The Q^p_{Weak} Experiment (Jefferson Lab, E02-020)

A precision search for new physics beyond the Standard Model via parity-violating e-p scattering at low Q^2

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Project Manager: G. Smith

The Collaboration

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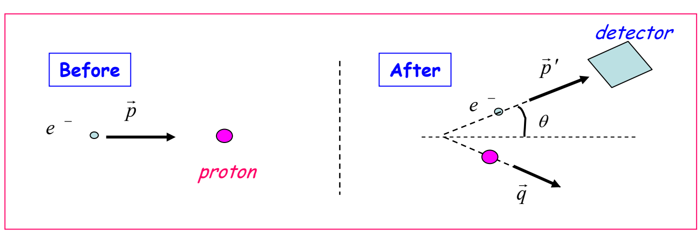
The Institutions

Jefferson Laboratory, California Institute of Technology, College of William & Mary, Hampton University, Los Alamos National Laboratory, Louisiana Technical University, Massachusetts Institute of Technology, Mississippi State University, Ohio University, TRIUMF, Universidad Nacional Autonoma de Mexico, University of Connecticut, University of Manitoba, University of New Hampshire, University of Northern British Columbia, Virginia Polytechnic Institute, Yerevan Physics Institute,

Electron scattering tutorial: (nonrelativistic)



Measure: $\Rightarrow$ $$\frac{d\sigma}{d\Omega}(\theta) = \left.\frac{d\sigma}{d\Omega}\right)_o \left[F(q^2)\right]^2$$

point charge result — "Form factor"

$$F(q^2) = \int e^{i\vec{q}.\vec{r}} \rho(\vec{r})\, d^3r$$

$$\lim(q^2 \to 0) \quad e^{i\vec{q}.\vec{r}} = 1$$
$$\Rightarrow F(q^2) = \int \rho(\vec{r})\, d^3r$$

$\Rightarrow$ Form factor at $q^2 = 0$ is the (normalized) electric charge of the proton

In reality, a relativistic description:

- The spin of the electron and proton have to be taken into account, leading to form factors of "electric" and "magnetic" character.
- 4-momentum transfer: $Q \equiv (\vec{q}, i\nu) = [(\vec{p} - \vec{p}\,'), i(E - E')]$
- replace $F(q^2)$ with $G_E(Q^2)$ and $G_M(Q^2)$
- scattering measurements at different angles but same Q^2 can disentangle the electric and magnetic contributions.

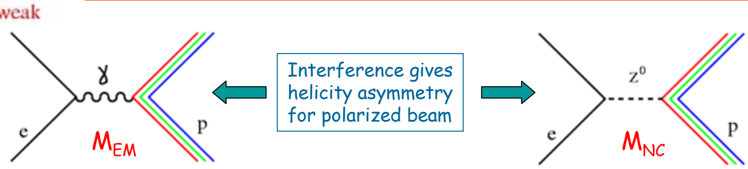
➡ **The $Q^2 \rightarrow 0$ limit of G_E gives the proton's electric charge.**

Parity violating electron scattering (PVES):

New form factors: $G^Z_E(Q^2)$ and $G^Z_M(Q^2)$ describe the electric and magnetic structure as probed by the Z boson

➡ **The $Q^2 \rightarrow 0$ limit of G^Z_E is the proton's weak charge.**

Parity-Violating Electron - Proton Scattering



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

$$\xrightarrow[\theta \rightarrow 0]{Q^2 \rightarrow 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, \boxed{Q^p_{weak}} + Q^4 B(Q^2)\right]$$

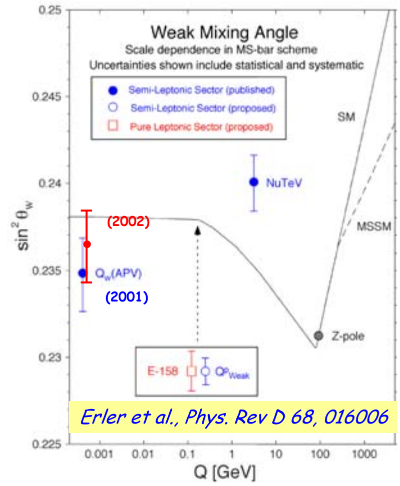
B = Hadronic form factors

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

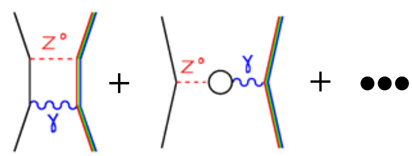
$Q^p_{weak} = 1 - 4\sin^2\theta_W$ has a definite prediction in the electroweak Standard Model

Measurement at low Q^2 tests the running of $\sin^2\theta_W$ to high precision at low energy

“Running of $\sin^2\theta_W$” in the Standard Model



Electroweak radiative corrections
$\rightarrow \sin^2\theta_W$ varies with Q



All “extracted” values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.

Q^p_{weak} and SLAC E158 (pure leptonic) have different sensitivities to proposed Standard Model extensions.

The running of $\sin^2\theta_W$ has not yet been tested precisely by experiment.

Experimental sensitivity: $Q^p_W = (1 - 4\sin^2\theta_W) \cong 0.072$

Physics Asymmetry: $A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$

Precision measurement: $\delta Q^p_W = \pm 4\% \Rightarrow \delta(\sin^2\theta_W) = \pm\ 0.3\%$

Requirements:

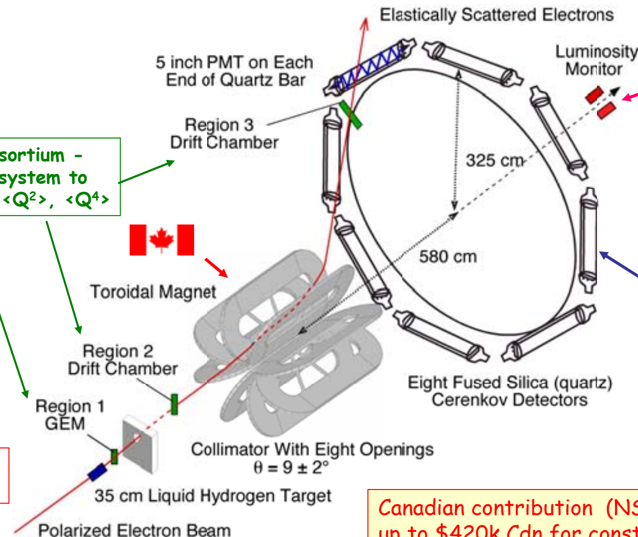
1. small Q^2 (0.03 GeV^2) *(low beam energy, small angle)*
2. knowledge of hadronic form factors $B(Q^2)$ *(other expts.)*

$$A\,(0.03\ \mathrm{GeV}^2) = A_{Q^p_W} + A_{hadronic} + A_{axial}$$
$$= -.19\ \mathrm{ppm} \quad -.09\ \mathrm{ppm} \quad -.01\ \mathrm{ppm}$$

3. large solid angle, integrating detector system for high sensitivity *($A \sim 10^{-7}$)*
4. highly quality polarized beam and polarimetry *(measured asymmetry is PA)*
5. measurement of detector-weighted $\langle Q^2\rangle$ and $\langle Q^4\rangle$
   (hybrid pulsed/integrating setup with tracking calibration)

.... **etc !!!**

Equipment must select & detect elastic e- at low Q^2



Univ. Consortium - Tracking system to calibrate $\langle Q^2 \rangle$, $\langle Q^4 \rangle$

VPI

detectors, electronics: LANL

JLab: beam, target, infra.

1.165 GeV, P = 0.8

Canadian contribution (NSERC)
up to $420k Cdn for construction
of magnet coils, managed by TRIUMF

Canadian Collaboration and Activities

U. Manitoba: J. Birchall, W.R. Falk, S.A. Page, W.D. Ramsay, L. Lee, W.T.H. van Oers
TRIUMF: C.A. Davis, J. Doornbos, **G. Clark***
UNBC: E. Korkmaz, T. Porcelli

(Blue: Research Associates)

Univ. Winnipeg: J. Martin (new faculty, 2004)

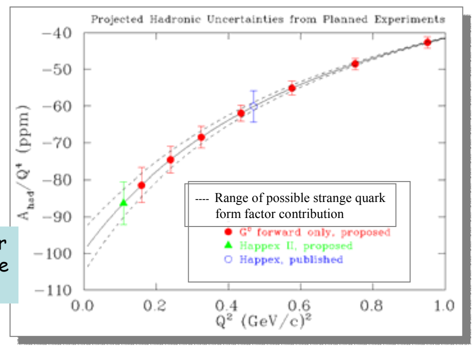
* management of coil construction project

- Co-spokesperson (SAP) and Work Package Manager (WTHVO)
- GEANT Monte Carlo studies focusing on systematic errors (J. Birchall)
- Detector and Q^2 working groups
- Magnetic field verification and mapping (based on G0 – W. Falk)
- Plan for 2 graduate students on this project, and 2 full time research associates (salaries of 4 shared between G0 and Q_{weak} phased in by 2004), plus summer and/or co-op students

Error Budget: Total: $\Delta Q^p_{weak}/Q^p_{weak}$ = 4 %

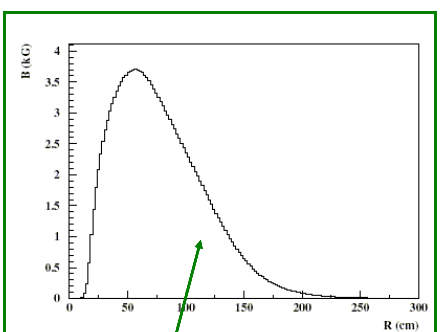
Statistical (2200 hours)	2.8%
Systematic:	
Hadronic structure corrections	2.0% ✓
Beam polarization	1.4%
Average Q^2 determination	1.0%
Helicity-correlated Beam Properties	0.6%
Uncertainty in Inelastic contamination	0.2%
Target window Background	<1.0%
Total systematic	2.9%

e.g. hadronic form factor extrapolation from other expts:

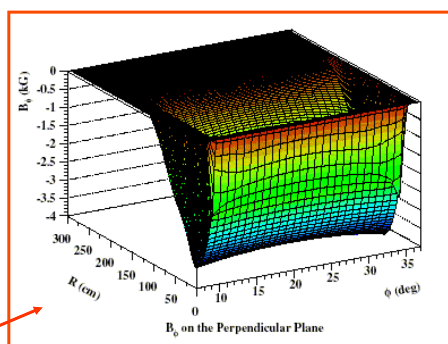


on the job list for fall 2004 – update this plot!

Instrumentation details: magnet – currently under construction



hollow, water-cooled coils, based on BLAST design from MIT-Bates



$\partial B\phi/\partial r$ gives required focussing of elastic electrons onto detectors

3d plot is in a plane through the magnet center, perpendicular to the beam.

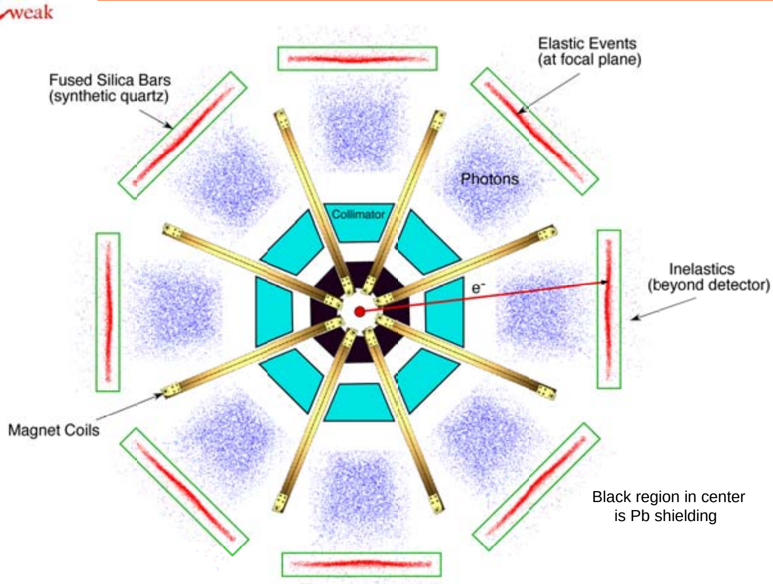
Geometrical Tolerance Requirements (JB)

8 – fold symmetry is **essential** for reduction of systematic errors:

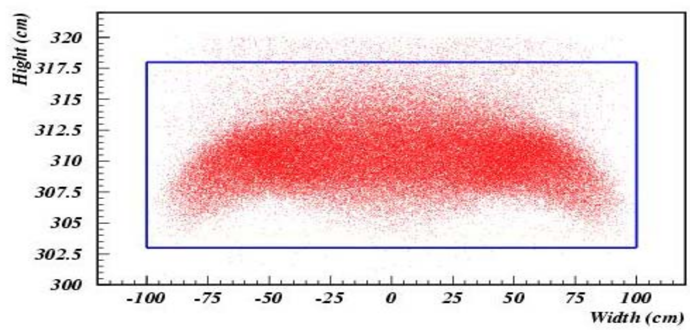
1. false asymmetry from helicity correlated beam motion
2. scale error due to change in $\langle Q^2 \rangle$

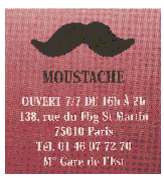
- 1% trim supplies will be included ; these can be used to fine tune and match elastic event rates on all 8 detectors (position neutral axis)
- Study of effects of individual coil misalignments is in progress.
- Few mm tolerances meet Q_{weak} goals and are technically achievable.
- Surveying techniques will position coils to ~ 1 mm accuracy, referred to alignment fixtures embedded in the coil structures
- Precise, 3-d field mapping device built by Canadian group for G0 will be used to map the field and verify coil locations/symmetry

Beam's Eye View with GEANT Simulated Events



Issue: shape of elastic "moustache" on the detector bars





- magnet focuses in θ, defocuses in ϕ
- "moustache" ends affect sensitivity to beam motion
- collimator design is critical – extensively studied and new design worked out, fall, 2004

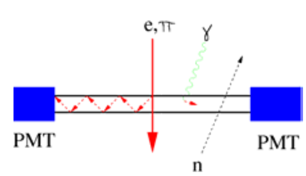
The Q^p_{weak} Detector and Electronics System (JLab/UM)

Focal plane detector requirements:

- Insensitivity to background γ, n, π.
- Radiation hardness (expect > 300 kRad).
- Operation at counting statistics.

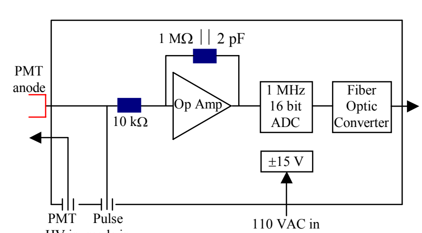
→ Fused Silica (synthetic quartz) Cerenkov detector.

- Plan to use 12 cm x 200 cm x 2.5 cm quartz bars read out at both ends by S20 photocathode PMTs (expect ~ 100 pe/event)



Electronics (LANL design, to be built at TRIUMF):

- Normally operates in integration mode.
- Will have option for pulse mode.
- Low electronic noise contribution. compared to counting statistics.
- 1 MHz 16 bit ADC will allow for over sampling.



Measurement of the Signal-to-Background Dilution Factor

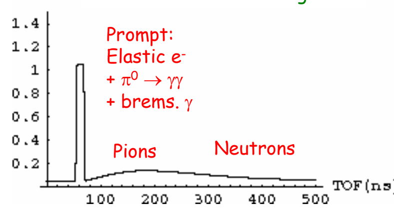
This is an integrating experiment, but we have to find out how much light comes from elastic electrons!

Hybrid TOF Measurement:

- Beam: 2 MHz (instead of 499), low current
- PMT anode → 1 GHz 8 bit transient digitizer

TOF distribution of the anode current
→ events of interest are in the prompt peak

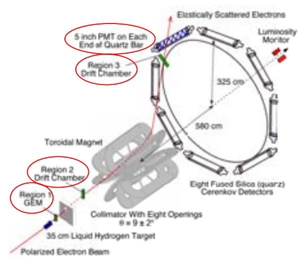
PMT Anode →
1 GHz 8 bit transient digitizer



Decompose Prompt Peak:

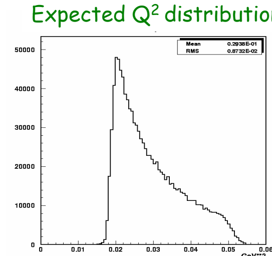
- Insert GEMs, drift chambers & scintillator.
- Run at low beam current ("pulse mode") in coincidence.

- Scintillator allows for neutral rejection.
- Tracking traces origin of scattered particles.



Determination of Average Q^2

Expected Q^2 distribution

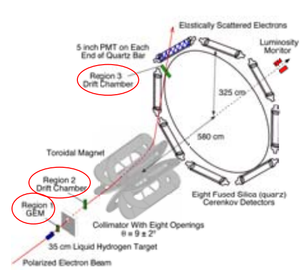


Need to know $\Delta\langle Q^2\rangle/\langle Q^2\rangle \sim 0.7\%$

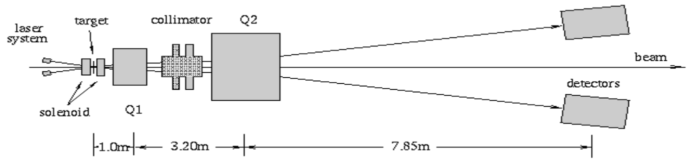
→ requires survey accuracy ~ 1 mrad
(~ 1 mm for alignment of precision collimator with respect to target)

Auxiliary measurements (at low beam current) will be made with 1 set of GEMs and 2 pairs of Drift Chambers to:

- Measure shape of focal plane distribution.
- Measure position-dependent detector efficiency.
- Compared measured Q^2 distribution to Monte-Carlo



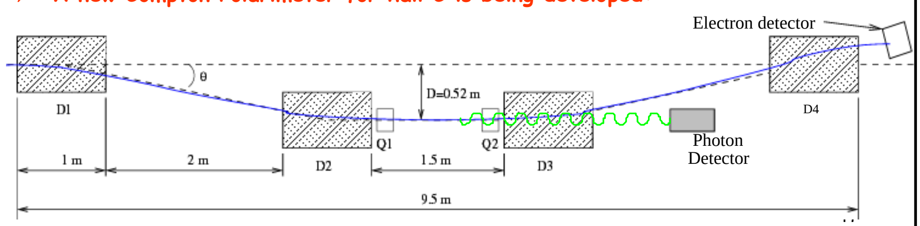
Precision Polarimetry (require ± 1%)



Existing ~1% Hall C Moller polarimeter. A superconducting solenoid drives the "pure iron" target foil into saturation. I_{Max} ~2 μA CW – too low ☹

The Moller cannot be used simultaneously with data taking ☹

→ **A new Compton Polarimeter for hall C is being developed:**



Summary and Outlook

- We have shown that it should be possible to measure Q_W^p to ± 4% and hence determine $\sin^2\theta_W$ to ± 0.3% with a precise low Q^2 parity-violating elastic scattering experiment at Jefferson Lab.
- The Standard Model prediction for $\Delta\sin^2\theta_W$ between the Z-pole and our energy scale corresponds to a 10σ measurement with very little "theoretical" uncertainty; sensitivity is dramatic compared to measurements in other systems.

Timeline:

- PAC approval with high priority, Jan. 2002 ☺
- Technical Design Review at JLab, Jan. 2003
- First construction funds approved for the magnet coils, April 2003
- NSF MRI approved to build the tracking system, summer 2003
- DOE/JLab funding package in place, first $$ spent – fall, 2003
- Total construction cost: $3.4M excluding Compton Polarimeter
- PAC "Jeopardy Proposal" in progress – due date is Dec. 6, 2004
- 3 year construction schedule, limited by flow of DOE/JLab funds
- **aim for installation in late 2006**

Canadian Group Timeline

2003: first NSERC funding; complete magnet design, simulation studies

2004: award QTOR contract; summer student → M.Sc. student on field mapper project (TBA)

ready to start a Ph.D. student

2005: coils shipped to MIT, assembly, field mapping & tests

2006: Install in Hall C at JLab