Symmetries, Parity-Violation & the Structure of the Proton

The $G^0$ & $Q_{\text{weak}}$ Experiments

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Symmetries, Parity-Violation & the Structure of the Proton

Parity Violation as a Tool for Probing the Structure of the Proton

1) Parity Conservation and Parity Violation
   Symmetries in Physics, Noether’s Theorem
   Parity Transformations & Observables

2) Probing Microscopic objects (e.g. proton, nucleus)
   What/How?
   Diffraction Patterns & Scattering objects
   Form Factors

3) Electroweak Structure of the Proton: \( G^0 \) & \( Q_{\text{weak}} \)
   \( G^0 \) and \( Q_{\text{weak}} \) experiments @ Jefferson Lab (JLab)
   Our present picture/model of the proton (e.g. quark models, …)
   (a) How do building blocks manifest themselves ?
   Our present picture of the Standard Model
   (b) Are there extensions beyond the Standard Model ?
Symmetries in Physics

*Everyday use (implicit)*
Mathematical/Quantitative counterpart (e.g. Rotational Symmetry)

*Link between Symmetries & Conservation Laws: Noether’s Theorem*

Wikipedia:
Noether's theorem *(1915, Emmy Noether)* is a central result in theoretical physics that expresses the one-to-one correspondence between the symmetries and the conservation laws.

Einstein (in reference to Noether): “…penetrating mathematical thinking…”

Some important examples of Noether’s theorem are the following:

• The energy is conserved if and only if the physical laws are invariant under time translation (if their form does not depend on time – Time-translation symmetry)

• The momentum is conserved iff the physical laws are invariant under spatial translations (if the laws do not depend on the position – Space-translation symmetry)

• The angular momentum is conserved iff the physical laws are invariant under rotations (if the laws do not care about the orientation – Rotational Symmetry)
Symmetries (Spatial, Discrete)

Rotation (90º)
Inversion/Reflection

$C_4$
4-fold rotational symmetry
Parity Operation (in 2D)

Space Reflection (Inversion) Symmetry

Mirror reflection: $\text{parity}$

Parity transformation: $\left( r \rightarrow -r \right)$
Parity Operation (in 3D)

The Parity transformation: \( (\mathbf{r} \rightarrow -\mathbf{r}) \)
- simultaneous reflection of all space coordinates through the origin
- equivalent to reflection plus 180° rotation
- if we assume rotational invariance, it is a mirror reflection
The Parity Transformation

\[ \hat{x} \times \hat{y} = \hat{z} \]

**Right-handed**

\[ \vec{r} \] (position)
\[ \vec{p} \] (momentum)
\[ \vec{L} = (\vec{r} \times \vec{p}) \]
\[ \vec{s} \] (intrinsic spin)

**Left-handed**

\[ \hat{x}^* \times \hat{y}^* = -\hat{z}^* \]
\[ -\vec{r} \]
\[ -\vec{p} \]
\[ \vec{L} = (\vec{r}^* \times \vec{p}^*) \]
\[ \vec{s} \]

\( \vec{L}, \vec{s} \) are pseudo or axial vectors

Distinct: Cannot “rotate” RHS into LHS
The Parity Transformation as Depicted in Popular Culture

1968  *Doppelganger*

*Journey To The Far Side Of The Sun* (US Title)

Parity analogue systems: “Right-handed” vs “Left-handed” systems
Parity Conservation (PC)

The absence of physics that would select a particular *handedness*

- Strong
- Electromagnetic
- Gravitational

*Independent of handedness (PC)*

Weak

*handedness-dependent (PNC)*

Example: Consider the Coulomb interaction of 2 protons

\[
\vec{r} = \vec{r}_1 - \vec{r}_2 \quad ; \quad |\vec{r}| = \sqrt{\vec{r} \cdot \vec{r}}
\]

\[
V(\vec{r}) = \frac{e^2}{4\pi\varepsilon_0} \frac{1}{|\vec{r}|} = V(-\vec{r})
\]

Conserves parity!

Counter example:

**Weak Interaction** violates parity *(PNC)*

→ has the form *(Vector – Axial vector) → handedness built-in*

\[
\sim (\vec{v} - \vec{a}) \cdot (\vec{v} - \vec{a}) \approx \vec{v} \cdot \vec{v} + \vec{a} \cdot \vec{a} - 2(\vec{v} \cdot \vec{a})
\]
Principle of a “beam-target” Parity-violation Measurement

Is this…
(spins parallel to momentum)

\[ \sigma^{(+)} \]

Scattering Rates

The same as this?
(spins antiparallel to momentum)

\[ \sigma^{(-)} \]

**Helicity:** \( h \sim \vec{s} \cdot \vec{p} \equiv (\text{pseudovector}) \cdot (\text{vector}) \)
\[ \equiv \text{pseudoscalar} \]

➢ To replace the experiment with its mirror image, you flip the beam helicity
Parity-sensitive Observables

In accelerator-based scattering experiments:

→ Prepare the beam \((e, p, n, \ldots)\) in \((+\) or \((-\) helicity states
  (Parity analogue states)
→ Observable: Parity-Violating Longitudinal Asymmetry, \(A\)
  Difference/sum of Parity analogue reactions rates

\[ A = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}} \]

→ \(A\) is usually very very small \(\sim (1-10) \times 10^{-7}\) \([0.1-1 \text{ ppm}]\)
  (Signature of the Weak interaction)

Conceptually straightforward \(\rightarrow\) but False Asymmetries!!

\[ A_{\text{measured}} = A_{\text{physics}} + A_{\text{false1}} + A_{\text{false2}} + \ldots \]

Many many sources of false asymmetries: keep \(\leq (1-10) \times 10^{-8}\)
→ High Precision Experiments \([0.01-0.1 \text{ ppm}]\)
Parity-Violation Experiments w/ e⁻ beams @ Jefferson Lab

Hall A

Hall C
(2) **Probing the Nucleus/Proton using subatomic beams**

Beam on Target → Scattering Amplitudes → Target structure (form factor)

“The Accelerator as a Microscope”.
Just bashing small things into other small things?

Consider Coulomb (electric) Scattering (eg, e⁻ from a Nucleus ← charge distr')

Q.M. Scattering Amplitude \( M \sim \langle \Psi_{\text{out}}^{e} | V_{\text{op}} | \Psi_{\text{in}}^{e} \rangle \)

Lowest Order (plane wave) Approx:

\[
M \approx \int e^{i(p' \cdot r)} V(r) e^{-i\vec{p} \cdot \vec{r}} \, d^3 r
\]

\[
M \approx \int V(\vec{r}) e^{i(\vec{p}' - \vec{p}) \cdot \vec{r}} \, d^3 r = \int V(\vec{r}) e^{i\vec{q} \cdot \vec{r}} \, d^3 r
\]

\[
M \approx \tilde{V}(\vec{q}) \equiv [ \text{Fourier Transform of } V(\vec{r}) ]
\]

Tx. Potential
Aside/Reminder: Fourier Transform (FT)

Function
$f(x) \rightarrow$ independent variable $x$

*also described by*

Fourier Transform
$F(k) \rightarrow$ conjugate variable $k$

\[
F(k) = \int f(x) e^{ik \cdot x} \, dx
\]

eg) Electrical Signal / Sound wave (mp3, WMP)

Amplitude

Freq. Spectrum (Spectral Components)

Amplitude or Power
Transition Potential & Amplitude

\[ M_{scat} \approx \tilde{V}(\bar{q}) = \int V(\bar{r}) \ e^{i \bar{q} \cdot \bar{r}} \ dr^3 \equiv F.T. \ of \ V(\bar{r}) \]

Consider a nucleus: Nuclear Charge Distribution \( \rho(r') \)

![Diagram showing interaction between electron and nucleus](image)

Interaction between \( e^- \) and \( dV' \) (at \( r' \))

\[ \nu(\bar{r} - \bar{r'}) \approx \frac{k \ Q_e Q(\bar{r'})}{|\bar{r} - \bar{r'}|} \]

Total Interaction between \( e^- \) and Nucleus:

\[ V(\bar{r}) = \int \nu(\bar{r} - \bar{r'}) \ \rho(\bar{r'}) \ dr'^3 \]

Convolution of \( \nu \ast \rho \)

**Convolution Theorem:**

The F.T. of a convolution of functions \( \equiv \) Product of the Individual transforms

\[ \tilde{V}(\bar{q}) \quad V(\bar{r}) = \nu \ast \rho \quad \tilde{\nu}(\bar{q}) \tilde{\rho}(\bar{q}) \]

\[ \therefore M_{scat} \approx \tilde{V}(\bar{q}) \approx \tilde{\nu}(\bar{q}) \tilde{\rho}(\bar{q}) \]

**Form Factor**

\[ \text{Force/Int} \approx \int \frac{1}{|\bar{r}|} e^{i \bar{q} \cdot \bar{r}} \ dr^3 = \frac{1}{q^2} \]

\[ \approx \int \rho(\bar{r}) e^{i \bar{q} \cdot \bar{r}} \ dr^3 \equiv F(\bar{q}) \ (\text{or} \ G(\bar{q})) \]
Cross Sections

Experiments measure “Cross Sections” (Rate/Prob./Intensity)

\[ \sigma \propto |M_{scat}|^2 \approx |\tilde{v}(q)\tilde{p}(q)|^2 \approx \left| \frac{1}{q^2} G(q) \right|^2 \]

\[ \sigma \equiv \sigma(\theta) \equiv \sigma(q) \sim I \]

“Probe” → By looking at σ(q)
☞ Really looking @ diffraction pattern
☞ Extracting the Form Factor [ G(q) or ρ ] (“separate out” the 1/q² term)
☞ Infer the shape/distribution of scattering object

“Listening to the shape of the drum”
Example: Proton EM Form Factors from Electron Scattering

“Measure” Electric Charge & Magnetic Moment as functions of $Q^2$ (momentum transfer)

- **Sachs Form Factors** (well established)
  - *(many, extensive measurements)*

- Small proton $\rightarrow$ slow fall-off

- Large proton $\rightarrow$ rapid fall-off

- Form Factor is essentially the Fourier transform of the spatial distribution.

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**Charge**

$G_{\gamma p}^E$

- Pointlike
- Actual

**Magnetic Moment**

$G_{\gamma p}^M$

- Pointlike
- Actual

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**Proton Densities**

$\lambda_E=\lambda_M=2$

- $\rho_m$
- $\rho_{ch}$

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Low spatial frequency

High spatial frequency
Parity-Violation in e-p Scattering:

JLab-Hall C “Parity” Experiments: G0 and Qweak

Using spin-polarized electrons and Parity-violation:
Probe the “weak” structure of the proton → learn something about:

- The strange quark currents in the proton (G0)  
  [Role of the sea quarks at low energy]

- The weak charge of the proton (Qweak)  
  [Search for new physics beyond the Standard Model]

electron – proton scattering: Electroweak Interaction

**Electromagnetic**  
(Virtual photon exchange)  
Probes proton’s EM structure, $G^\gamma$

**Weak**  
(Virtual $Z^0$ exchange)  
Probes proton’s “Weak” structure, $G^Z$
Electromagnetic vs Weak Processes and Parity-Violation

Scattering Amplitude $M = M_\gamma + M_Z$; with $M_\gamma \gg M_Z$ (factor of $\sim 10^5$)
But: $M_\gamma \Rightarrow$ parity conserving, while $M_Z \Rightarrow$ parity non-conserving

Compare 2 parity-sensitive cross-sections (whose parity-conserving parts are identical)

Scattering Asymmetry:

$$A = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \sim \frac{M_\gamma M_Z}{|M_\gamma|^2}$$
Recap (so far)

Scattering Processes (Cross Sections/Diffraction Pattern) $\rightarrow$ Form Factors

**Coulomb Scattering**

$$\sigma \approx |M_{\text{scat}}|^2 \approx |\tilde{v}(q)\tilde{p}(q)|^2 \approx \left| \frac{1}{q^2} G(q) \right|^2$$

**Parity-Violation $\rightarrow$ “Weak” Interaction components (of F.F.)**

$$A = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \sim M_\gamma M_Z / |M_\gamma|^2$$

$$A = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \sim f(q) \times G_\gamma G_Z / |G_\gamma|^2$$
Proton Structure: An open question

What does a proton look like?

\[ |p\rangle \approx \alpha |qqq\rangle + \beta |qqq\ g\rangle + \gamma |qqq\ q\bar{q}\rangle + \ldots \]

A Proton has 3 Quarks (Valence Quarks) (uud)

There may be contributions from gluons to the Proton’s structure (?)

There may be contributions from a “sea” of Quark-AntiQuark pairs (?) {strange-antistrange quark pairs (??)}

Strange quarks present only in the sea (Proton has no “net” strangeness)
Measurement of the Strange Quark Currents in the Proton

**G0 Collaboration:**
Canada (TRIUMF, U.Manitoba, UNBC, U.Winnipeg), France, USA

Measure $G^z_p$: Weak vector-current form factor
- a “**new**” & **fundamental** property of the proton
- Similar to normal electric & magnetic form factors, but for “weak” interaction (weak charge, weak magnetic)

\[
G^\gamma_E, G^\gamma_M: \text{EM charge & magnetic FF} \quad \rho \rightarrow G_E
\]
\[
G^Z_E, G^Z_M: \text{weak charge & magnetic FF}
\]

\[
G^Z_p, G^\gamma_p, G^\gamma_n \Rightarrow G^{s,p}
\]

**Strangeness form factor of proton**
Role of sea quarks at low $E$

\[
G^{s,p}_E = (1 - 4\sin^2\theta_W) \ G^\gamma_p - G^\gamma_n - G^Z_p
\]
\[
G^{s,p}_M = (1 - 4\sin^2\theta_W) \ G^\gamma_p - G^\gamma_n - G^Z_p
\]
Form Factors from Parity-Violating Asymmetry

Parity-Violating Asymmetry

\[ A = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}} \sim \frac{f(q) \cdot G_f G_z}{|G_\gamma|^2} \]

Proton Weak Form Factors

\[ A(Q^2) = - \frac{(G_F Q^2)}{\pi \alpha \sqrt{2}} \{ \frac{\varepsilon G_E^z G_E^z + \tau G_M^z G_M^z + \eta G_M^z G_A}{\varepsilon(G_E^z)^2 + \tau(G_M^z)^2} \} \quad [\frac{1}{P_Z}] \]

(where \(\varepsilon, \tau, \eta\) are kinematical parameters)

Want to determine \(G_E^Z\) and \(G_M^Z\)

Do 2 measurements of \(A\) at each momentum \(tx\) value (\(q\) or \(Q^2\))

For a given \(Q^2\), \(\varepsilon\) ranges from 1 (small angles) \(\rightarrow\) 0 (large angles)

i) At small \((\text{forward})\) angles, measure a combination of \(G_E^Z\) and \(G_M^Z\)

ii) At large \((\text{backward})\) angles, measure \(G_M^Z\)

\(\rightarrow\) Combine both measurements to \text{extract} \(G_E^Z\)

**G0 MEASUREMENTS:**

A) Forward Angle Mode
B) Backward Angle Mode
Goal: Measure $A_z \sim 5 \times 10^{-6}$ to $(\Delta A/A) \sim \pm 5 \% (10^{-7})$

Systematics: (h.c. variables)

- $\Delta E < 2.5 \times 10^{-8}$
- $\Delta I_b/I_b < 1 \text{ ppm}$
- $\Delta x < 20 \text{ nm}$
- $\Delta \theta < 2 \text{ nrad}$

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Forward Angle mode

- $Q^2 = 1.0$
- $Q^2 = 0.1$
- $3 \text{ GeV beam}$

Backward Angle mode

- $Q^2 \propto E_{\text{beam}}$
- $0.3-0.7 \text{ GeV beam}$

G0 Schematic Layout and Experiment Parameters
Forward Angle Configuration

G^0 beam monitoring girder

cryogenic supply
Forward Angle Configuration

- G^0 beam monitoring girder
- Cryogenic supply
- Superconducting magnet (SMS)
- 8 sector Iron-free

8 sector iron-free diagram
Forward Angle Configuration

- G⁰ beam monitoring girder
- Cryogenic supply
- Target service module and LH₂ target
- 20 cm LH₂ cell
- 250 W heat load (40 µA beam)
Forward Angle Configuration

Focal Plane Detectors (Ferris-Wheel)

16 FPDs per octant, diff $Q^2$

$G^0$ beam monitoring girder
Forward Angle Configuration

Measure flight-time of particles
Identify recoil p’s from BG pions

Incident electron
Target
Collimators
FP Detectors

G0 Target-Magnet-FPD in Hall C
First Results from G0 Experiment

Phase I

(Forward Angle Measurement, Fall/2002 – Summer/2004)

\[ A(Q^2) = -\left(\frac{G_F Q^2}{\pi \alpha \sqrt{2}}\right) \left\{ \frac{\epsilon G^*_E G_E + \tau G^*_M G_M + \eta G^*_M G_A}{\epsilon (G^*_E)^2 + \tau (G^*_M)^2} \right\} \left[ \frac{1}{P_Z} \right] \]
G0 Back-Angle Configuration

Magnet & Detector Package *turned around*; Detect back-scattered electrons

Additional Detectors; 2\textsuperscript{nd} (\textit{Mini}) Ferris-Wheel Support Structure
Back-Angle Configuration: Cryostat-Exit Detectors

Magnet & Detector Package *turned around*

Measure back-scattered electrons (*instead of recoil p’s*)

- Require additional det.s: Cryostat-Exit Detectors (CED) (9 detectors per octant, fabricated at TRIUMF)
- CED-FPD coincidence to separate *elastics/inelastics* $e^-$ (cannot use Time-of-Flight $\rightarrow$ electrons are relativistic)
**Back-Angle Configuration: Aerogel Cerenkov Detectors**

Back-scattered electron:
CED-FPD coinc. separates elastic & inelastic $e^-$'s

Background pions:
Need to separate $\pi^-$ (backgnd) from $e^-$ (signal)

Cerenkov Detectors:
“Discriminate” electrons from pions by their velocity ($e$’s create light in Cerenkov det., but pions do not).

8 detectors: 4 Canadian
4 French

**Aerogel Cerenkov**
$11 \times 11 \times 1 \text{ cm}^3$ tiles (5 deep)

Aerogel, $n \sim 1.03$

If $v > 0.97c$ (speed of light in aerogel medium), Cerenkov radiation created

Fabricated & tested @ TRIUMF
**Backward Angle Measurement** *(Recently started Mar/2006)*

Nov/2005: Backangle Detector octants *(Mini-Ferris Wheel)* installed in Hall C (JLab)

Mar/2006: Backangle Detector system cabled & taking cosmic data
LH$_2$/LD$_2$ Target installed
Backward Angle Measurement (Recently started Mar/2006)

Spring 2006: Commissioning and 1st Data Run in Backward Angle Mode
System (Detectors/Target/Beam) checked out
1st set of (preliminary) production data obtained
1st set of Parity-violating asymmetries measured

Present Status of the G0 Experiment
Forward Angle Measurement Completed
Presently, in Backward Angle Configuration

G0 Backangle Measurements @ $Q^2 = 0.6, 0.23$ GeV$^2$
- Run in Mar-Apr ’06 at $Q^2 = 0.6$ GeV$^2$ (Commissioning & H target)
- Run in July-Aug ’06 at $Q^2 = 0.23$ GeV$^2$ next (H and D targets)
- Run in Sep-Dec ’06 at $Q^2 = 0.6$ GeV$^2$ (H and D targets)
- Run in Jan-Feb ’07 at $Q^2 = 0.23$ GeV$^2$ (H and D targets)
Physics Beyond the Standard Model?

Standard Model: “Pillar of fundamental physics for ~ 30 years”
Electromagnetic, Weak, Strong interactions

Fermions (“matter particles”): 
- leptons: (e, ν_e, μ, ν_μ, τ, ν_τ)
- quarks: (u, d, s, c, b, t)

Gauge Bosons (“force carriers”): 
(γ, W^+, W^–, Z, g, H)

Electroweak sector:
Unification of Electromagnetic (EM) and Weak Interactions
→ Electroweak Interaction (EW)

Proposed by Weinberg-Salam (γ, Z, W^±)
- predicted existence Z, W^± → discovered later at CERN
Impressive agreement between Standard Model & EW observables

Issues: (Did not explain)
Large number of parameters (masses, couplings, mixing angles)
Origin of: quantization of EM charge and weak hypercharge,
  P and CP violation, number of generations,…
Neutrino oscillations
Mass (scalar) hierarchy problem

Q: Extensions (“new” physics) beyond the Standard Model?
A Search for Physics at the TeV Scale Via a Measurement of the Proton’s Weak Charge

Q\text{weak} Collaboration:
Canada (TRIUMF, U.Manitoba, UNBC, U.Winnipeg), USA

Measure $Q_p^{\text{weak}}$: Weak charge of the proton; $Q_p^{\text{weak}} = 1 - 4\sin^2\theta_W$

- **first precision measurement** of this property of the proton
- fundamental measurement of the running of $\sin^2\theta_W$ at low energies

At low energies and small scattering angles, the “weak charge” of the proton is proportional to the Parity-Violating asymmetry (in e-p scattering):

$$A \sim \left[ Q^2 Q_{\text{weak}}^p + Q^4 B(Q^2) \right] \sim \left[ Q^2 Q_{\text{weak}}^p \right]; \quad \left\{ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ - \sigma^-} \right\}$$

contains $G_{E,M}^\gamma$, $G_{E,M}^Z$ form factors

$Q_{\text{weak}}^p = 1 - 4 \sin^2\theta_W \approx 0.072 \rightarrow$ a well-defined experimental observable
$\rightarrow$ has a definite prediction in the Standard Model

→ Goal: Asymmetry Measurement: $\Delta A \sim 1 \times 10^{-8} \rightarrow \Delta Q_{\text{weak}}^p \sim \pm 4\% \rightarrow \Delta \sin^2\theta_W \sim \pm 0.3\%$
→ Sensitive to *new physics (particles)* at $\sim 4.6 \text{ TeV}$ scale
Running of the Weak Mixing Angle

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

New Physics ??

Value of $\sin^2 \theta_W$ at ~0.17 GeV/c:
SLAC E158: (e-e)
PV Moller Scattering $\Rightarrow Q^e_{\text{weak}}$
Complementary
JLab $Q^p_{\text{weak}}$ (e-p)
Useful Diagnostic for New Physics

Weak charge measurements: $Q^p_{\text{weak}}$, $Q^e_{\text{weak}}$

E158 recent results: $\sin^2 \theta_W = 0.2397 \pm 0.0010 \text{ (stat)} \pm 0.0008 \text{ (sys)}$
**Layout of the Qweak Experiment**

- Drift Chambers & Scintillators
- QTOR Magnet
- 35 cm LH₂ Target & Scattering Chamber (2200W beam heating)
- Double Collimator, GEM’s & Mini-torus
- 3” Pb Beamline Shielding
- Fused Silica (quartz) Cerenkov Det.s (recessed into concrete shield)

\[ Q^2 = 0.03 \ (GeV/c)^2 \]
**Qweak Toroidal (QTOR) Magnet**

- 8 sector toroidal magnet
- water cooled copper coils
- 8600 A, 1.2 MW
- 4.3 m long, 1.5 m wide coils, simple racetrack shape
- ~3300 kg per coil
- Magnet coils → Canadian
- Field mapping with G0 Mapper (TRIUMF-designed & built)

\[ \int \vec{B} \cdot d\vec{l} = 0.67 \text{ T.m} \]

Qweak experiment presently in design & prototyping phase
## SUMMARY

**G0**
- G0 will measure a *new*, fundamental property of the proton. ($G_{Zp}^p$, weak current distribution)
- Measurement of $G_{Zp}^p$ allows decomposition of the proton ground state matrix elements into quark flavour contributions ($G_{u,p}^p$, $G_{d,p}^p$, & $G_{s,p}^p$ – proton strange quark current distribution; direct measurement of the quark sea).
  
  > The physics is of great current interest.

**Q\text{\tiny weak}**
- First precision measurement of the weak charge of the proton. ($Q_{\text{\tiny weak}}$)
- Fundamental measurement of the running of $\sin^2\theta_W$ at low energy.
- Sensitive search for new physics at the ~4.6 TeV scale.

Parity-violation is a useful tool indeed.
**Proton “Weak” Form Factors & Strange Quarks**

Flavour decomposition ("Proton is made up of quarks of different flavours")

\[ G_{E,M}^{\gamma p} \rightarrow \Sigma (\text{electric charge of quark } q_j) \times G_{E,M}^{q_j,p} \]

\[ G_{E,M}^{Z p} \rightarrow \Sigma (\text{weak charge of quark } q_j) \times G_{E,M}^{q_j,p} \]

\[ G_{E,M}^{q_j,p} \text{ empirical, “unknown”} \]

\[ q_j = \{ u, d, s, c, t, b \} \]

Rewrite as a sum of contribution from each flavour (neglect heavy quarks c, t, b)

\[ G_{E,M}^{\gamma p} = (2/3) \ G_{E,M}^{u,p} - (1/3) \ G_{E,M}^{d,p} - (1/3) \ G_{E,M}^{s,p} \]

\[ G_{E,M}^{Z p} = (1/4 - 2/3 \sin^2 \theta_W) \ G_{E,M}^{u,p} - (1/4 - 1/3 \sin^2 \theta_W) \ G_{E,M}^{d,p} - (1/4 - 1/3 \sin^2 \theta_W) \ G_{E,M}^{s,p} \]

\[ G_{E,M}^{\gamma n} = (2/3) \ G_{E,M}^{d,p} - (1/3) \ G_{E,M}^{u,p} - (1/3) \ G_{E,M}^{s,p} \]

\[ \downarrow \]

**Assuming Charge Symmetry** between the proton and neutron

\[ \downarrow \]

\[ G_{E,M}^{u,p} = (3 - 4\sin^2 \theta_W) \ G_{E,M}^{\gamma p} - G_{E,M}^{Z p} \]

\[ G_{E,M}^{d,p} = (2 - 4\sin^2 \theta_W) \ G_{E,M}^{\gamma p} + G_{E,M}^{\gamma n} - G_{E,M}^{Z p} \]

\[ G_{E,M}^{s,p} = (1 - 4\sin^2 \theta_W) \ G_{E,M}^{\gamma p} - G_{E,M}^{\gamma n} - G_{E,M}^{Z p} \]