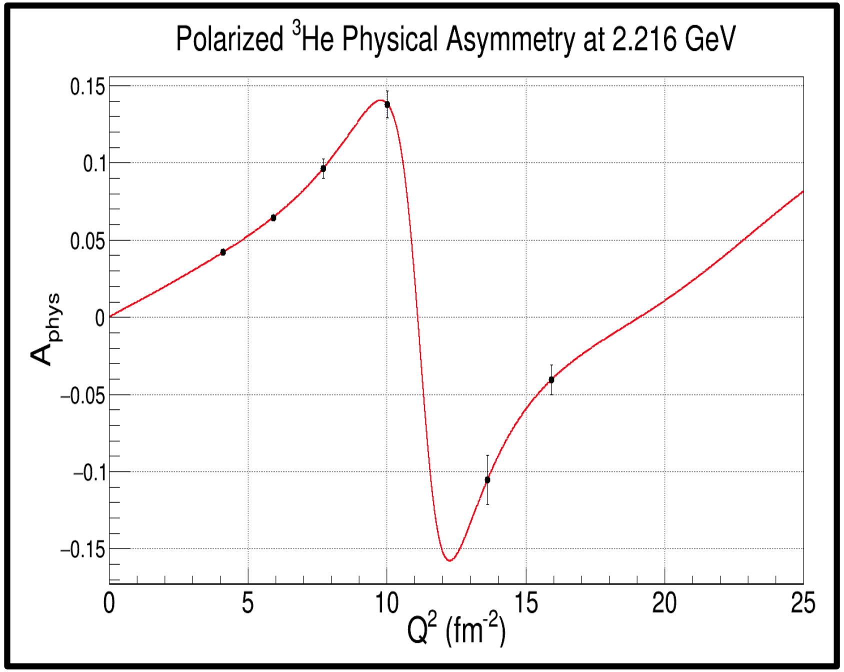
- Significant discrepancies between theoretical and experimental ^{3}He FFs (particularly G_M).
- All higher Q^2 data are from unpolarized electron scattering results.

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

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:**

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

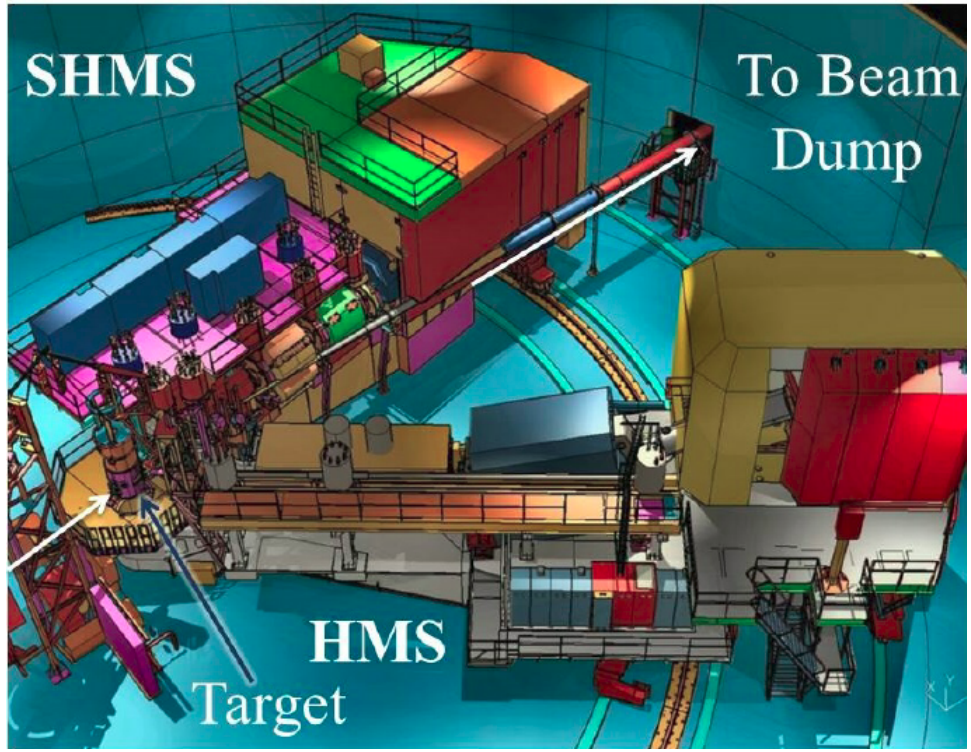


New independent tool to map FFs without the issues of unpolarized Rosenbluth measurements!

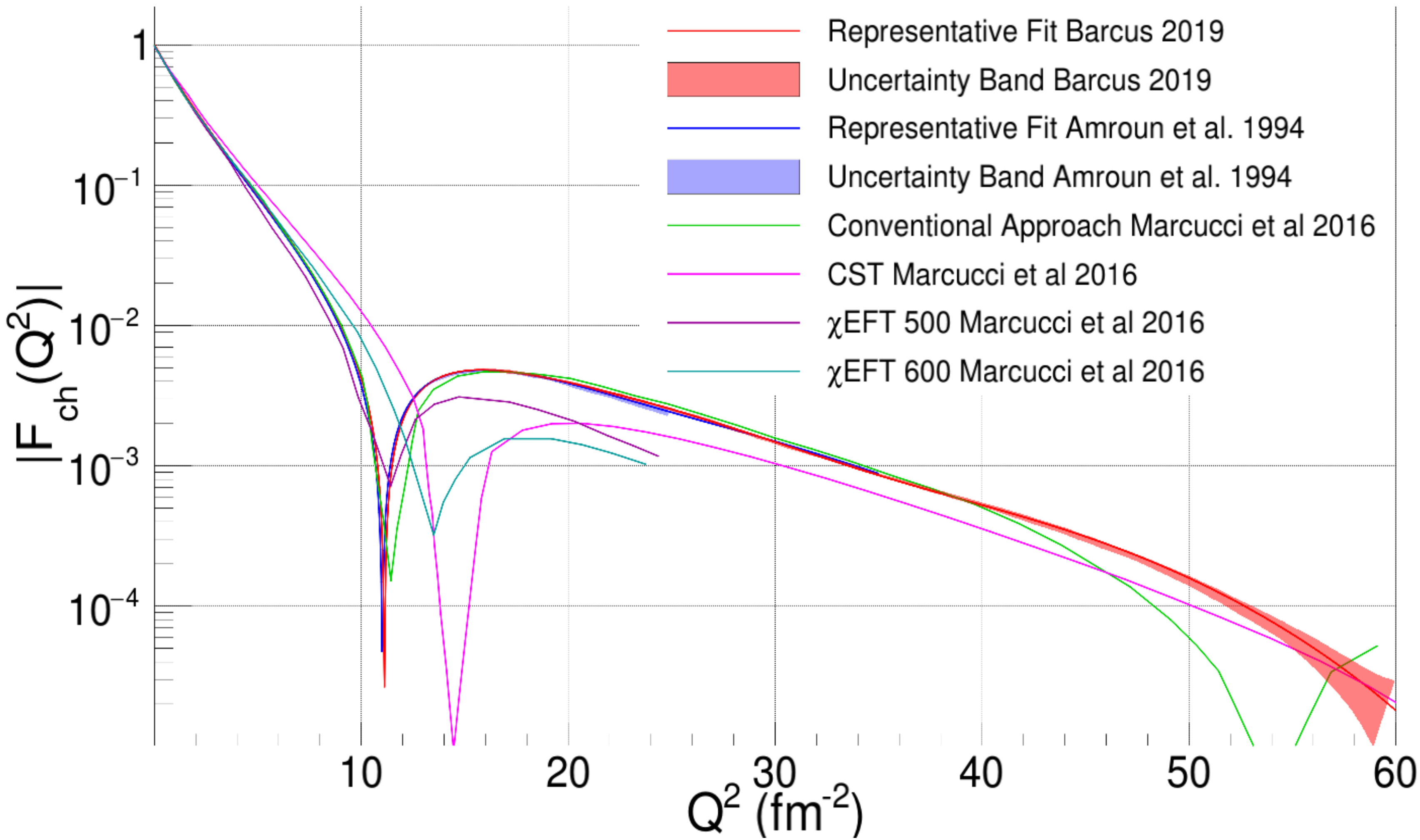
E12-06-121A: Proposed Procedure

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