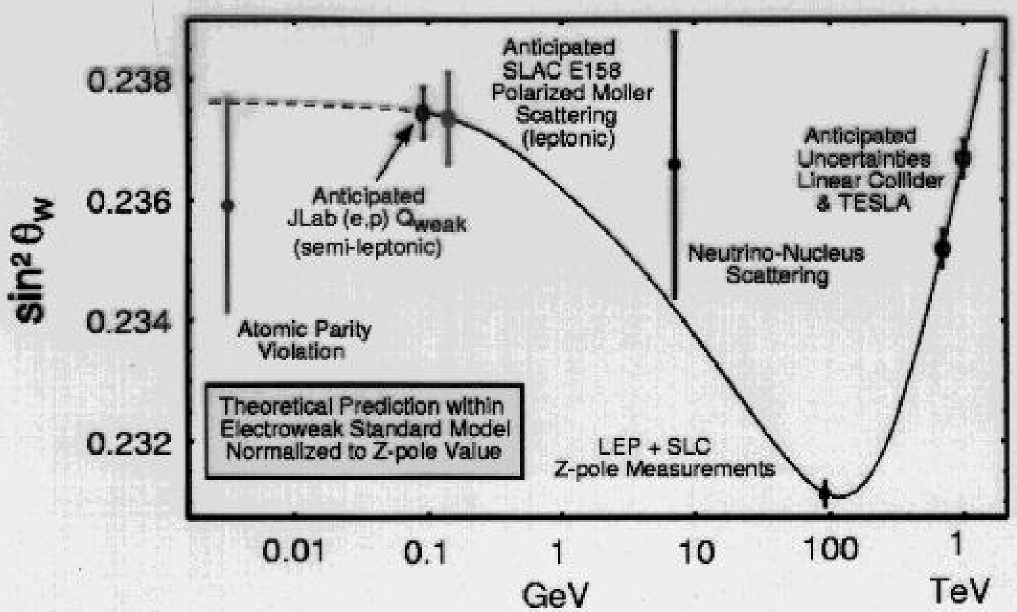
Q (weak):

Search for new physics at the TeV scale

LOWq Workshop
August 23-25, 2001

Running of $\sin^2\theta_W$

(Assuming No New Physics Beyond the Standard Model)

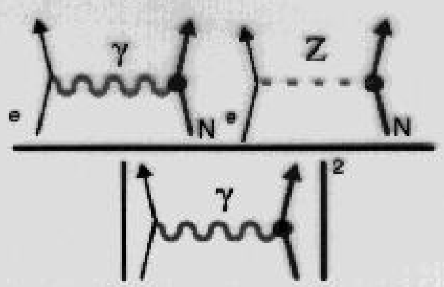


New physics will likely manifest itself differently in the purely leptonic and semi-leptonic sectors.

Therefore, both measurements are essential in any comprehensive search for new physics.

Searching for New Physics at the TeV Scale

polarized electrons
unpolarized target



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

for a nucleon:

$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1 - 4\sin^2\theta_W)\varepsilon' G_M^{\gamma} G_A^{e}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$

$\varepsilon = 1 / [1 + 2(1 + \tau) \tan^2 \theta/2]$ $\qquad$ $\varepsilon' = [\tau(1+\tau)(1-\varepsilon^2)]^{1/2}$

$\tau = Q^2/4m^2$ $\qquad$ Q^2 is the four momentum transfer

θ is the laboratory electron scattering angle

When $\theta \rightarrow 0$, $\varepsilon \rightarrow 1$, $\varepsilon' \rightarrow 0$, and $\tau << 1$ the asymmetry becomes:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] [Q^2 Q^p_{weak} + F^p(Q^2, \theta)] \text{ --->}$$

$$\left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] [Q^2 Q^p_{weak} + Q^4 B(Q^2)] \qquad Q^p_{weak} = 1 - 4\sin^2\theta_w$$

Uncertainty due to this term becomes small for $Q^2 \sim 0.03$

$$A_z = \left[-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \Big[\varepsilon G_E^{\gamma p} \left\{ (1 - 4\sin^2\vartheta_W) G_E^{\gamma p} - G_E^{\gamma n} - G_E^{s} \right\}$$

$$+ \tau G_M^{\gamma p} \left\{ (1 - 4\sin^2\vartheta_W) G_M^{\gamma p} - G_M^{\gamma n} - G_M^{s} \right\}$$

$$- (1 - 4\sin^2\vartheta_W) \varepsilon' G_M^{\gamma p} G_A^{e} \Big] \Big/ \left[\varepsilon (G_E^{\gamma p})^2 + \tau (G_M^{\gamma p})^2 \right]$$

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note $G_M^{\gamma p}(Q^2 = 0) = 2.79$

$G_M^{\gamma n}(Q^2 = 0) = -1.91$

$G_E^{\gamma p}(Q^2 = 0) = 1$

$G_E^{\gamma n}(Q^2 = 0) = 0$

for $Q^2/c^2 = 0.03 (GeV/c)^2$ or $Q^2 = 0.03\ GeV^2$ and $\vartheta = 9^\circ$:

$\tau \cong 0.0085$

$\varepsilon = 0.9875$ also $(1 - 4\sin^2\vartheta_W) = 0.0760$

$\varepsilon' = 0.0146$

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then $A_Z = \left[-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right]$

$$\left[(1-4\sin^2\vartheta_W)(1-\delta_1) - \frac{G_E^{\gamma n}}{G_E^{\gamma p}}(1-\delta_1) - \frac{G_E^{\gamma s}}{G_E^{\gamma p}}(1-\delta_1) + \tau\frac{(G_M^{\gamma p})^2(1-4\sin^2\vartheta_W)}{\varepsilon(G_E^{\gamma p})^2}(1-\delta_1) - \tau\frac{G_M^{\gamma p}G_M^{\gamma n}}{\varepsilon(G_E^{\gamma p})^2}(1-\delta_1) - \tau\frac{G_M^{\gamma p}G_M^{s}}{\varepsilon(G_E^{\gamma p})^2}(1-\delta_1) - (1-4\sin^2\vartheta_W)\varepsilon'\frac{G_M^{\gamma p}G_A^{e}}{\varepsilon(G_E^{\gamma p})^2}(1-\delta_1) \right]$$

$\delta_1 = \frac{\tau}{\varepsilon}\frac{(G_M^{\gamma p})^2}{(G_E^{\gamma p})^2} = 0.067$

$G_E^s = 0$

at $Q^2 = 0$

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or $A_Z = \left[-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \left[(1-4\sin^2\vartheta_W) + Q^2 B(Q^2) \right]$

What is the Weak Charge of Proton?

- PV asymmetry:

$$A = a_0\tau(Q_w^P + \rho_{eff}\tau) + \vartheta(\tau^3)$$
where $\tau = Q^2/4M_p^2$
$$Q_w^P \equiv 1 - 4\sin^2\theta_w \big|_{\tau=0}$$
$$\rho_{eff} = \varepsilon(\theta_e)(\rho_n + \rho_s) + \mu_p(\mu_n + \mu_s)$$
$$\rho_n = (dG_E^n/d\tau)\big|_{\tau=0}$$

$a_0 = 3.1 \times 10^{-4}$ at tree level

- HAPPEX II & G^0 will determine ρ_{eff} to $\delta\rho_{eff} \sim< 0.3$

- Nuclear physics enters at order τ^2:

  - Box diagrams also enter at order τ^2.
  - Low Q^2 of $0.03[\text{GeV/c}]^2$ suppresses effects of uncertainties in form factors.

- ~ 4% measurement (combined statistical & systematic errors) of Q^P_w feasible.

Why a Precision SM Test is Possible at JLab

Interpretability:

- New precision form factor measurements coming out of Jlab – G^n_E, G^p_E, …

$$\Downarrow$$

- Required "input" to HAPPEX, G^0, to extract G^s_M, G^s_E and Q^2 dependence.

$$\Downarrow$$

- Required "input" for Q^p_{weak} to test SM and extract $Q^p_{weak} = 1 - 4\sin^2\theta_w$.

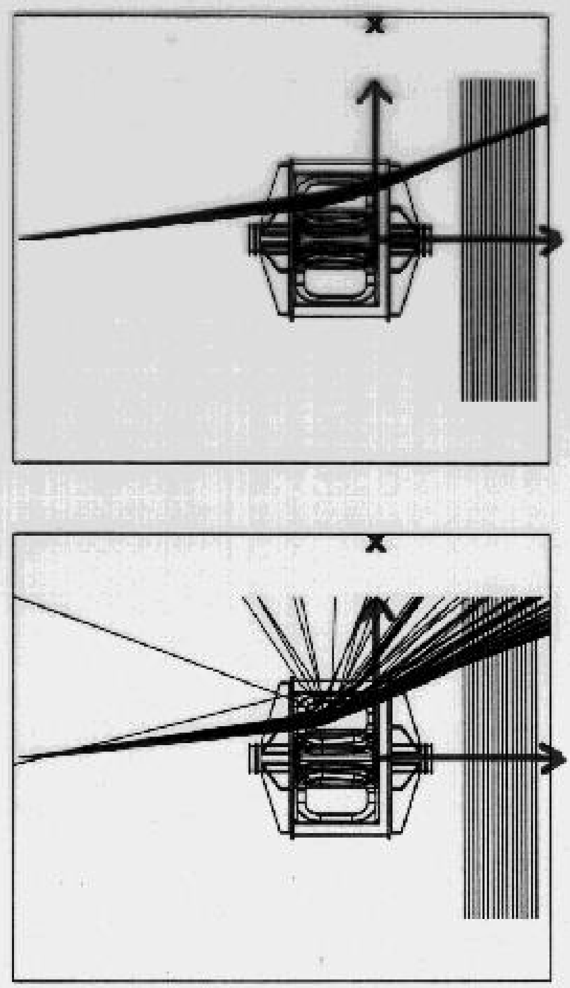
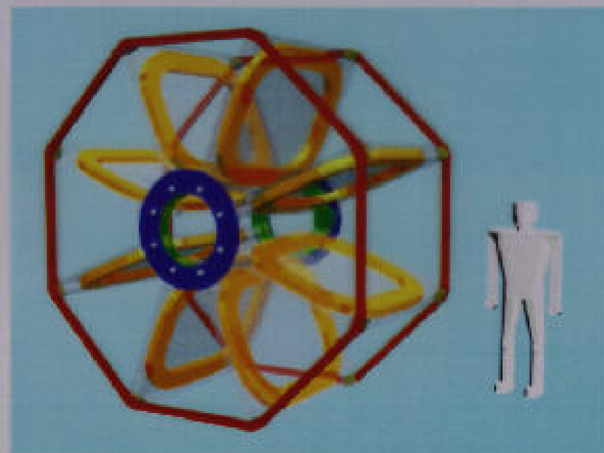


Figure 3: The side view of the test setup with a sample of elastic (top) and inelastic (bottom) trajectories restricted to $\theta_e = 9.0 \pm 1.5$ deg and $\phi_e = 0.0 \pm 15.0$ deg. The beam axis and direction is given by the horizontal arrow. The vertical arrow labeled X is a zero position along the beam axis in the standard G^0 coordinate system.

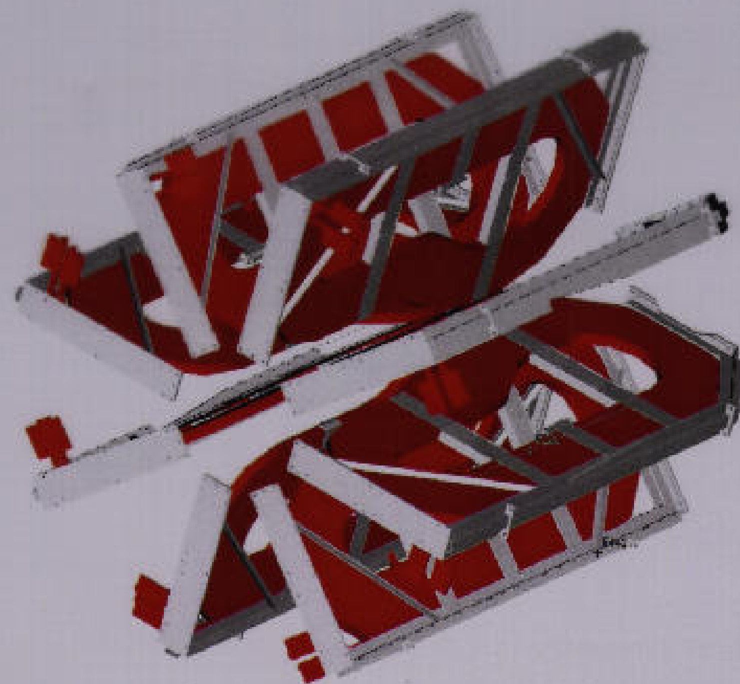
G0 Superconducting Toroidal Magnet

8-Sector
R ~ 2 m
L ~ 2 m
Iron-free
I_O ~ 5 kA
T_O ~ 4.5 K



Entire assembly housed within cryostat

BLAST Coils with sub-frames



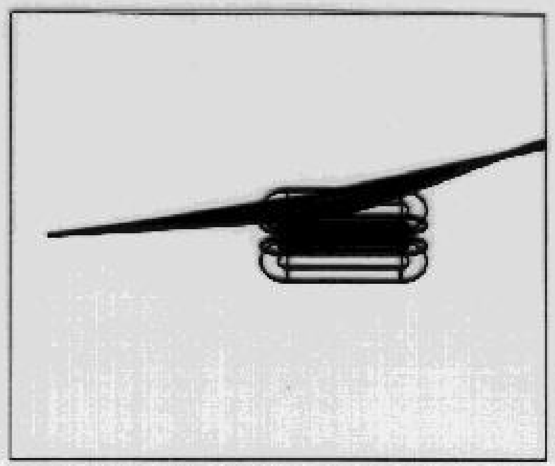


Figure 4: A good elastic focus using the BLAST toroid.

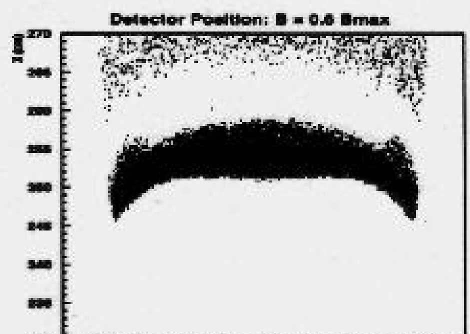


Figure 5: Separation of elastically (lower distribution) and inelastically (upper distribution) scattered electrons on selected detector position. The kinematics is restricted to $\theta_e = 9.0 \pm 1.5$ deg and $\phi_e = 0.0 \pm 15.0$ deg.

Contamination from target materials

Table 2: Contributions of the various scattering processes in the hydrogen target and the windows at the Q_W^p central kinematics. t is the target thickness in particles/cm^2, R_{cont} is the fractional contribution to the rate in the detector, and A_{cont} is the contribution to the overall asymmetry ($=-0.27$ ppm) from that process. The relative contamination of the elastic proton asymmetry from each process is shown in the last column.

Process	σ (μb/sR)	A (ppm)	t (cm^{-2})	R_{cont} (%)	A_{cont} (ppm)	$\frac{A_{cont}}{(-.30)}$ (%)
Protons in LH_2 (elastic)	88	-0.31	1.3×10^{24}	97.8	-0.30	
Protons in Al (quasi-elastic)	88	-0.31	1.4×10^{22}	1.05	-0.0033	1.1
Neutrons in Al (quasi-elastic)	3	-3.1	1.5×10^{22}	0.04	-0.0012	0.4
^{27}Al nucleus (elastic)	1234	+3.0	1.05×10^{21}	1.1	+0.033	-11.0

Additional Work to Prepare a Proposal

- Define choice of magnet technology.
- Optimize spectrometer design for highest rates at selected nominal Q^2.
- Refine plan to reduce uncertainty in absolute determination of average Q^2 to ~1%.
- Refine plan to reduce uncertainty in Q^p_{weak} due to target window backgrounds to 1% (Be window?).
- Minimize uncertainty due to nucleon form factors (eg., optimize the choice of Q^2, extrapolating the HAPPEX, Mainz and G^0 results to $Q^2 = 0.03$, or by making short measurements at higher Q^2 as part of the Q^p_{weak} proposal)

Q_{weak} Experiment

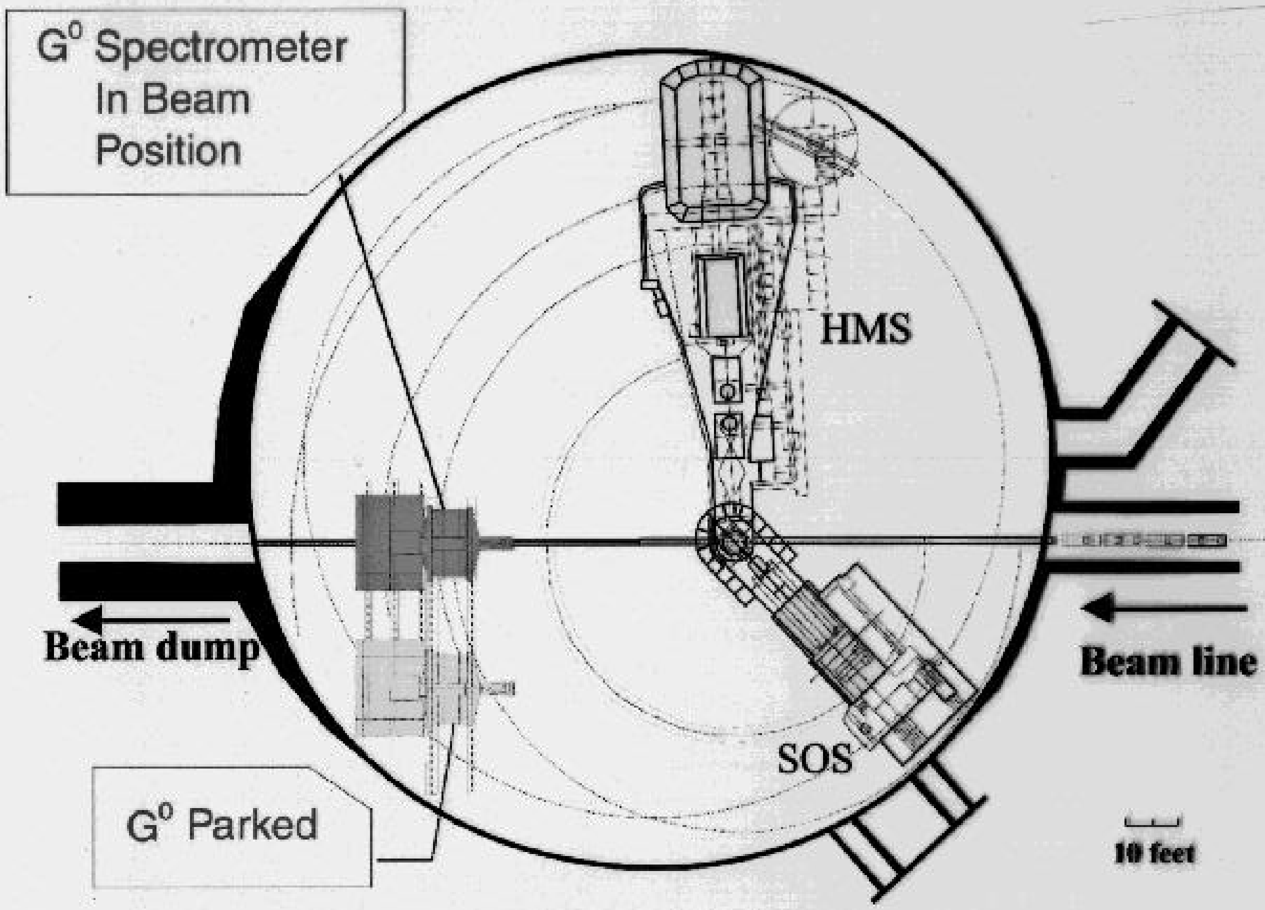
Running Conditions

Incident Beam Energy	1.165 GeV/c
Beam Polarization	80%
Beam Current	180μA
Hydrogen Target Length	35 cm
Running Time	2000 hours
Nominal Scattering Angle	9 degrees
Scattering Angle Acceptance	±2 degrees
Phi Acceptance	70% of 2π
Solid Angle	$\Delta\Omega$ = 39 msr
Acceptance Average Q^2	$\langle Q^2 \rangle = 0.03\ (GeV/c)^2$
Acceptance Averaged Asymmetry	$\langle A \rangle = -0.3$ ppm
Integrated Cross Section	4.3 μB
Intergrated Rate (all sectors)	7.24 GHz

Error Budget

Source of Uncertainty	Contribution to $\delta A/A$
Statistical	2.75%
Hadronic Structure	2%
Absolute Q^2 Determination	1%
Beam Polarimetry	1%
Target Window Background	1%
Other Backgrounds	1%
TOTAL	3.9%

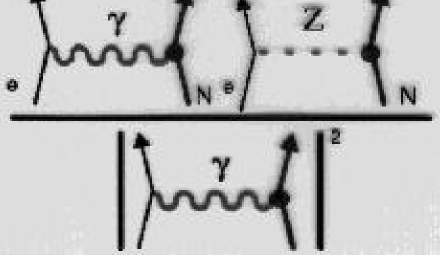
Layout of G0 Experiment in Hall C



Parity Violating Electron Scattering

polarized electrons
unpolarized target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



for a nucleon:

$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1-4\sin^2\theta_W)\varepsilon' G_M^{\gamma} G_A^{e}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$

forward angles
HAPPEX, Mainz, G^0: sensitive to

G_E^s and G_M^s

backward angles
SAMPLE, G^0: sensitive to

G_M^s and G_A^e

axial-vector
e-N form factor

$$\tau = \frac{Q^2}{4M^2}$$
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\tfrac{\theta}{2}\right)\right]^{-1}$$
$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

Overall goal of parity-violating electron scattering programs:
determine

G_E^s and G_M^s

separately over a wide range (0.1 to 1.0) $(\mathrm{GeV}/c)^2$ of Q^2