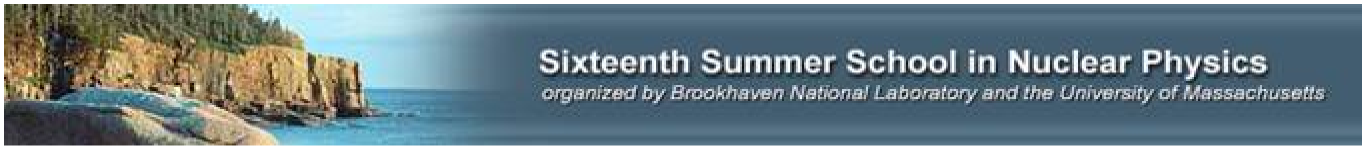
Electroweak Physics

Mark Pitt   Virginia Tech



16th Summer School in Nuclear Physics

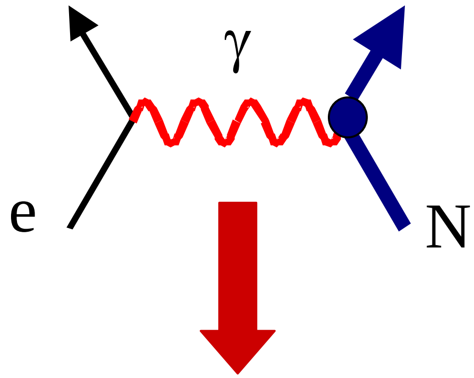
Electroweak physics is a broad subject. I will limit these lectures to:

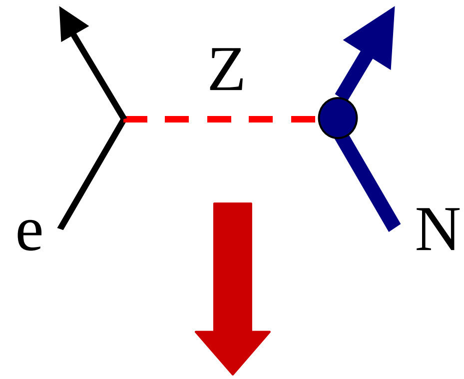
- Low energies/momentum transfers $\rightarrow$ $Q^2 < 1\ (GeV/c)^2$
- Elastic scattering only (mostly e + N reactions but some ν + N and e + e)

These lectures will cover the majority of the electroweak physics going on at electron accelerators in the nuclear physics category.

Lecture 1

What are we going to cover?





$e + N \rightarrow e + N$ N = nucleon

Electromagnetic Form Factors

$(G_E^p, G_M^p, G_E^n, G_M^n)$

- G_E^p, G_M^p ratio
  - 2 photon physics
- improved knowledge of G_E^n

$\vec{e} + N \rightarrow e + N$ N = nucleon

Parity-violating electron scattering

Neutral Weak Form Factors

$(G_E^{Z,p}, G_M^{Z,p}, G_E^{Z,n}, G_M^{Z,n}, G_A^e)$

- Strange vector form factors
- Nucleon's anapole moment

Low energy Standard Model Tests

- Weak charge of the electron
- Weak charge of the proton
- Weak charge of the neutron

We will also cover the experimental techniques unique to the parity-violating electron scattering types of experiments.

Some Useful Resource Material on this Topic

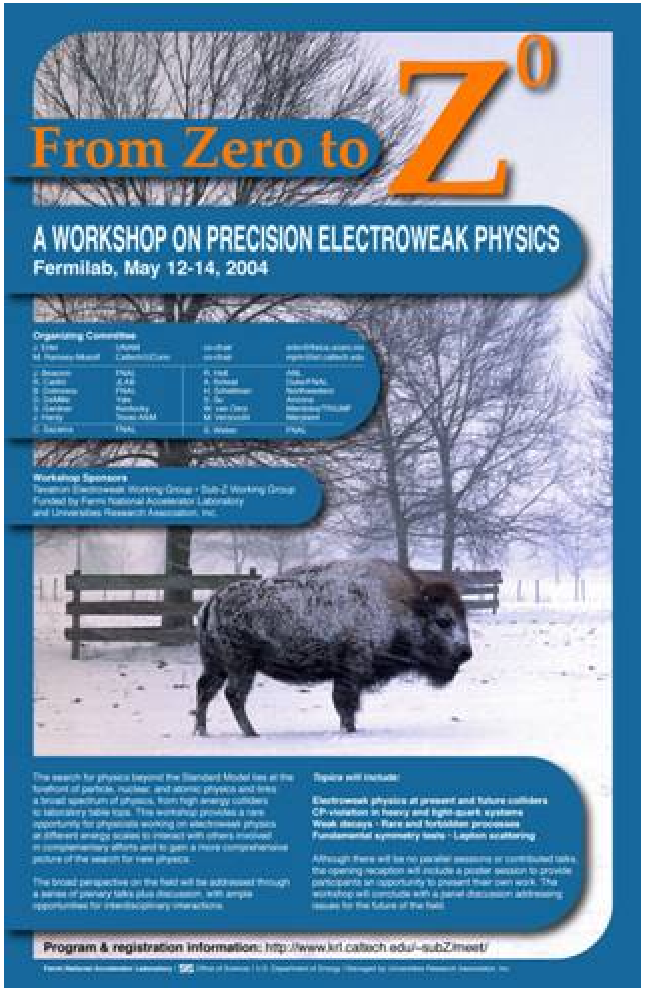
Good recent review articles:

K.S. Kumar and P.A. Souder, Prog. Part. Nucl. Phys. **45**, S333 (2000)
D.H. Beck and B.R. Holstein, Int. J. Mod. Phys. **E10**, 1 (2001)
D.H. Beck and R.D. McKeown, Ann. Rev. Nucl. Part. Sci. **51**, 189 (2001)

And two very recent topical workshops →
(talks posted online at both sites)

http://www.krl.caltech.edu/~subZ/meet/index.html

http://lpsc.in2p3.fr/congres/pavi2004/



Outline of Lectures

1. Develop the formalism of parity-violating electron scattering
   with stops for:
   - electromagnetic form factors
   - QCD and nucleon "strangeness"

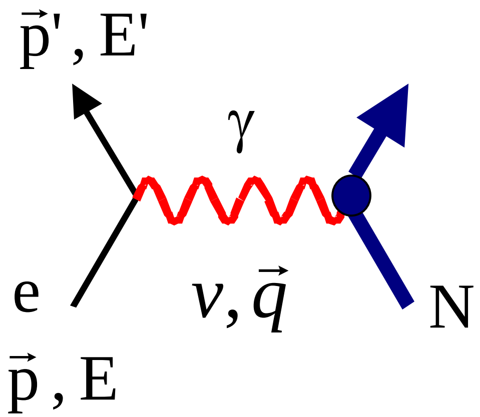
2. Experimental aspects unique to all parity-violating electron scattering experiments

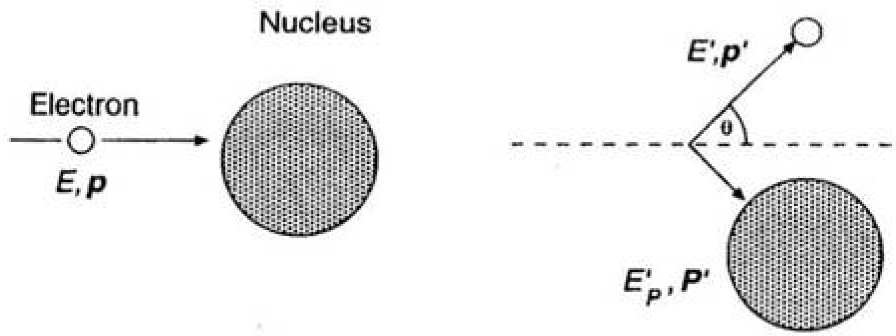
3. Review of experiments devoted to strange form factor measurements (including new results just reported last week)

4. Motivation for low energy Standard Model tests

5. Review of experiments devoted to low energy Standard Model tests

Kinematics of Elastic Electron-Nucleon Scattering





$\nu = E - E'$ energy transfer to recoiling nucleon

$\vec{q} = \vec{p} - \vec{p}'$ 3-momentum transfer to recoiling nucleon

$q^2 = \nu^2 - \vec{q}^{\,2} \equiv -Q^2$ squared 4-momentum transfer

$Q^2 = 4\,E\,E' \sin^2\left(\frac{\theta_e}{2}\right)$ Lorentz invariant

Recall the Dirac Equation and Currents

Dirac equation for free electron: $$(i\gamma^\mu \partial_\mu - m)\,\psi = 0$$

where:

$$\gamma^\mu = \left(\gamma^0, \vec{\gamma}\right) \qquad \gamma^0 = \begin{pmatrix} \vec{1} & 0 \\ 0 & -\vec{1} \end{pmatrix} \qquad \vec{\gamma} = \begin{pmatrix} 0 & \vec{\sigma} \\ -\vec{\sigma} & 0 \end{pmatrix}$$

with: $\mu = 0$ time, $\mu = 1,2,3$ space

leads to electron four-vector current density:

$$j^\mu = -e\,\overline{\psi}\gamma^\mu\psi$$ where the adjoint is: $$\overline{\psi} \equiv \psi^+\gamma^0$$

satisfies the continuity equation: $$\partial_\mu j^\mu = 0$$

Bilinear Covariants and Their Symmetry Properties

We describe physical processes through interacting currents
$\rightarrow$ need to construct most general form of currents consistent with Lorentz invariance

Terms of the form	$\bar{\psi}\,(4\times 4)\,\psi$	P	T	C
Scalar	$\bar{\psi}\psi$	$+1$	$+1$	$+1$
Pseudoscalar	$\bar{\psi}\gamma^5\psi$	-1	-1	$+1$
Vector	$\bar{\psi}\gamma^\mu\psi$	$(-1)^\mu$	$(-1)^\mu$	-1
Axial Vector	$\bar{\psi}\gamma^\mu\gamma^5\psi$	$-(-1)^\mu$	$(-1)^\mu$	$+1$
Tensor	$\bar{\psi}\sigma^{\mu\nu}\psi$	$(-1)^\mu(-1)^\nu$	$-(-1)^\mu(-1)^\nu$	-1

where $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$

P: parity operator (spatial inversion)
T: time reversal
C: charge conjugation

Note: P (V*V) = +1 P (A*A) = + 1 P (A*V) = -1

Relation Between Cross Sections and Matrix Elements

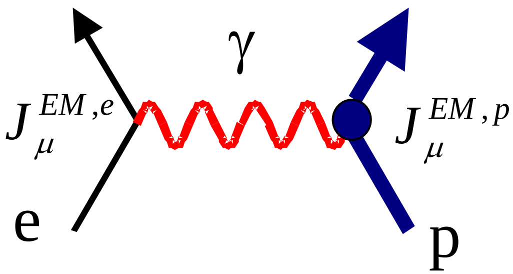
For a process $A + B \rightarrow C + D$

the differential cross section is

$$\left.\frac{d\sigma}{d\Omega}\right|_{cm} = \frac{1}{64\pi^2 s}\frac{p_f}{p_i}\left|M\right|^2$$

The physics is all in the matrix element M

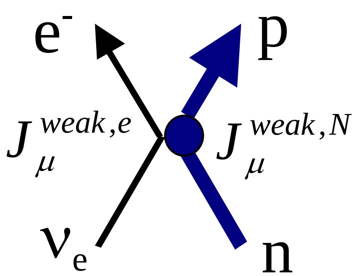
Electromagnetic and Weak Interactions : Historical View



EM: e + p → e + p elastic scattering

$$M = J_\mu^{EM,p} \left(-\frac{e^2}{Q^2} \right) J^{\mu,EM,e} = \left(\overline{\psi}_p \gamma_\mu \psi_p \right) \left(-\frac{e^2}{Q^2} \right) \left(\overline{\psi}_e \gamma^\mu \psi_e \right)$$

V × V



Weak: $n \rightarrow e^- + p + \bar{\nu}_e$ neutron beta decay

Fermi (1932) : contact interaction, form inspired by EM

$$M = J_\mu^{weak,N} \, G_F \, J^{\mu,weak,e} = \left(\overline{\psi}_p \gamma_\mu \psi_n \right) G_F \left(\overline{\psi}_e \gamma^\mu \psi_{\nu_e} \right)$$

V × V

Parity Violation (1956, Lee, Yang; 1957, Wu): required modification to form of current - need axial vector as well as vector to get a parity-violating interaction

$$M = J_\mu^{weak,N} \, G_F \, J^{\mu,weak,e} = \left(\overline{\psi}_p \gamma_\mu \left(1 - \gamma^5\right) \psi_n \right) G_F \left(\overline{\psi}_e \gamma^\mu \left(1 - \gamma^5\right) \psi_{\nu_e} \right)$$

(V - A) × (V - A)

Note: weak interaction process here is charged current (CC)

But Zel'Dovich Suggests - What About Neutral Weak Currents ?

LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964–966 (March, 1959)

WE assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.,} \quad (1)$$

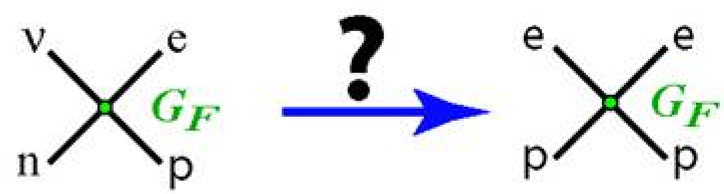
there exists an interaction

$$g(\bar{P}OP)(\bar{e}^- O e^-) \quad (2)$$

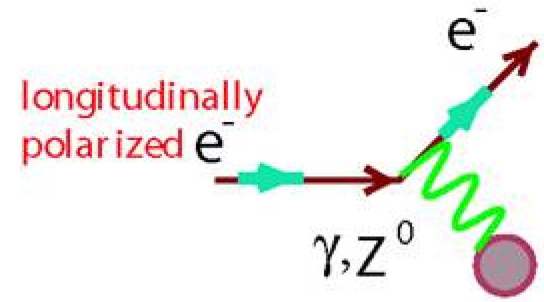
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Zel'dovich '59:

- Is there a neutral analog to beta-decay?
- Would determine sign of G_F



The Neutral Current, Zel'Dovich continued



Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

$$\sigma \; \alpha \, | A_\gamma + A_{weak} |^2$$

parity nonconservation via weak-electromagnetic interference

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2.

$$A_{LR} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma}$$

parity violating asymmetry

$$\sim \frac{G_F Q^2}{4 \pi \alpha}$$

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

$$Q^2 \sim 0.1 - 1 \text{ GeV}^2$$

$$\downarrow$$

$$A_{LR} \lesssim 10^{-6} - 10^{-4}$$

Standard Model of Electroweak Interactions (1967)

Weinberg-Salam Model (1967): electroweak - unified EM and weak
→ SU(2) x U(1) gauge theory with spontaneous symmetry breaking

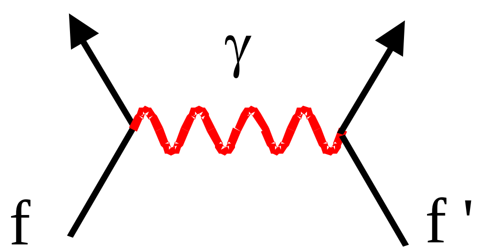
fermions:

Leptons:	e^-, ν_e	μ^-, ν_μ	τ^-, ν_τ	+	anti-particles
Quarks:	u , d	s , c	b , t	+	anti-particles

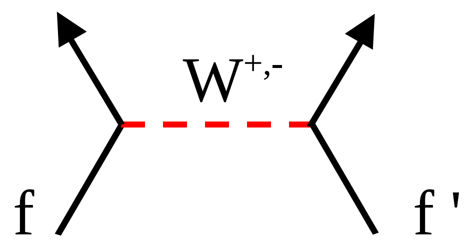
gauge bosons:

EM: γ (m_γ = 0)

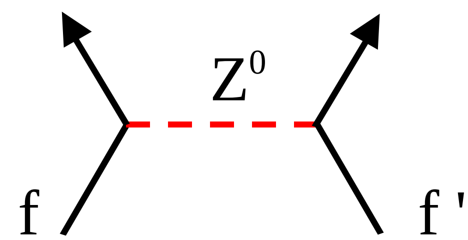
weak: $W^{+,-}$ (m_W = 80 GeV/c^2) Z^0 (m_Z = 91 GeV/c^2)



electromagnetic interaction:
charged fermions participate



charged current weak interaction:
all fermions participate



neutral current weak :
all fermions participate

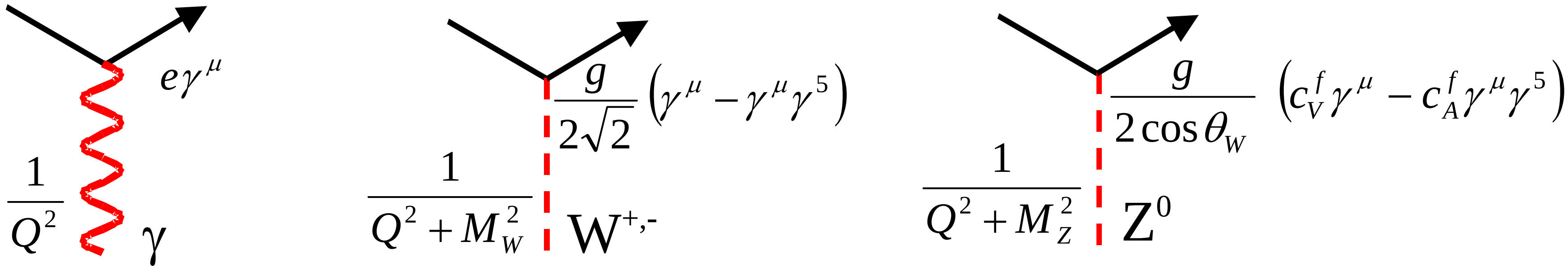
Neutral weak currents first observed at CERN in 1973
in reactions like

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

Feynman Rules for Calculating M in the Standard Model

The fundamental parameter of the Standard Model is the weak mixing angle - θ_W $\sin\theta_W = \frac{e}{g}$ where e and g are the electromagnetic and weak couplings

Feynman rules:



γ - only couples to electromagnetic vector current

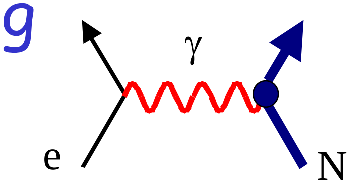
W, Z - couple to both weak vector and axial-vector currents

$$M_{EM} \propto \frac{e^2}{Q^2} \qquad M_{weak} \propto \frac{g^2}{Q^2 + M_{W,Z}^2}$$

$$\text{For } Q^2 << M_Z^2 \qquad \frac{M_{weak}}{M_{EM}} \sim \frac{g^2 Q^2}{e^2 M_{W,Z}^2}$$

$$\text{Note: } G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2} \quad \text{is the Fermi coupling constant}$$

Electromagnetic e- p Elastic Scattering



From the Feynman rules, the matrix element is:

$$M = J_\mu^{EM,p}\left(-\frac{e^2}{Q^2}\right)J^{\mu,EM,e} = \left(J_\mu^{EM,p}\right)\left(-\frac{e^2}{Q^2}\right)\left(\overline{\psi}_e\gamma^\mu\psi_e\right)$$

But the proton (unlike the electron) is not a point-like Dirac particle (need to introduce form factors to characterize its structure):

$$\left\langle N \,|\, J_\mu^\gamma \,|\, N\right\rangle = \overline{u}_N\left(F_1^\gamma(Q^2)\gamma_\mu + F_2^\gamma(Q^2)\frac{i\sigma_{\mu\nu}q^\nu}{2M_N}\right)u_N$$

↑ Dirac ↑ Pauli

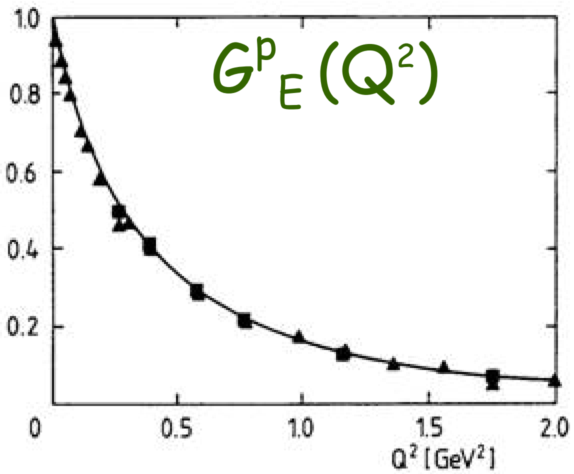
Another way to write the form factors is the Sachs definition:

$$G_E = F_1 - \tau F_2 \qquad G_M = F_1 + F_2 \qquad \tau = \frac{Q^2}{4M_N^2}$$

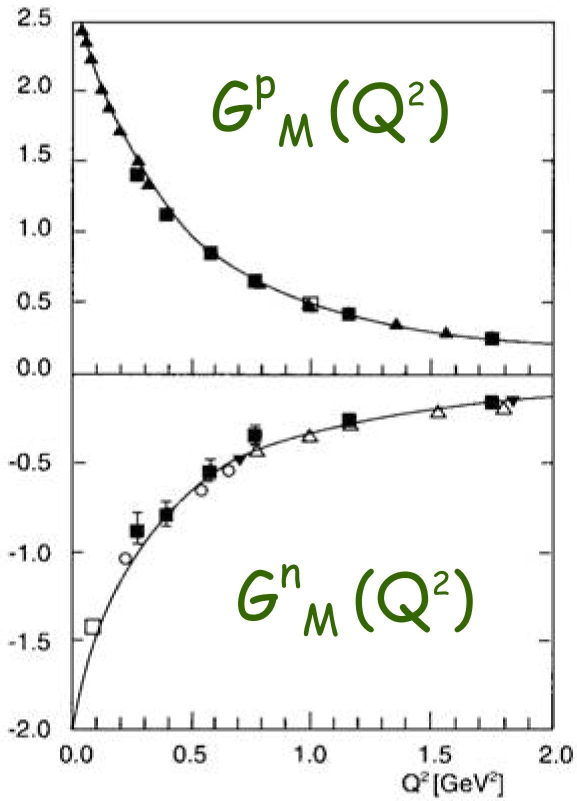
The cross section for e-p elastic scattering is then given as: (Rosenbluth formula)

$$\frac{d\sigma}{d\Omega} \propto \left|M^2\right| = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2\frac{\theta_e}{2}\right]$$

Proton and Neutron EM Form Factors: Measurements



$G_E^p(0) = q$
$= +e$



$G_M^p(0) = \mu_p$
$= 2.79\,\mu_N$

$G_M^n(0) = \mu_n$
$= -1.91\,\mu_N$

$$Q^2 \sim 0 \; - \; 2\,\text{GeV}^2$$

All follow (appear) to follow dipole form:

$$G_D(Q^2) = \frac{1}{\left[1+\left(\frac{Q^2}{0.71\,(\text{GeV}/c)^2}\right)\right]^2}$$

In Breit frame

Fourier transform yields spatial distribution

$\rho(R) = \rho_o \exp(-R/R_o)$ where $R_o \sim 0.25$ fm

E $\rightarrow$ spatial charge distribution
M $\rightarrow$ spatial magnetization distribution

Nucleon Spacelike ($q^2 < 0$) Electromagnetic Form Factors

$$J^{\gamma}_{\mu} = F^{\gamma}_1 \gamma_{\mu} + F^{\gamma}_2 \frac{i\sigma_{\mu\nu} q^{\nu}}{2M_N}$$

↑ Dirac ↑ Pauli

Sachs: $G_E = F_1 - \tau F_2 \quad G_M = F_1 + F_2$

$$\tau = \frac{Q^2}{4M_N^2}$$

- 1960's – early 1990's : G^p_E, G^p_M, G^n_E, G^n_M measured using Rosenbluth separation in e + p (elastic) and e + d (quasielastic):

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

- early 1990's – present: Polarization observables and ratio techniques used

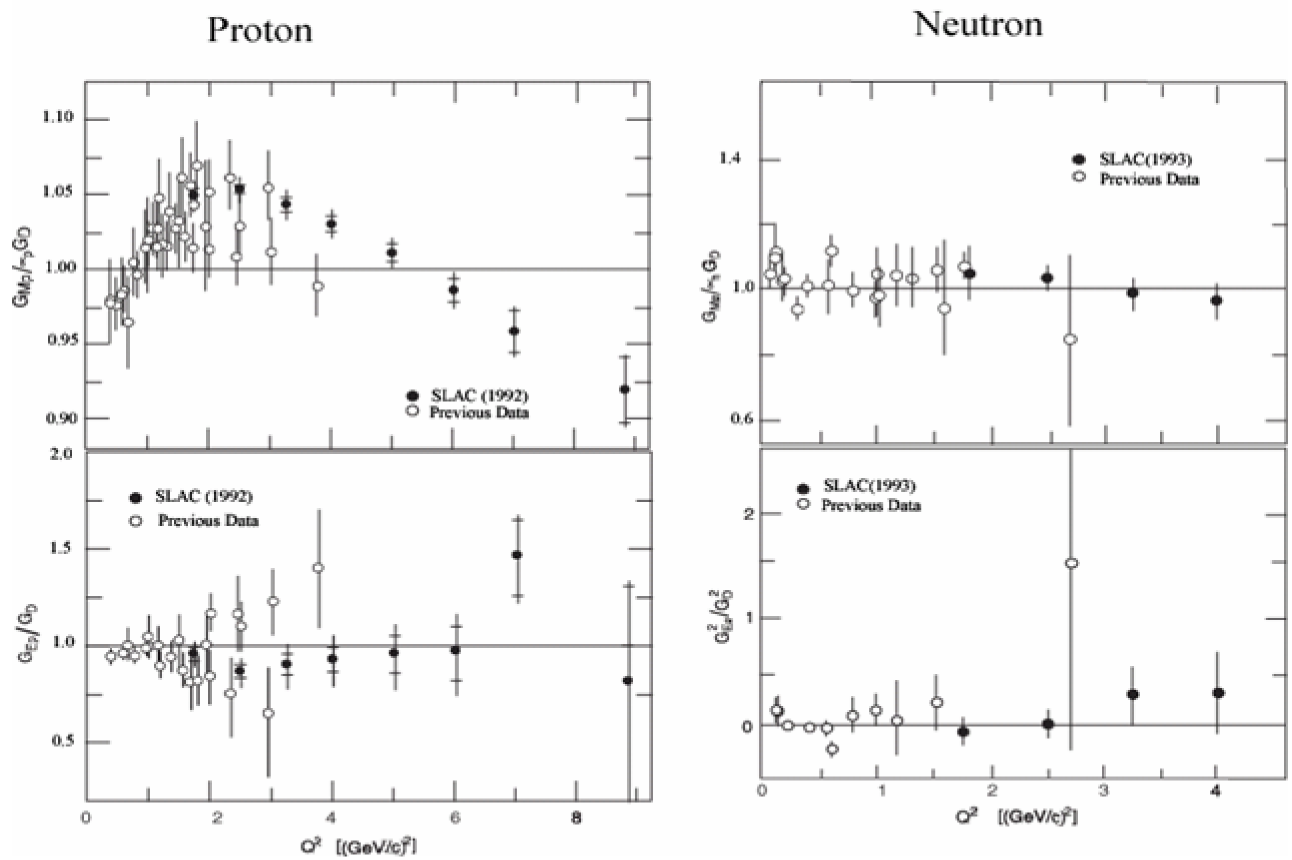
$$\vec{e} + \vec{N} \rightarrow e' + N' \qquad \vec{e} + N \rightarrow e' + \vec{N}'$$

$$\frac{d\sigma}{d\Omega} = \underbrace{\ldots(G_E^2 + \ldots G_M^2)}_{(d\sigma/d\Omega)_{unpol}} + \underbrace{\ldots P_e P_N^{\perp} G_E G_M}_{A_{\perp}} + \underbrace{\ldots P_e P_N^{\parallel} G_M^2}_{A_{\parallel}}$$

Nucleon Spacelike EM Form Factors, World Data - 1993

Relative error ~ 2%

~ 10-20%



~ 5-10%

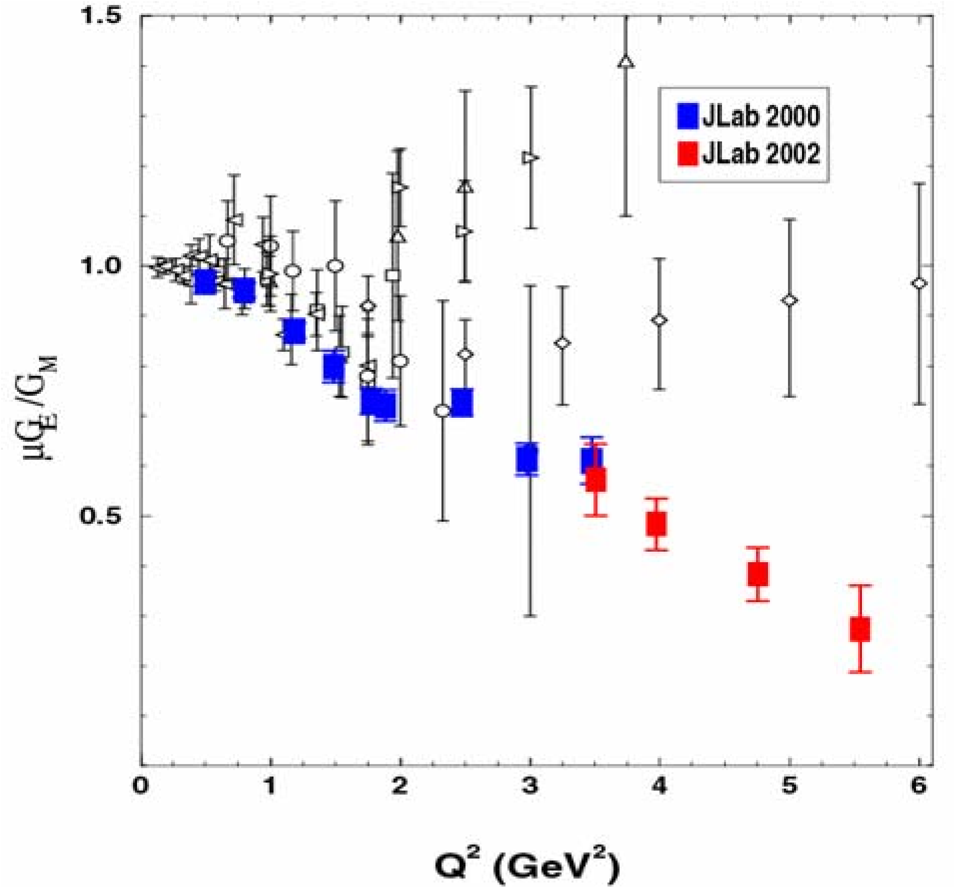
~ 50-100%

Knowledge of nucleon spacelike EM form factors in 1993:

→ G^p_E , G^p_M, G^n_M follow dipole form $G_D = (1 + Q^2/0.71)^{-2}$ at ~20% level

→ $G^n_E \sim 0$ (from quasielastic e-d data)

Proton Electromagnetic Form Factor Ratio: G^p_E / G^p_M



Older data: Rosenbluth separation

JLab 2000: M. K. Jones, *et al.*

JLab 2002: O. Gayou, *et al.*

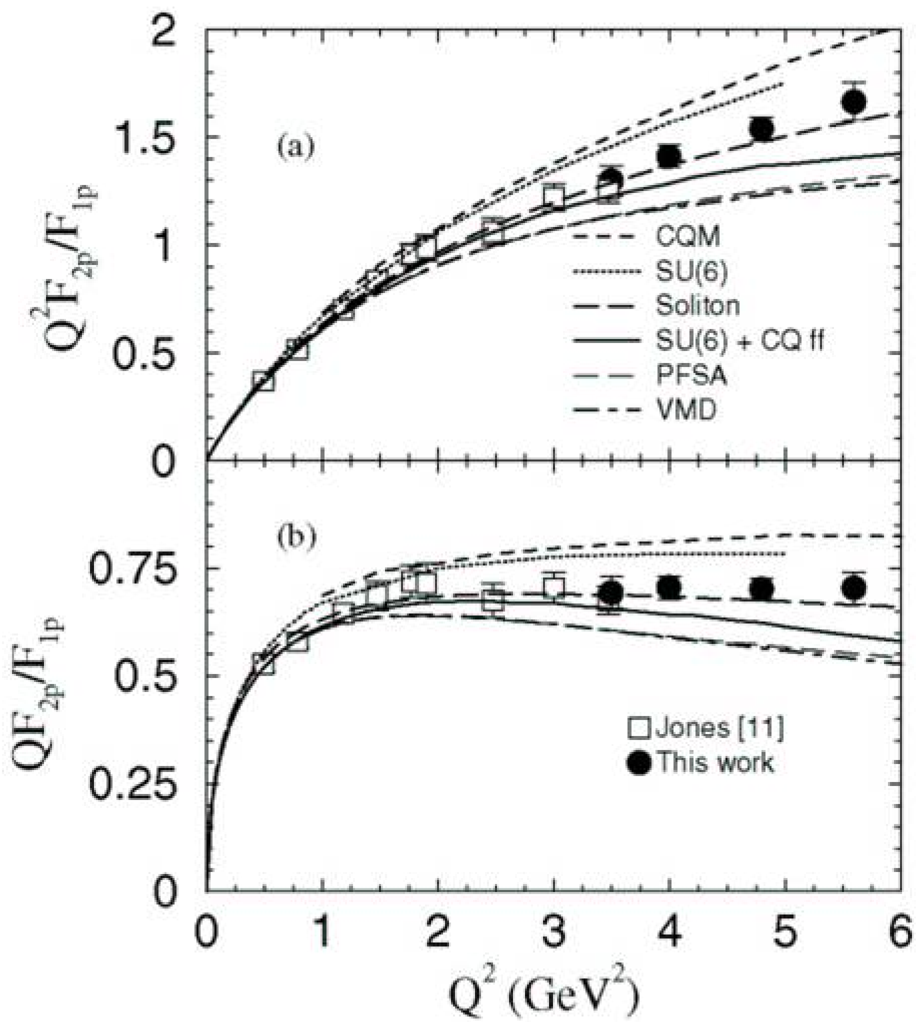
using measurements of recoil proton polarization in Hall A with

$$\vec{e} + p \rightarrow e + \vec{p}$$

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

→ Difference in the spatial distribution of charge and magnetization currents in the proton

Proton EM Form Factor Ratio F^p_2 / F^p_1 : pQCD predictions



pQCD prediction: As $Q^2 \to \infty$

$F^p_1 \propto 1/Q^4$ $F^p_2 \propto 1/Q^6$

$Q^2 F^p_2 / F^p_1 \to$ constant

$\to$ not being reached yet

Ralston, *et al.* suggested different scaling behavior:

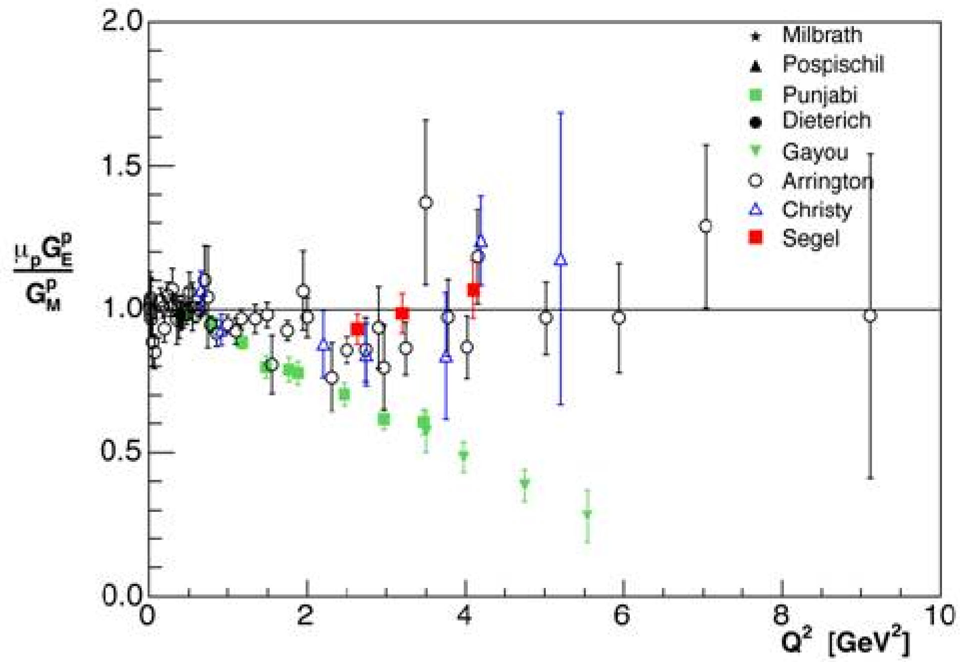
$F^p_2 / F^p_1 \propto 1/Q$

when quark orbital angular momentum included

Comparison of Polarization Transfer and Rosenbluth Techniques

Recent work on Rosenbluth:

- reanalyis of old SLAC data (Arrington)
- reanalysis of old JLAB data (Christy)
- new "Super-Rosenbluth" measurement in Hall A (Segel, Arrington)



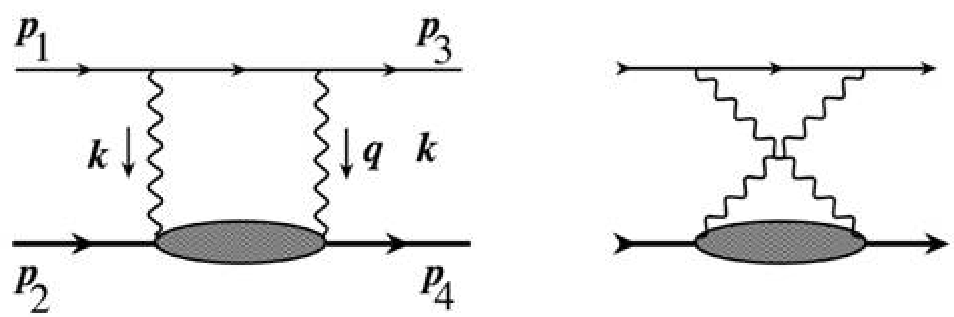
Conclusion:

- No problem with Rosenbluth
- No problem with polarization transfer

What about radiative corrections?
Have 2-photon graphs been underestimated in the past?

M. Vanderhaeghen and others say YES.

Using the G_E^p and G_M^p from polarization transfer and improved calculation of two photon graphs, they can reproduce the Rosenbluth results.



Still an active area, more later if time...

Neutron Electric Form Factor

Data from:
beam-target asymmetries
recoil polarization
in:

$\vec{d}\,(\vec{e}, e'\,n)$

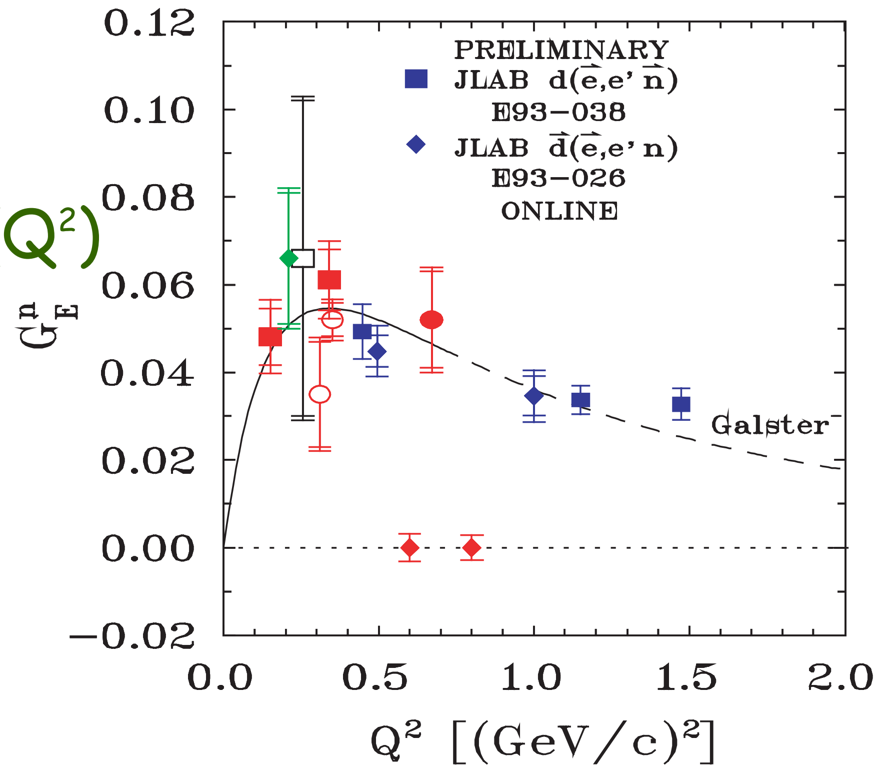
$d\,(\vec{e}, e'\,\vec{n})$

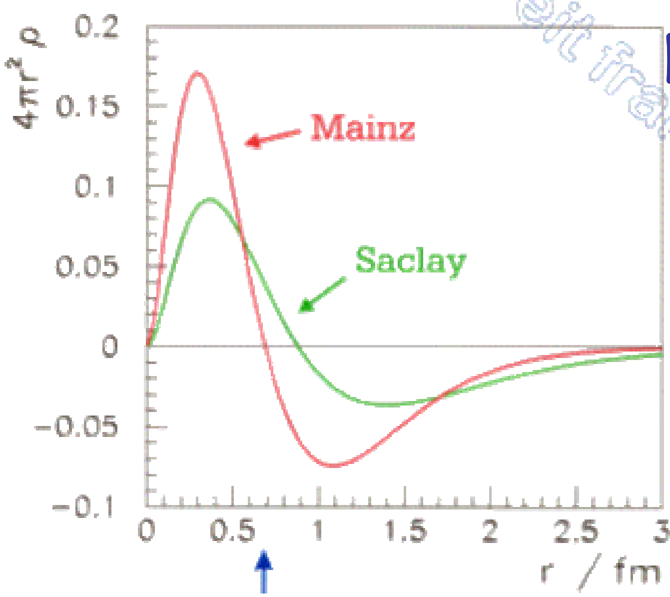
$^3\vec{He}\,(\vec{e}, e'\,n)$

at:

Mainz MAMI
Jefferson Lab
NIKHEF
MIT-Bates

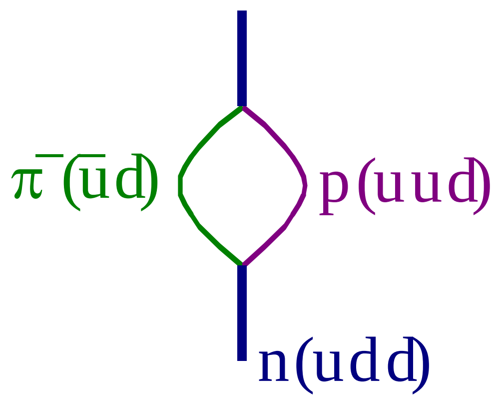
$G^n_E(Q^2)$



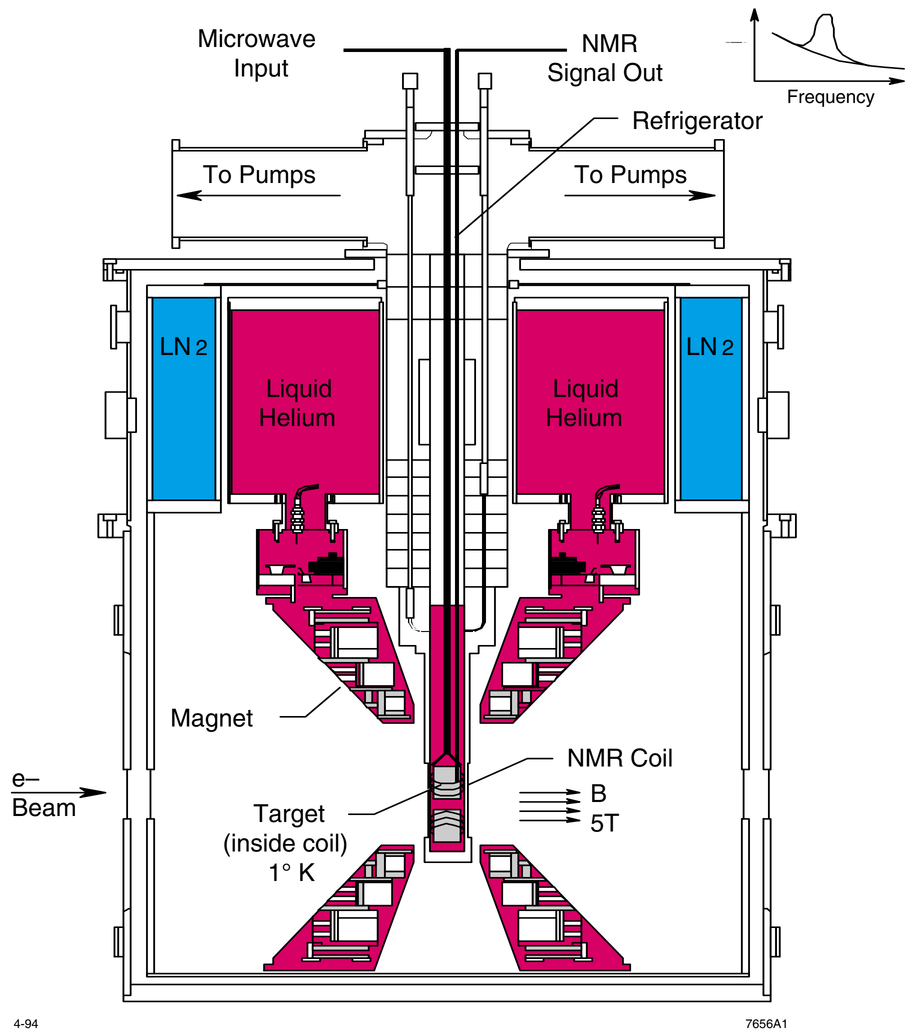


! Breit frame !

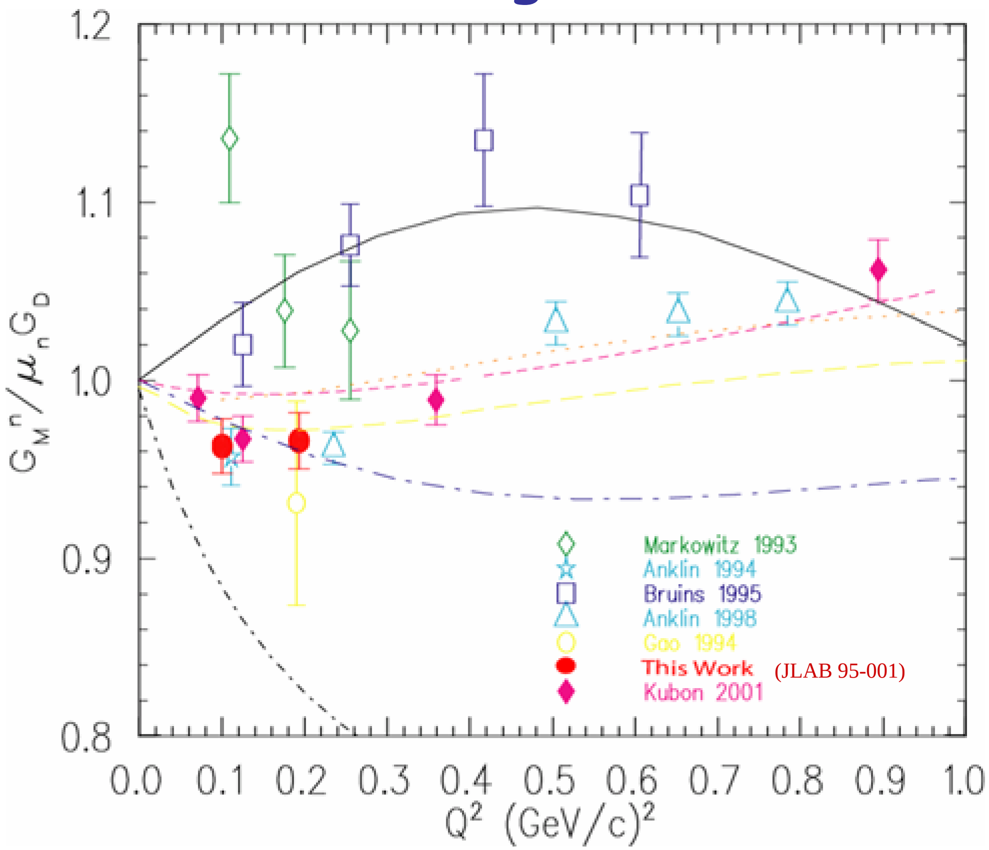
Neutron Electric Charge Distribution



ND_3 DNP Polarized Target Apparatus of JLAB E93-026



Neutron's Magnetic Form Factor G^n_M : Current Status



The most precise recent data comes from ratio measurements:

$$\frac{\sigma(d(e,e'n))}{\sigma(d(e,e'p))}$$

at NIKHEF/Mainz (Anklin, Kubon, et al.)
and ELSA at Bonn (Bruins, et al.)

Large (8-10%) systematic discrepancy between the two data sets : likely due to error in neutron detection efficiency

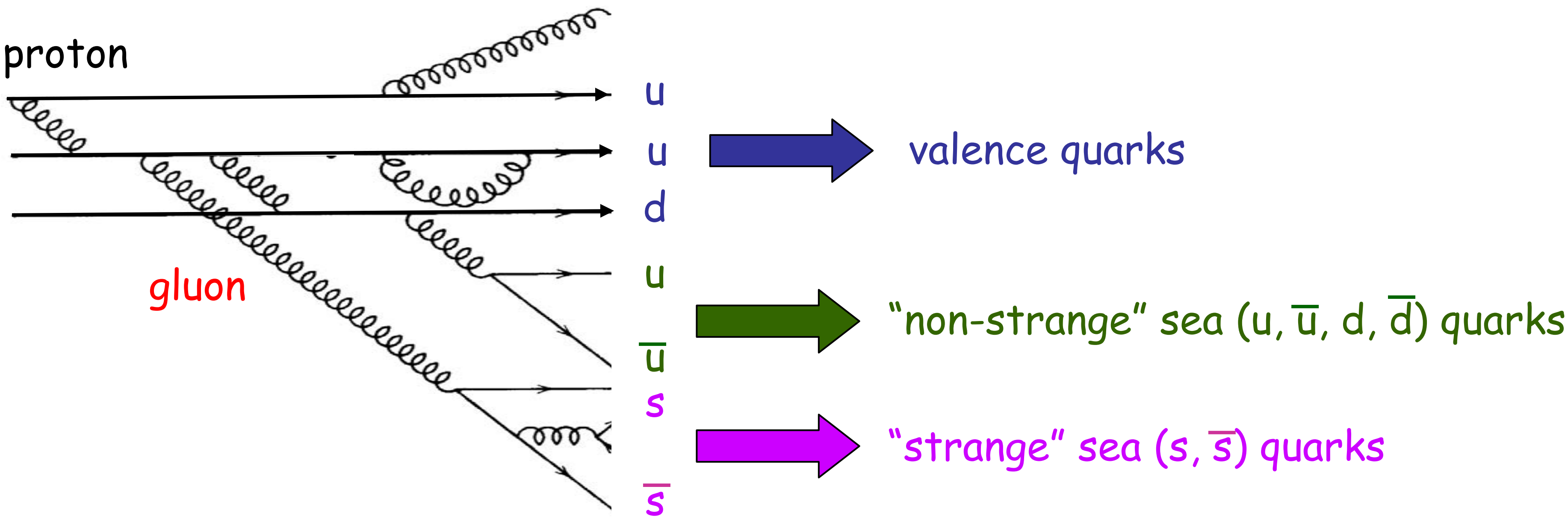
Newest data: JLAB 95-001 (Xu, et al. 2000) $^3\overrightarrow{He}(\vec{e}, e')$ in Hall A
agrees with NIKHEF/Mainz data at Q^2 = 0.1, 0.2 GeV^2
→ more data exists (Q^2 = 0.3 - 0.6 GeV^2) but requires improved nuclear corrections (relativistic effects need to be included)

How can we get the nucleon form factors theoretically?

Quantum chromodynamics (QCD): believed to be the correct theory of strong interactions

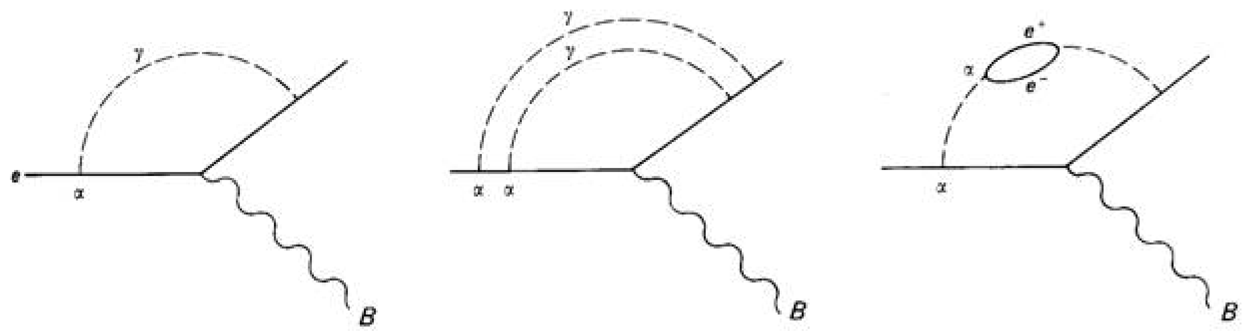
- quarks (3 colors for each)   inteacting via exchange of
- gluons (8 types)

Until recently only stable objects were mesons (2 quark) and baryons (3 quark)

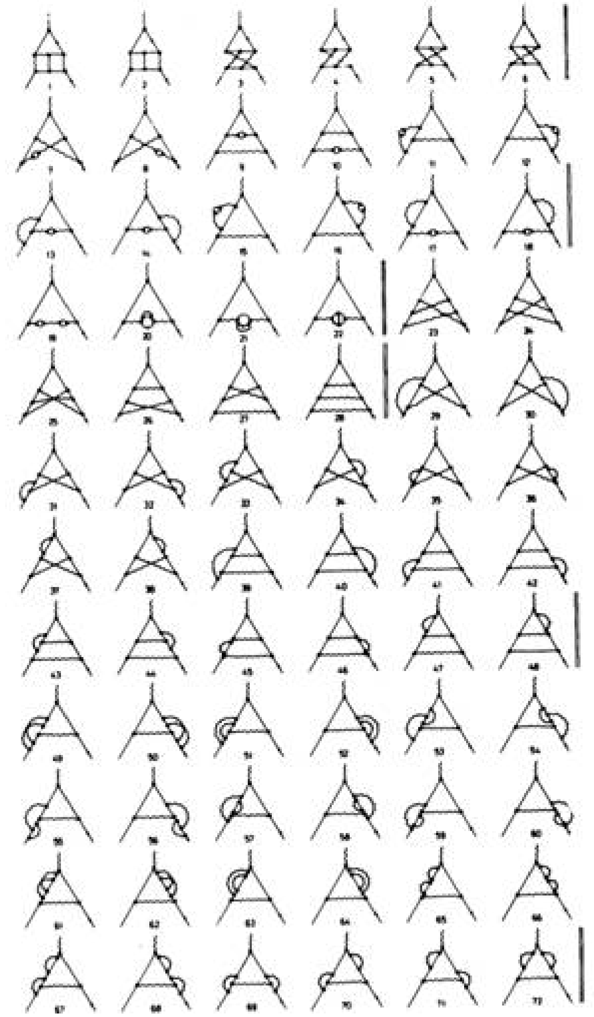


So we know the constituents of the proton, we have a quantum field theory for their interaction → why can't we solve for its structure?

Calculation of Electron's Magnetic Moment in QED



(a) (b) (c)



Quantum Electrodynamics (QED):
theory of interacting electrons and photons

perturbation expansion in $\alpha \sim 1/137$

$((g-2)/2)_{theory} = (115965230 \pm 10) \times 10^{-11}$

$((g-2)/2)_{experiment} = (115965219 \pm 1) \times 10^{-11}$

agreement at 1 part in 10^8 level

Non-perturbative QCD

Quantum Chromodynamics (QCD):
theory of interacting quarks and gluons

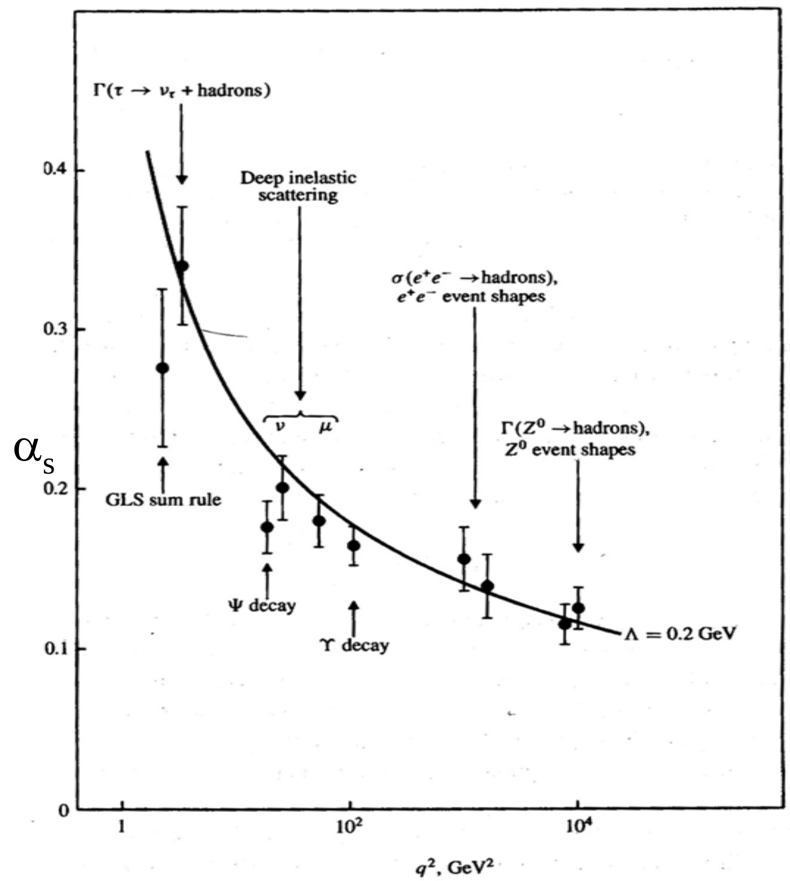
For quarks inside the nucleon,
typical momenta q ~ 0.3 GeV/c

$\rightarrow \alpha_s \sim 1$ cannot solve perturbatively

(unlike QED where $\alpha \sim 1/137$)

Eventually, lattice QCD should provide the solution;
In meantime we can measured well-defined nucleon properties that will serve as benchmarks for lattice QCD

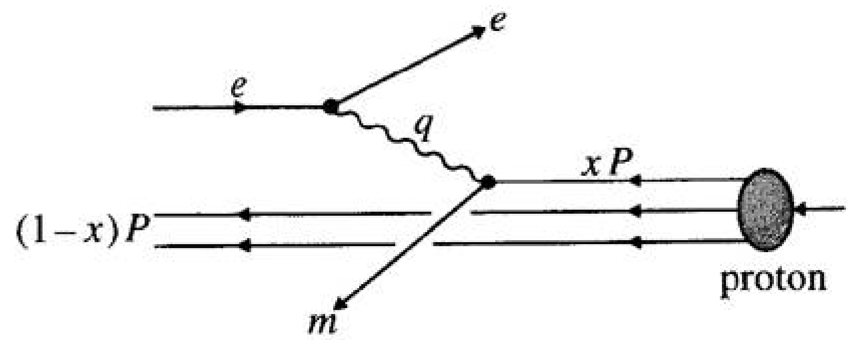
QCD(running of α_s)



like the sea of strange quarks, for example!

Do Strange Quarks Contribute to Nucleon Properties?

Deep inelastic scattering,
contributions of constituents (partons)
to total momentum of proton:



valence quarks: u_V 21%
d_V 9%

sea quarks: $(u+\bar{u})$: 7% $(d+\bar{d})$: 8% $(s+\bar{s})$: 5%
$(c+\bar{c})$: 3% $(b+\bar{b})$: 1%

gluons: 46%

$$\nu_\mu + s \rightarrow c + X + \mu^-$$

$$c \searrow \mu^+ + \nu_\mu$$

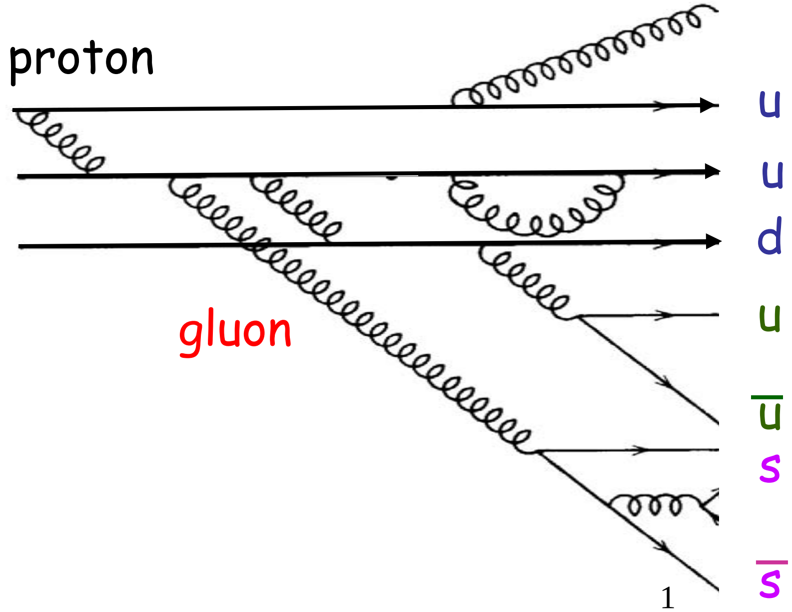
Proton spin:
measured in polarized deep
inelastic scattering

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q + J_g$$

$$\Delta u + \Delta d + \Delta s = 0.30 \pm 0.10$$
$$\Delta s = -0.1 \pm 0.03$$

→ "Proton spin crisis"

What role do strange quarks play in nucleon properties?



→ valence quarks

→ "non-strange" sea (u, $\bar{u}$, d, $\bar{d}$) quarks

→ "strange" sea (s, $\bar{s}$) quarks

Momentum: $\int_0^1 x(s+\bar{s})dx \sim 4\%$ (DIS)

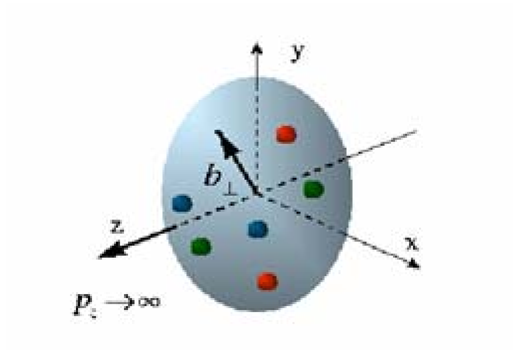
Spin: $< N|\bar{s}\gamma^5 s|N > \sim -10\%$ (polarized DIS)

Mass: $< N|\bar{s}s|N > \sim 30\%$ (πN σ - term)

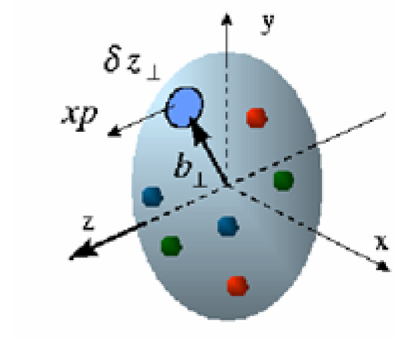
Charge and current: $< N|\bar{s}\,\gamma^\mu s|N > \; = \; ?? \;\rightarrow\; G_E^s \;\; G_M^s$

Main goal of these experiments : To determine the contributions of the strange quark sea ($\bar{s}$ s) to the electromagnetic properties of the nucleon ("strange form factors").

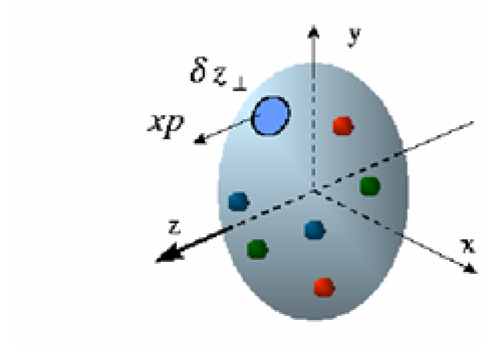
The complete nucleon landscape - unified description



Elastic scattering:
transverse quark distribution
in coordinate space



Deep exclusive scattering (DES):
Generalized parton dist. (GPD):
fully-correlated quark distribution
in coordinate and momentum space



Deep inelastic scattering (DIS):
longitudinal quark distribution
in momentum space

Electric and magnetic form factors well-measured

$G_E \quad G_M$ for p, n

BUT quark flavor decomposition of these form factors is not yet known

$G^u_{E,M} \qquad G^d_{E,M} \qquad G^s_{E,M}$

Measured nucleon momentum fractions

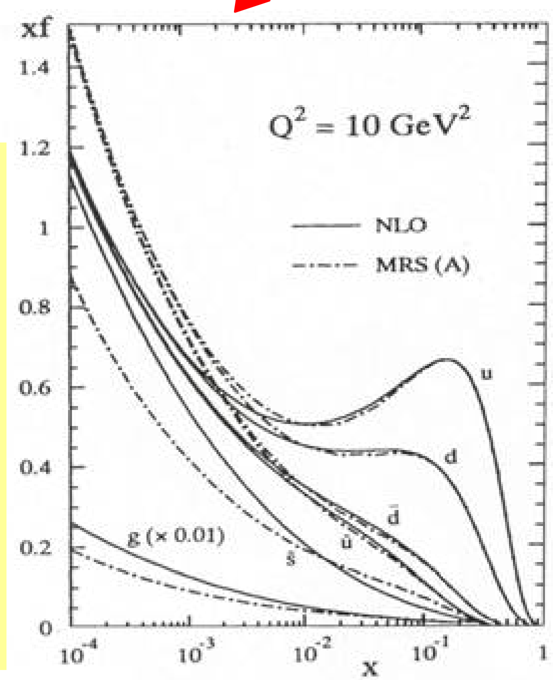
$(Q^2 = 2\,\mathrm{GeV}^2)$:

$\varepsilon_{u+\bar{u}} \sim 37\%$

$\varepsilon_{d+\bar{d}} \sim 20\%$

$\varepsilon_{s+\bar{s}} \sim 4\%$

$\varepsilon_{glue} \sim 39\%$



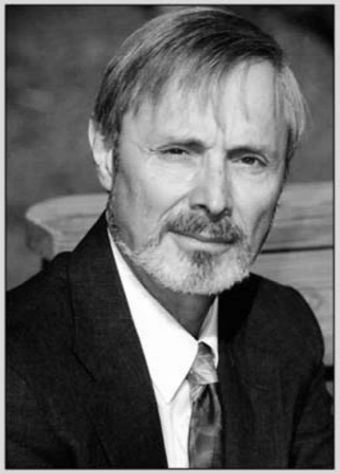
The question to be answered by this research:

How does the sea of strange quarks ($s\bar{s}$ pairs) inside the proton (or neutron) contribute to its electromagnetic properties: G^p_E, G^p_M, G^n_E, G^n_M?

$\rightarrow$ Let's measure the strange form factors G^s_E, G^s_M directly and find out.

JLAB "contracted" to understand nuclei

In 1993 Congress passed and the President signed into law the Government Performance and Results Act (GPRA); and as a consequence, we are being held more and more stringently to meet certain objective, quantifiable, and measurable goals. Our performance based contract with the Department of Energy is an expression of this thinking, and future goals for the Office of Science include not only objectives for reliable facility operations but the achievement of scientific objectives, such as describing by 2015 the properties of nucleons and light nuclei in terms of properties and interactions of quarks and gluons.



Christoph Leemann
Jefferson Lab Director

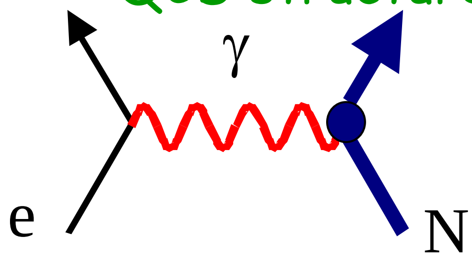
From the Director

Performance management: The basis of continuous improvement

Nucleon form factors measured in elastic e-N scattering

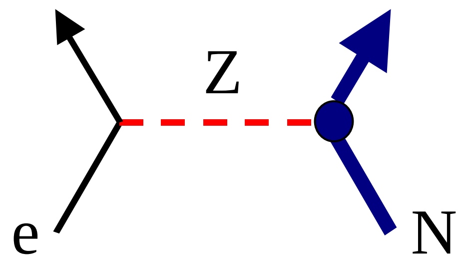
Nucleon form factors

- well defined experimental observables
- provide an important benchmark for testing non-perturbative QCD structure of the nucleon



$$< N | J_\mu^\gamma | N > \quad \rightarrow \quad G_E^\gamma , G_M^\gamma$$

electromagnetic form factors



$$< N | J_\mu^Z | N > \quad \rightarrow \quad G_E^Z , G_M^Z$$

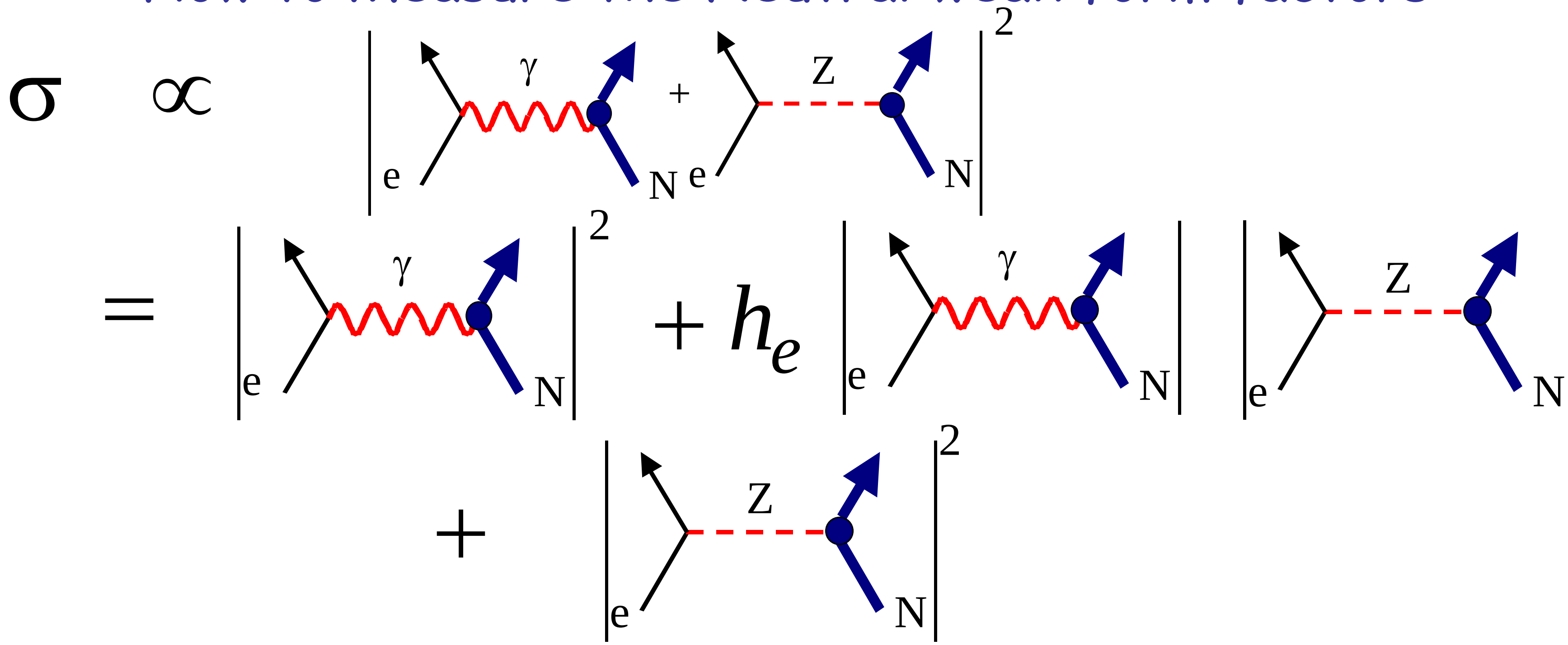
neutral weak form factors

- Measured precision of EM form factors in 0.1 - 1 GeV^2 Q^2 range ~ 2 - 4%
- Projected precision of NW form factors in 0.1 - 1 GeV^2 Q^2 range ~ 10% from the current generation of experiments (for magnetic)

where the nucleon wavefunction is:

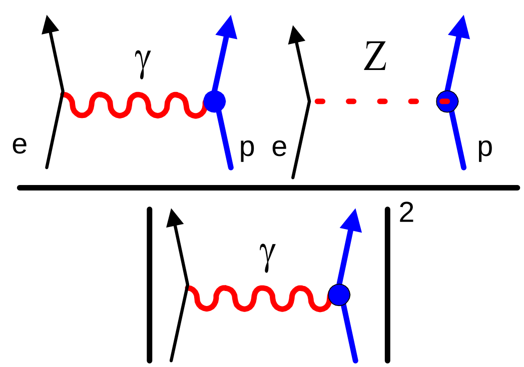
$$| N > \; = \; | uud > + | uudg > + | uuds\bar{s} > + | uudu\bar{u} > + ...$$

How to Measure the Neutral weak form factors



$\vec{e} + N$
(elastic scattering)

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



$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \times (\text{form factors}) \approx 10^{-5} - 10^{-6}$$

Derive the Parity-Violating Asymmetry (hand-waving)

$$J_\mu^{EM,e} = Q_e \overline{\psi}_e \gamma_\mu \psi_e = Q_e V_\mu^{EM,e} \qquad J_\mu^{NC,e} = \left(-1+4\sin^2\theta_W\right)\overline{\psi}_e\gamma_\mu\psi_e + \overline{\psi}_e\gamma_5\gamma_\mu\psi_e = g_V^e V_\mu^{NC,e} + g_A^e A_\mu^{NC,e}$$

$$J_\mu^{EM,N} = V_\mu^{EM,N} \qquad J_\mu^{NC,N} = V_\mu^{NC,N} + A_\mu^{NC,N}$$

$$M_{EM} \sim \left(\frac{1}{Q^2}\right) Q_e V_\mu^{EM,e} V_\mu^{EM,N}$$

$$M_{NC} \sim \frac{G}{2\sqrt{2}}\left[g_V^e V_\mu^{NC,e} V_\mu^{NC,N} + g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + g_V^e V_\mu^{NC,e} A_\mu^{NC,N} + g_A^e A_\mu^{NC,e} A_\mu^{NC,N}\right]$$

$$M = M_{EM} + M_{NC}$$

Cross section proportional to:

$$|M|^2 = |M_{EM}|^2 + 2\,\mathrm{Re}(M_{EM}^* M_{NC}) + |M_{NC}|^2$$

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{2\,\mathrm{Re}(M_{EM}^* M_{NC}^{PV})}{|M_{EM}|^2 + \ldots}$$

$$= \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_V^e V_\mu^{NC,e} A_\mu^{NC,N}\right)}{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N}\right)^2}$$

Derive the Parity-Violating Asymmetry (hand-waving), cont.

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_V^e V_\mu^{NC,e} A_\mu^{NC,N}\right)}{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N}\right)^2}$$

$$\boxed{A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{2\sigma_{unpol}}}$$

$$A_E = \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2)$$
$$A_M = \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2)$$
$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2)$$

$\tau = Q^2/4M^2$

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

Now how do the neutral weak form factors G_E^Z and G_M^Z give us information about the strange form factors?

First some notation

Recall, we defined the nucleon Dirac and Pauli form factors through :

$$\left\langle N \mid J_\mu^\gamma \mid N \right\rangle = \bar{u}_N \left(F_1^\gamma(Q^2)\gamma_\mu + F_2^\gamma(Q^2)\frac{i\sigma_{\mu\nu}q^\nu}{2M_N} \right) u_N$$

Define the nucleon form factors associated with a given quark current q as :

$$\left\langle N \mid \bar{q}\gamma_\mu q \mid N \right\rangle = \bar{u}_N \left(F_1^q\gamma_\mu + F_2^q\frac{i\sigma_{\mu\nu}q^\nu}{2M_N} \right) u_N$$

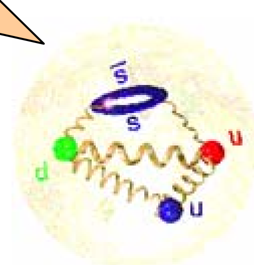
The Sachs form factors are then :

$$G_E^q = F_1^q - \tau F_2^q \quad G_M^q = F_1^q + F_2^q$$

Neutral weak form factors → strange form factors

STANDARD MODEL COUPLINGS

	q^γ	q^Z	a^Z
e	–1	$-1 + 4\sin^2\theta_W$	+1
u	+2/3	$1 - 8/3\sin^2\theta_W$	–1
d	–1/3	$-1 + 4/3\sin^2\theta_W$	+1
s	–1/3	$-1 + 4/3\sin^2\theta_W$	+1



$= \sum_i ($

A SEARCH FOR NEW PHYSICS

Qweak

E158

A precision measurement of the Weak Mixing Angle in Møller Scattering

Flavor decomposition of nucleon E/M form factors:

$$< p | J^{\gamma}_{\mu} | p >: \quad G^{\gamma,p}_{E,M} = \frac{2}{3} G^{u,p}_{E,M} - \frac{1}{3} G^{d,p}_{E,M} - \frac{1}{3} G^{s,p}_{E,M}$$

$$< n | J^{\gamma}_{\mu} | n >: \quad G^{\gamma,n}_{E,M} = \frac{2}{3} G^{u,n}_{E,M} - \frac{1}{3} G^{d,n}_{E,M} - \frac{1}{3} G^{s,n}_{E,M}$$

$$< p | J^{Z}_{\mu} | p >: \quad G^{Z,p}_{E,M} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G^{u,p}_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^{d,p}_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^{s,p}_{E,M}$$

Invoke proton/neutron charge symmetry → 3 equations, 3 unknowns

$$\left(G^{\gamma,p}_{E,M}, G^{\gamma,n}_{E,M}, G^{Z,p}_{E,M}\right) \Leftrightarrow \left(G^{u}_{E,M}, G^{d}_{E,M}, G^{s}_{E,M}\right)$$

Validity of charge symmetry breaking assumption

$$u \leftrightarrow d$$

$$G_{E,M}^{u,p} = G_{E,M}^{d,n} \qquad G_{E,M}^{d,p} = G_{E,M}^{u,n} \qquad G_{E,M}^{s,p} = G_{E,M}^{s,n}$$

Size of charge symmetry breaking effects in some n,p observables:

- n - p mass difference $\rightarrow$ $(m_n - m_p)/m_n$ ~ 0.14%
- polarized elastic scattering $\vec{n}$ + p, $\vec{p}$+n $\Delta A = A_n - A_p = (33 \pm 6) \times 10^{-4}$
  Vigdor et al, PRC 46, 410 (1992)
- Forward backward asymmetry n + p $\rightarrow$ d + π^0 $A_{fb} \sim (17 \pm 10) \times 10^{-4}$
  Opper et al., nucl-ex 0306027 (2003)

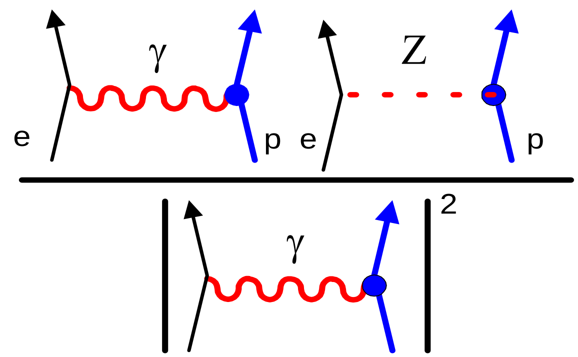
$\rightarrow$ For vector form factors theoretical CSB estimates indicate < 1% violations (unobservable with currently anticipated uncertainties)

(Miller PRC 57, 1492 (1998) Lewis and Mobed, PRD 59, 073002(1999)

Parity Violating Electron Scattering - Probe of Neutral Weak Form Factors

polarized electrons, unpolarized target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{2\sigma_{unpol}}$$



$$A_E = \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2)$$
$$A_M = \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2)$$
$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2)$$

$\rightarrow G_E^s$
$\rightarrow G_M^s$
$\rightarrow G_A^e$

Strange electric and magnetic form factors,
+ axial form factor

At a given Q^2 decomposition of G^s_E, G^s_M, G^e_A
Requires 3 measurements for full decomposition:

Forward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + d (quasi-elastic)