PR12-11-009
Recoil Polarization measurement of G_{En} for Q^2 from 4—7 GeV^2 in Hall C

Spokespersons
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Neutron electric form factor

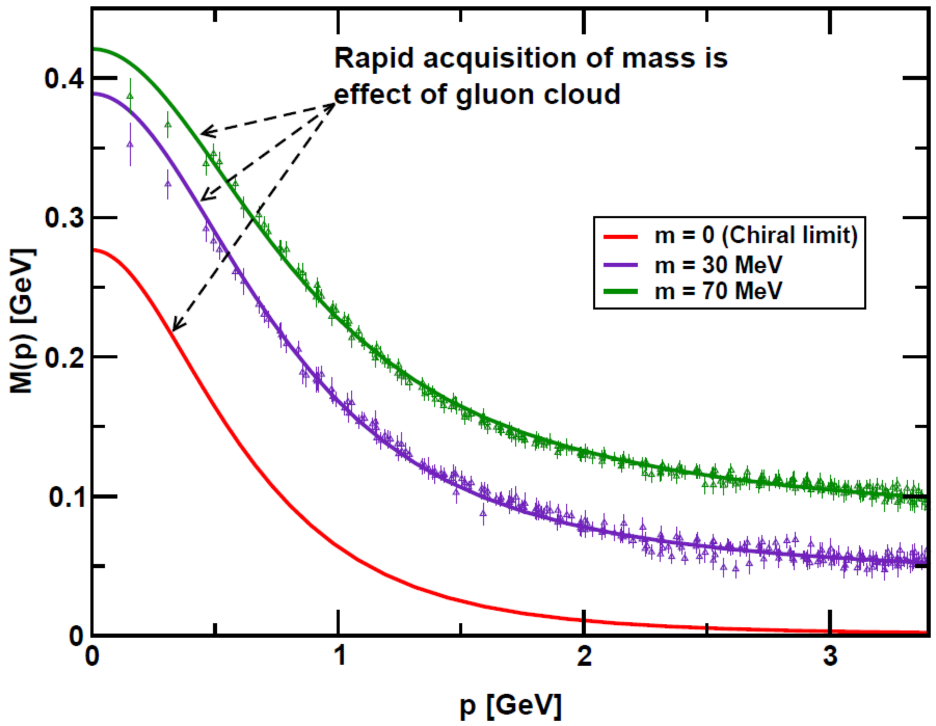
- **Form factors are fundamental quantities describing structure of the nucleon, and are related to spatial structure. All other electromagnetic form factors measured to significantly higher Q^2 than G_{En} (currently limited to 3.4 GeV^2)**

- **E12-09-016 will extend this to 10 GeV^2 using polarized ^3He target**
  - **Significant systematics due to larger proton backgrounds, worse inelastic/quasielastic separation, beam and target polarization uncertainty**
  - **Recoil polarization measurement from ^2H can provide additional data with smaller (and very different) systematics**

- **Measurements of G_{En} in high Q^2 range provide important insight**
  - **Complete set of form factors in region with small pion cloud contributions**
  - **Extract scalar, vector form factors, allows separation of up, down quark contributions (neglecting strangeness)**
  - **Directly sensitive to up and down quark distributions in quark core**
  - **Model-independent extraction of neutron infinite-momentum frame [IMF] charge density** *[Miller (2007) ; Venkat, et al. (2010)]*
  - **Important comparisons to QCD-based calculations**
    - **Lattice QCD: isovector form factor (G_{Ep}-G_{En}) cancels disconnected diagrams**
    - **Region of interest for Dyson-Schwinger Equation calculations**

Transition from bare to dressed quarks

- Dressed quark mass function M(p)
  - Curves: Dyson-Schwinger calc.
  - Points: unquenched Lattice QCD
- High energy interactions sensitive to 'undressed' quarks, $m \approx m_{bare}$
- Low energy interactions sensitive to fully dressed constituent quarks
- Form factor measurements going to higher Q^2 probe transition region between these two limits

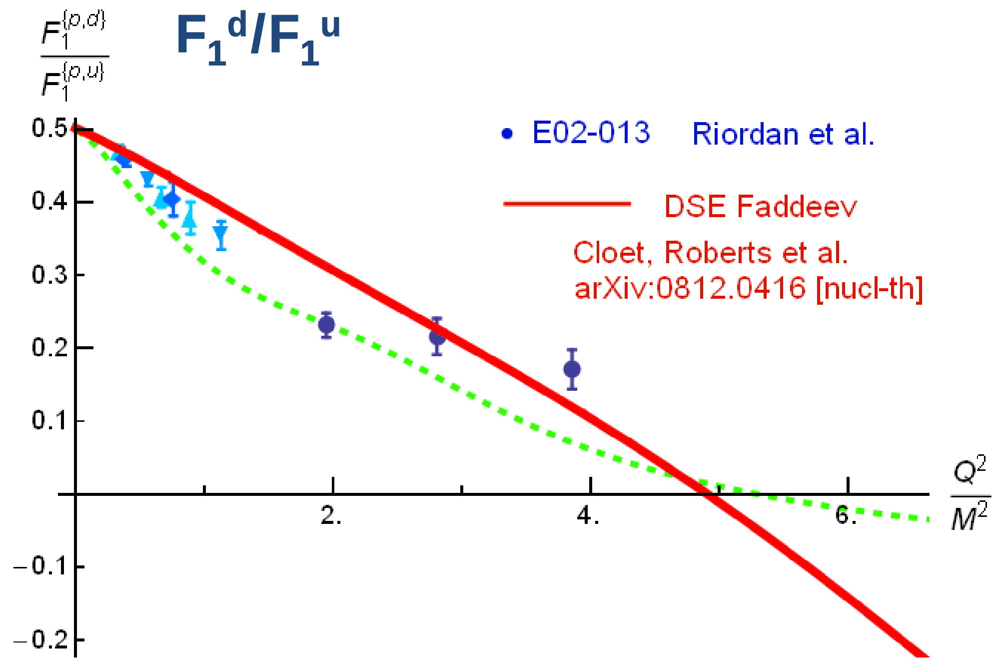


Separation of up, down quarks

- Separate u, d in comprehensive analysis of nucleon form factors
→ Study non point-like scalar, axial-vector diquark correlations

- Singly-represented *d*-quark is most likely to be struck in association with *1⁺* diquark & these form factor contributions are soft

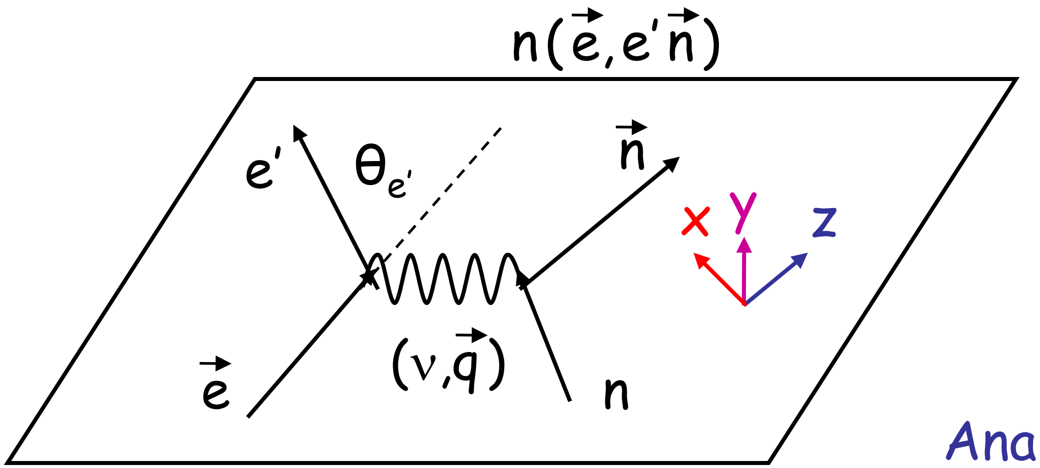
- *u*-quark is predominantly linked with harder *0⁺* diquark contributions



- Follows that
  - *d*-quark Dirac form factor is softer than that of *u*-quark
  - F_1^d/F_1^u passes through zero
  - Location of zero depends on relative probability $1^+/0^+$ diquarks in proton
- Same physics explains $d_v(x)/u_v(x)$ at $x \sim 1$

C. D. Roberts, PHY ANL

Recoil Polarimetery Technique



electron scattering plane

Recoil polarization

$$P_x = -P_e K_t G_{En} G_{Mn}$$

$$P_z = P_e K_\ell G_{Mn}^2$$

Analyzed by second scattering in polarimeter with analyzing power A_y

Ratio Technique:
Measure P_x and P_z

$$\longrightarrow \quad \frac{P_x}{P_z} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}} \quad \longrightarrow$$

small systematics
$A_y(\theta)$ and P_e cancel

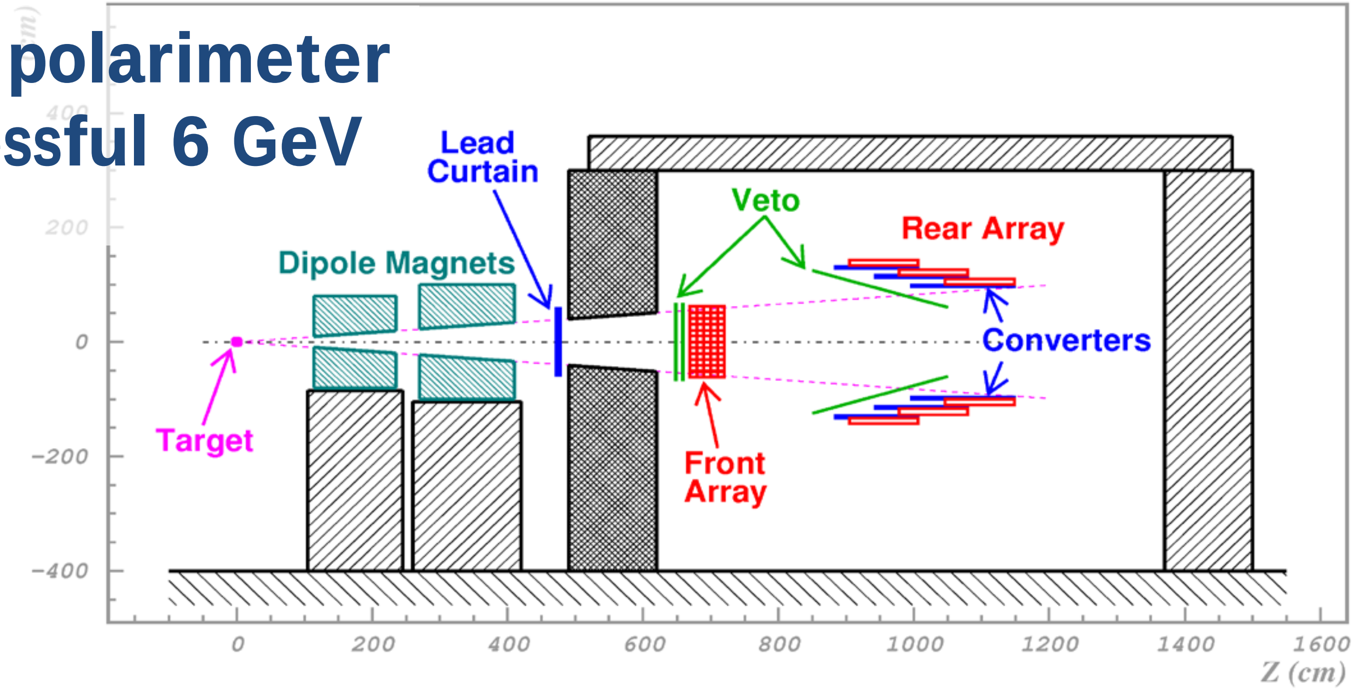
Electrons detected in SHMS

Neutron spin precessed in dipole magnet

Neutron detected, polarization analyzed in neutron polarimeter

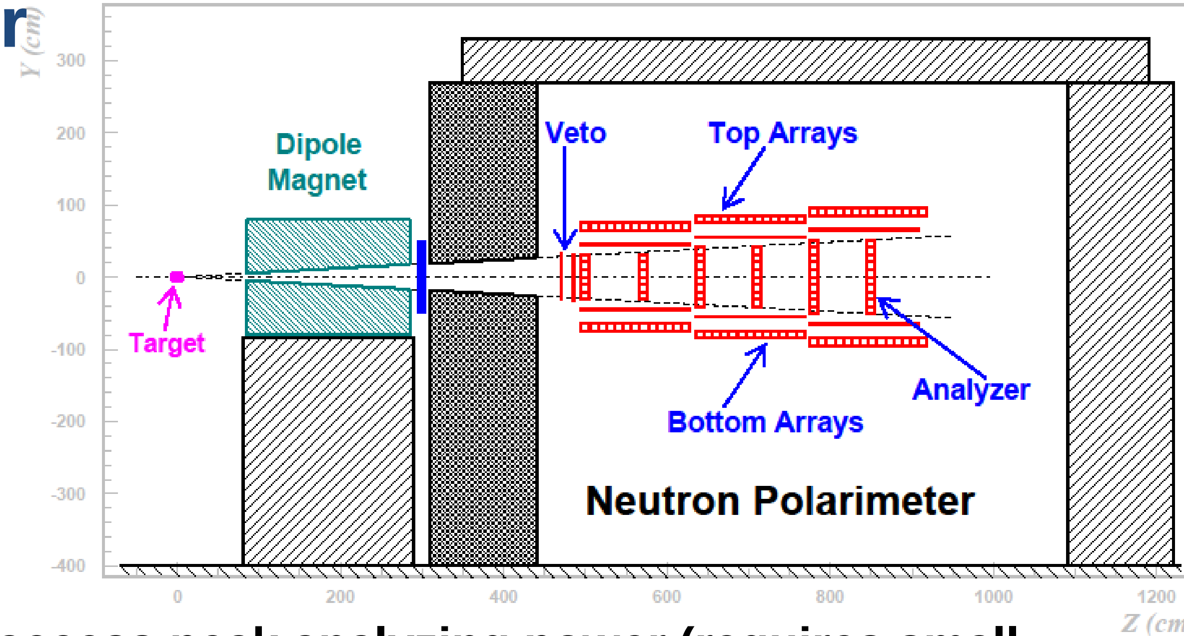
Detect two linear combinations of P_x and P_z (two spin precession angles)

Initial E09-006 polarimeter based on successful 6 GeV experiment



- Unpolarized target allows high luminosity (compensate low analyzing power)
- Two linear combinations of P_x, P_z measured in one detector → <u><$A_y(\theta)$> cancels in ratio</u> [Previous G_{Ep} experiments had to apply cuts to match horizontal and vertical θ-distributions, G_{Ep}(5) & PR11-001 will have to apply cuts or correct with model of $A_y(\theta)$ distribution]
- <u>Minimize backgrounds</u>: Shielded bunker, rear array cannot see target
- Cross-ratio technique → <u>beam charge asymmetry and NPOL geometrical asymmetry cancel in the ratio</u>
- Minimal sensitivity to FSI, MEC, IC, choice of NN potential for ^{2}H wavefunction

Updated polarimeter



- **Previous design could not access peak analyzing power (requires small neutron scattering angles at high Q^2)**
- **New design:**
  - **Segmented analyzing scintillator**
  - **Detection of struck proton rather than scattered neutron**
  - **Reconstruct recoil proton direction to 5-6° yields 1.5-2° in neutron angle**

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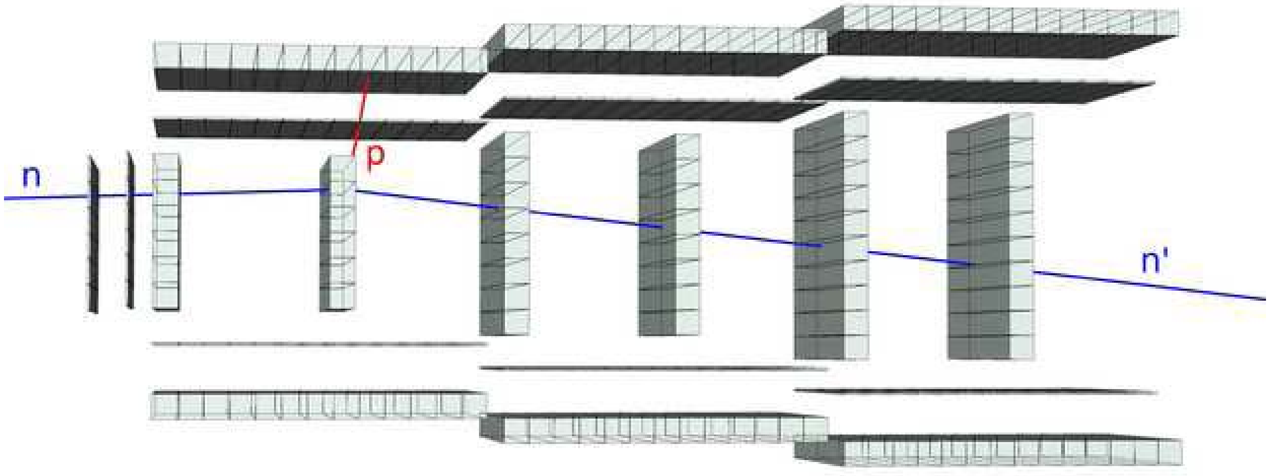
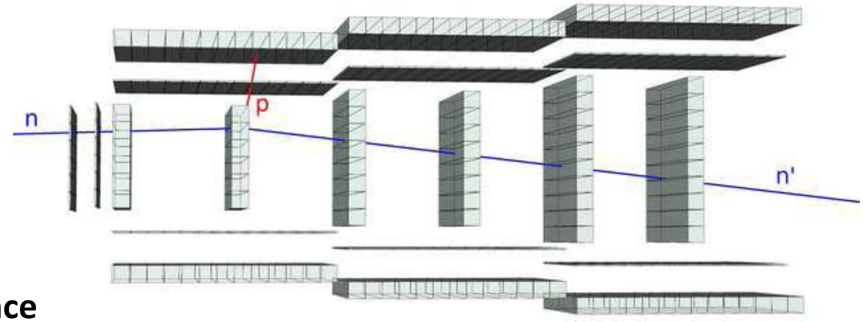


- Previous design could not access peak analyzing power (requires small neutron scattering angles at high Q^2)
- New design:
  - Segmented analyzing scintillator
  - Detection of struck proton rather than scattered neutron
  - Reconstruct recoil proton direction to 5-6° yields 1.5-2° in neutron angle
- Access small neutron angles (large cross section and analyzing power)
- Thin analyzer layers reduces multiple interactions (which reduce A_y)
- Segmentation of analyzer (plus proton PID and reconstruction) eliminate losses due to random analyzer hits blocking good e-n quasielastic events
  - "Corrupted fraction" was 25-35% for E09-006 design

Detector simulation details



- Approach to calculating rates, selection of QE events, etc… not changed with new design
  - MCEEP (including radiative effects) for rate/acceptance
  - GENGEN simulation for selection of QE events (calibrated against JLab, SLAC data from 1-7 GeV^2)

- Modeling of the new analyzer
  - FLUKA for proton, neutron interactions [Pb shield, veto, analyzing scintillators, top/bottom arrays], include estimated inefficiency and impact of PID cuts on rates
  - Background spectra from P. Degtyarenko's code (Geant3.21/GCALOR/DINREG]
  - Take rates from all particles to estimate background
  - Use elastic/QE n-p scattering only for physics rates
  - Assume analyzing power from inclusive n-CH_2 scattering, even though dilution from Carbon will be less as only n-p and not n-n QE events contribute

- Conservative approach taken: [FOM α $N \cdot A_y^2 \cdot P_e^2$]
  - Figure of merit (FOM) increased by >50% from PAC35 version (same polarimeter), as we replaced conservative estimates for factors we hadn't fully evaluated and made small geometry optimizations
  - Accounted for inefficiencies in SHMS, top/bottom arrays, etc… in addition to overall analyzer efficiency
  - Assumed conservative dipole field and gap values with assumption that final parameters would provide improved FOM. If not, we can go to low field option which has same (or greater) FOM
  - Room to optimize, e.g. thinner neutron bars in front if protons in first 1-2cm have much lower efficiency

- Note: this design optimized for high Q^2 where increasing momentum of struck protons increases the efficiency

Estimation of analyzing power

From JLab E93-038:

$\langle A_y \rangle$= 14.4% for P_n (lab)= 1.45 GeV

For proton scattering on CH_2

(NIM A538 (2005) 431)

$A_y \sim 1 / P_p$(lab)

Assume analyzing power for neutrons scales the same as for protons → estimate **$\langle A_y \rangle$ = 4.6%** for P_n = 4.51 GeV

Measurements from Ladygin, et al., (n-p elastic scattering) support the $1/P_n$ scaling for high P_n for the peak analyzing power

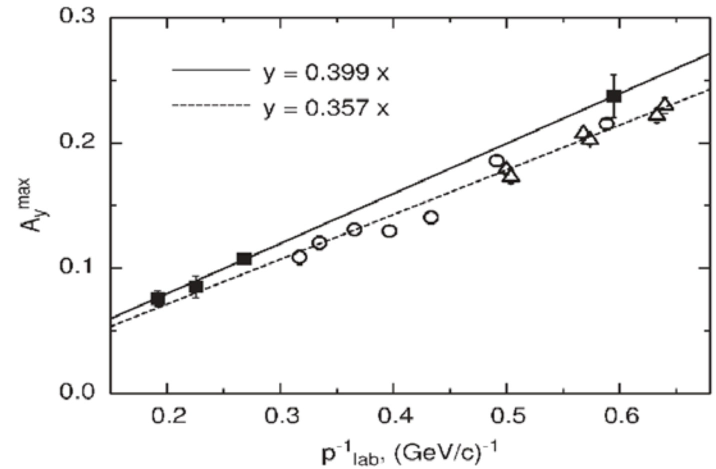
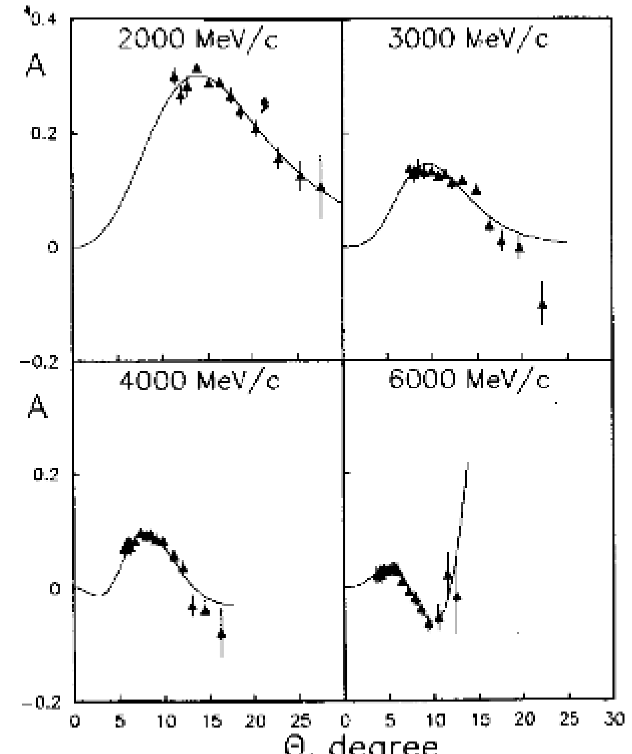


Fig. 5. Momentum dependence of CH_2- and C-data. Solid squares—current data, open circles— Ref. [4], open triangles—Ref. [5]. Solid line—fit of CH_2-data, dashed line—fit of C-data.



TAC Review Comments

✔ "The upgraded [polarimeter] design looks to be well characterized through MC simulations, with attention paid to background rates, false asymmetry and dilution effects. All seem well in hand, and are thoroughly cross checked against prior data taken in Hall C." … "This is an experienced collaboration with a proven, low-risk technique."

Polarimeter technical design was also a key issue from the PAC35 report

✔ "The proposal makes the assumption that neutron analyzing powers scale as 1/p as proton analyzing powers do. As there is a lack of neutron analyzing power measurements at the higher Q2, assumptions about statistical errors bars or running time could be optimistic."

Analyzing power for CH_2 at high P_n not precisely known, but $1/P_n$ extrapolation is supported by n-p measurements in same P_n range

✔ "[Full specifications of BM-111 dipole not fully available]." "…the collaboration needs to show that they have a viable technical and cost solution for the dipole on the neutron line which is consistent with their proposed spin precession angles, beam request, and projected error bars."

For the original (PAC34) analyzer, the high field dipole allowed optimal spin precession and reduced loss due to random coincidences blocking good events. The new design is much less sensitive to random coincidences, so the <u>high field option is nice but not at all critical</u>.

If BM-111 specifications do not clearly allow for optimal spin precession with sufficient acceptance, we will go with the low field option for which Charybdis is sufficient. This would provide a small increase in the figure of merit (proposal assumed 4.0 T-m for BM-111 rather than the optimal 4.3 T-m), and would allow for a larger vertical acceptance in the polarimeter.

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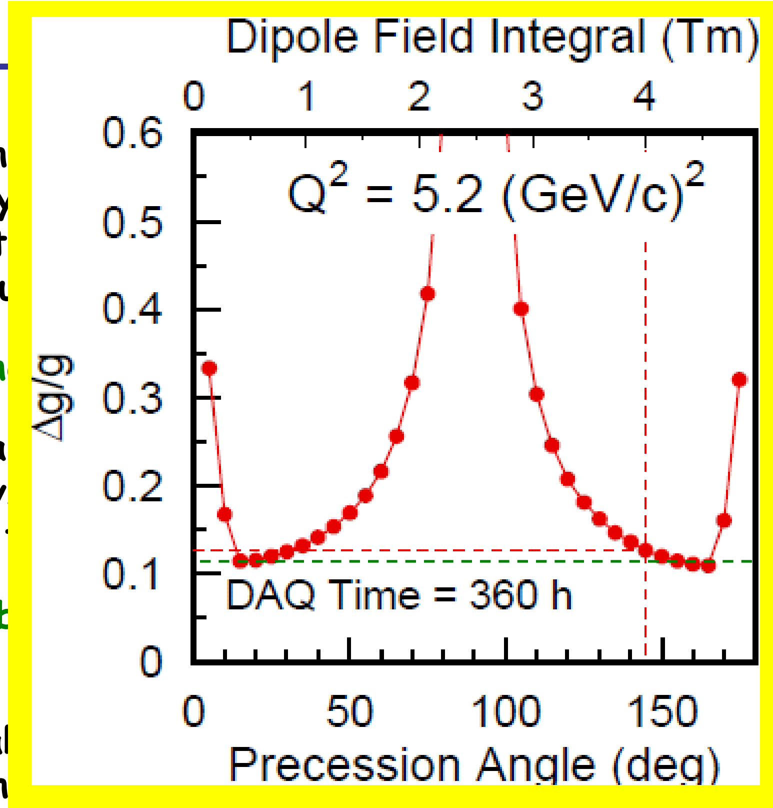

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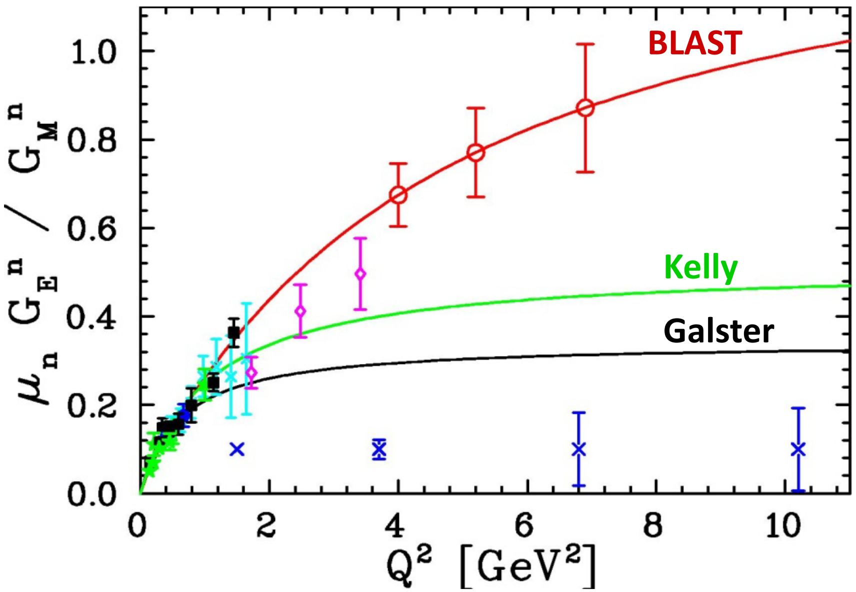
Kinematics, Beam Request

80 μA beam, 80% polarization, 40-cm LD_2 target

Four-Momentum Transfer, Q^2 $(\mathrm{GeV}/c)^2$	3.95	5.22	6.88
Beam Energy, E_0 (GeV)	4.4	6.6	11.0
Electron Scattering Angle, θ_e (deg)	36.53	26.31	16.79
Scattered Electron Momentum, P_e' (GeV/c)	2.288	3.815	7.330
Neutron Scattering Angle, θ_n (deg)	28.0	28.0	28.0
Neutron Momentum, P_n (GeV/c)	2.901	3.602	4.511
Statistical uncertainty [assumes BLAST fit]:	10.1%	12.7%	16.3%
Systematic uncertainty:	2.5-3% for all settings		
Beam Time on LD2 [days]	10	15	30
Beam Time (LH2, Dummy, other) [days]	1	1.5	2.5

60 days production + 7 days checkout with beam for 67 total PAC days

Three Q^2 values, starting near high end of 6 GeV data and extending significantly into the region of the 12 GeV ^{3}He measurement



Q^2 (GeV/c)^2	4.0	5.2	6.9
E_0 (GeV)	4.4	6.6	11.0
θ_e (deg)	36.3	26.3	16.8
Real-Event Rate (Hz)	2.93	2.64	2.29
A_Y (%)	7.2	5.8	4.6
LD2 DAQ Time (days)	10	15	30
LH2, Dummy, other (days)	1	1.5	2.5
$\delta R/R$ [stat & syst]	10.5%	13.0%	16.6%

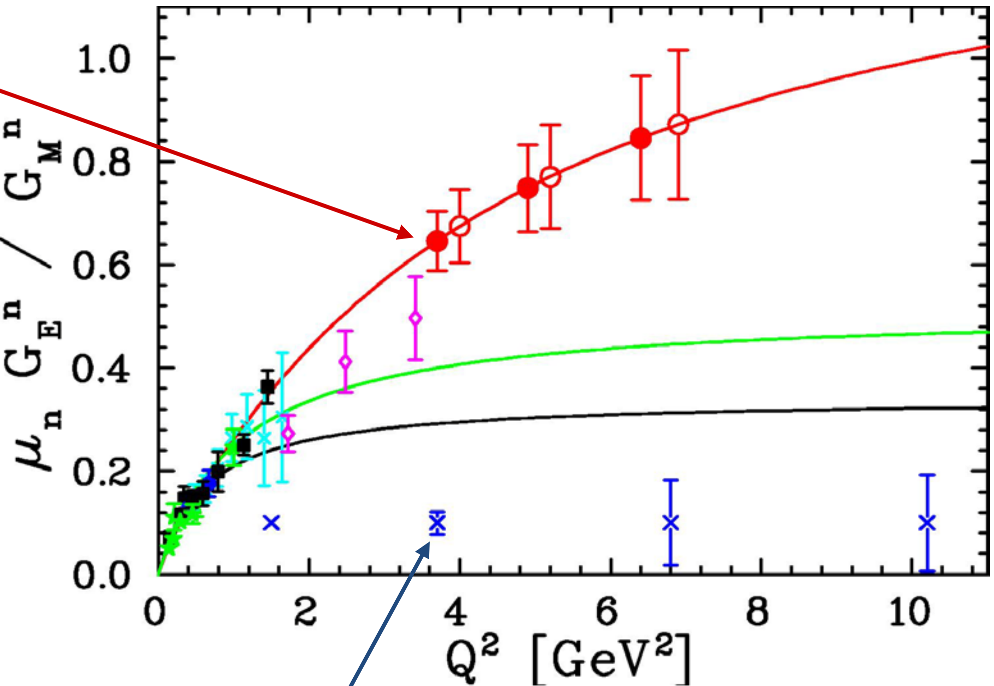
- More complete evaluation of nucleon models, comparison in region of quark core dominance
- Model-independent information of nucleon structure; Direct comparison of G_{Ep} and G_{En} to examine the difference between up and down quark contributions
- New constraints on the neutron Generalized Parton Distributions
- Extraction of detailed charge structure of neutron
- **Direct comparison with results of 6 and 12 GeV G_{En} measurements from ^{3}He, with lower backgrounds, smaller/different systematic uncertainties and nuclear corrections**

Options for lower Q^2, higher precision

- Simulations done for original kinematics (high Q^2, worst backgrounds) and final kinematics not selected because updated ^{3}He runplan not known
  - Want best overlap of 6 GeV and 12 GeV experiments

- Shift NPOL from 38 to 39.5 degrees
  - 5-8% reduction in Q^2
  - 40-50% increase in figure of merit

- Additional improvements
  - 10-20% improvement from better spin precession (high or low-field option)
  - Low field option allows increased vertical acceptance: additional 30-50% increase (projections not shown)



E12-09-016 Updated runplan: extra Q^2 point, estimated systematics down to 2.4-6.6% (from 8-13% in original proposal), statistics much worse (factor 2-3 lower statistics for Q^2=6.8 and 10.2) [priv. communication, B. Wojtsekhowski]