Strange Quarks in the Nucleon Sea

Konrad A. Aniol, Fall 2010

Physics and Astronomy

Outline

1) What are the fundamental “atoms” or elements of the world?

2) How do these elements combine to produce protons and neutrons (nucleons)?

3) What forces are important to understand the structure of the nucleons?

4) Why are nucleon masses so different in character from atomic masses?

5) How can we measure the charge and magnetization distributions in nucleons?

6) What type of experimental measurements are available at accelerator labs to find strange quark effects in nucleons.

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

1) Here is the particle physics table of the elements. http://pdg.lbl.gov/

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

2) Protons and neutrons are nucleons

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

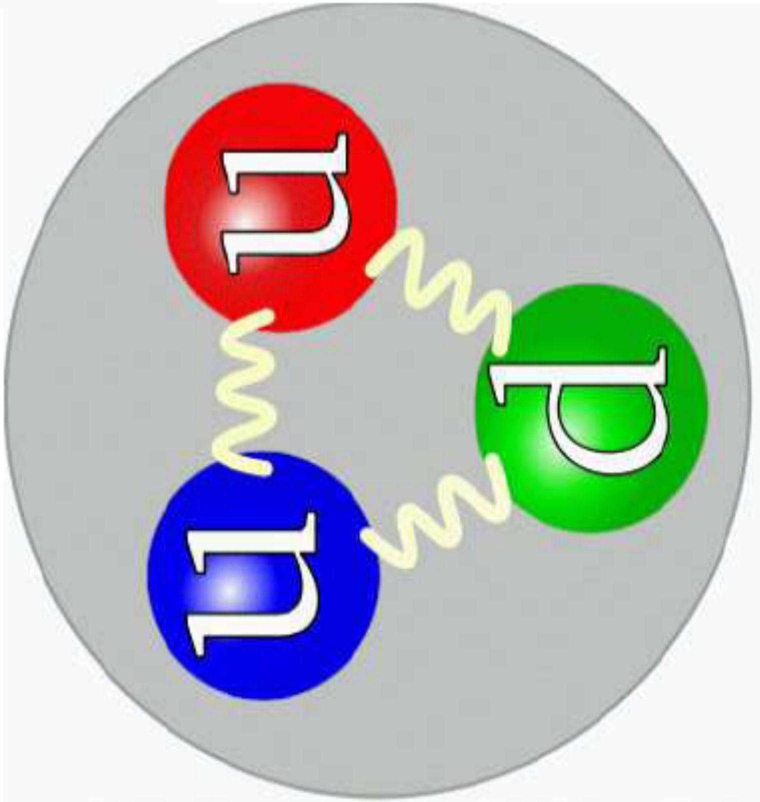
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

3) Important forces determining the structure of nucleons.

Gives us a third observable to see strange quarks contributions

Allows us to map the charge and magnetization in nucleons

Attraction between quarks and gluons – holds the nucleons together



In a simple model of three constituent quarks the quark masses are about 330 MeV.

proton

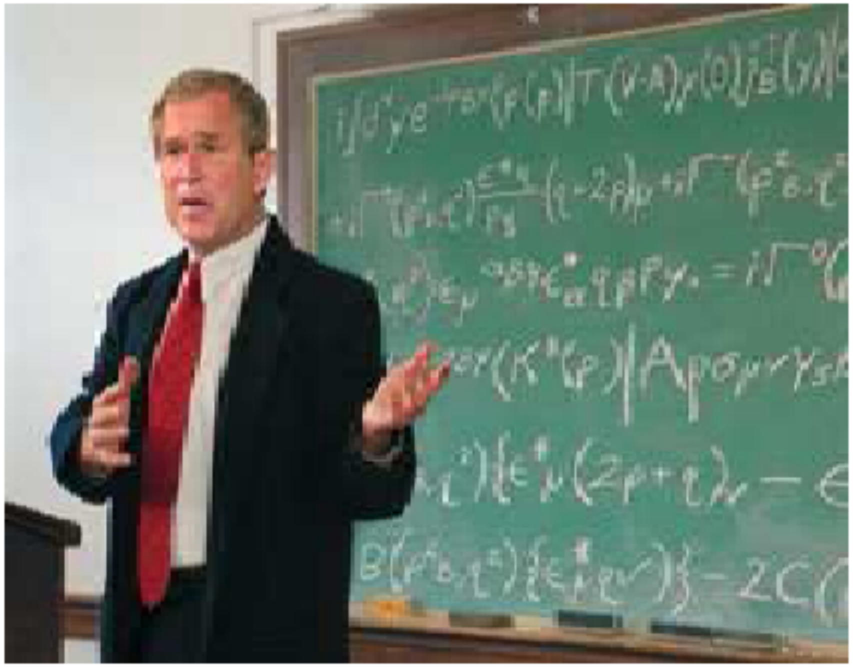
http://www.phys.anl.gov/theory/zfftr/08UND.pdf

How does this picture of constituent quarks compare to the measured proton mass?

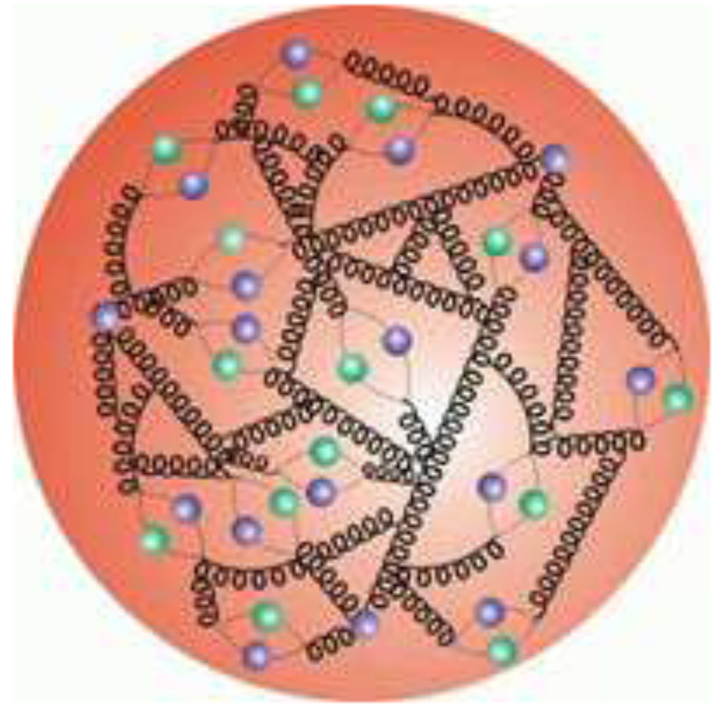
How do the masses of some systems compare to the masses of their constituents?

System	Sum mass of constituents MeV	True mass of system MeV	(true mass)/ (constituent)
Hydrogen atom, p + e	938.783 $+13.6 \times 10^{-6}$	938.783	0.999999986
^{12}C nucleus 6p + 6n + 6e	11270.088	11177.928	0.9918
Proton 2u + d	11	938.272	85.3

What is going on?

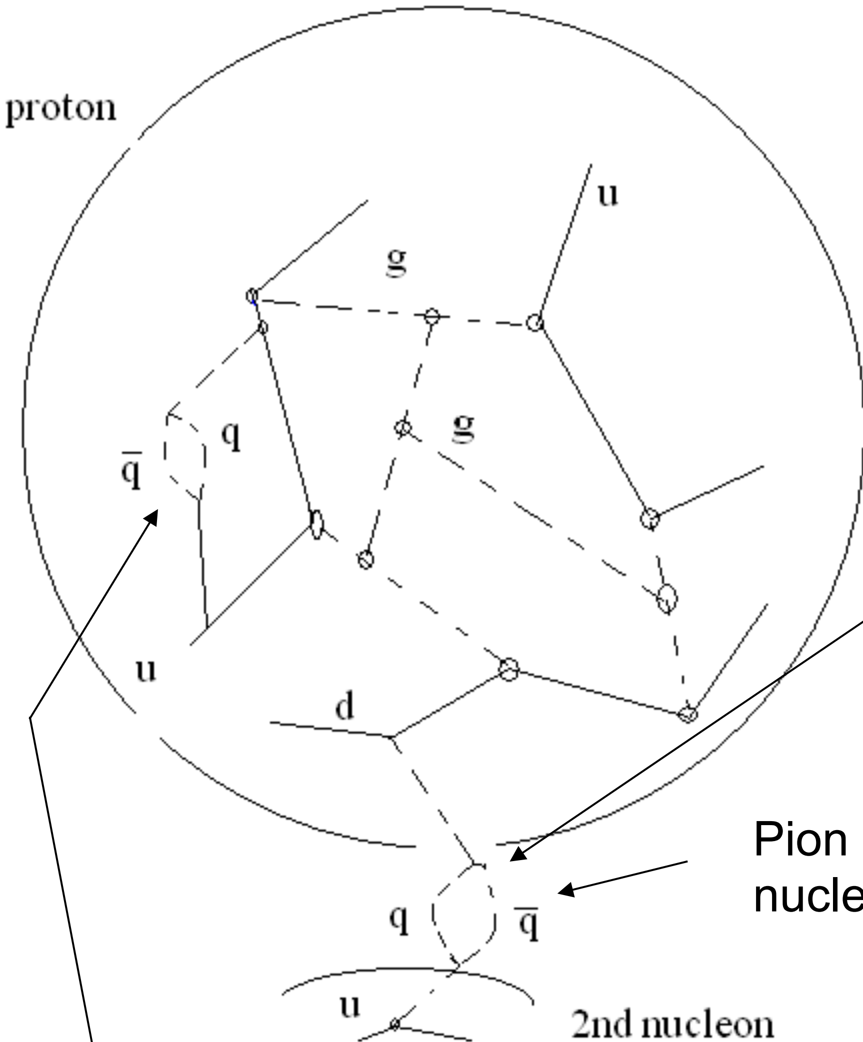


What is the explanation?



http://www.phys.anl.gov/theory/zfftr/08UND.pdf

4) The mass of the proton is very much larger than the masses of its 3 current quarks. We ascribe this to the existence of an intense gluon field inside the proton.



The strong gluon field, g, carries color and so gluons can interact with themselves as well as with the quarks, u and d. Most of the mass of the nucleon comes from the energy in the gluon field, $M=E/c^2$.

The quark – anti quark pairs are called sea quarks.

Pion cloud terms contributing to nucleon-nucleon interactions

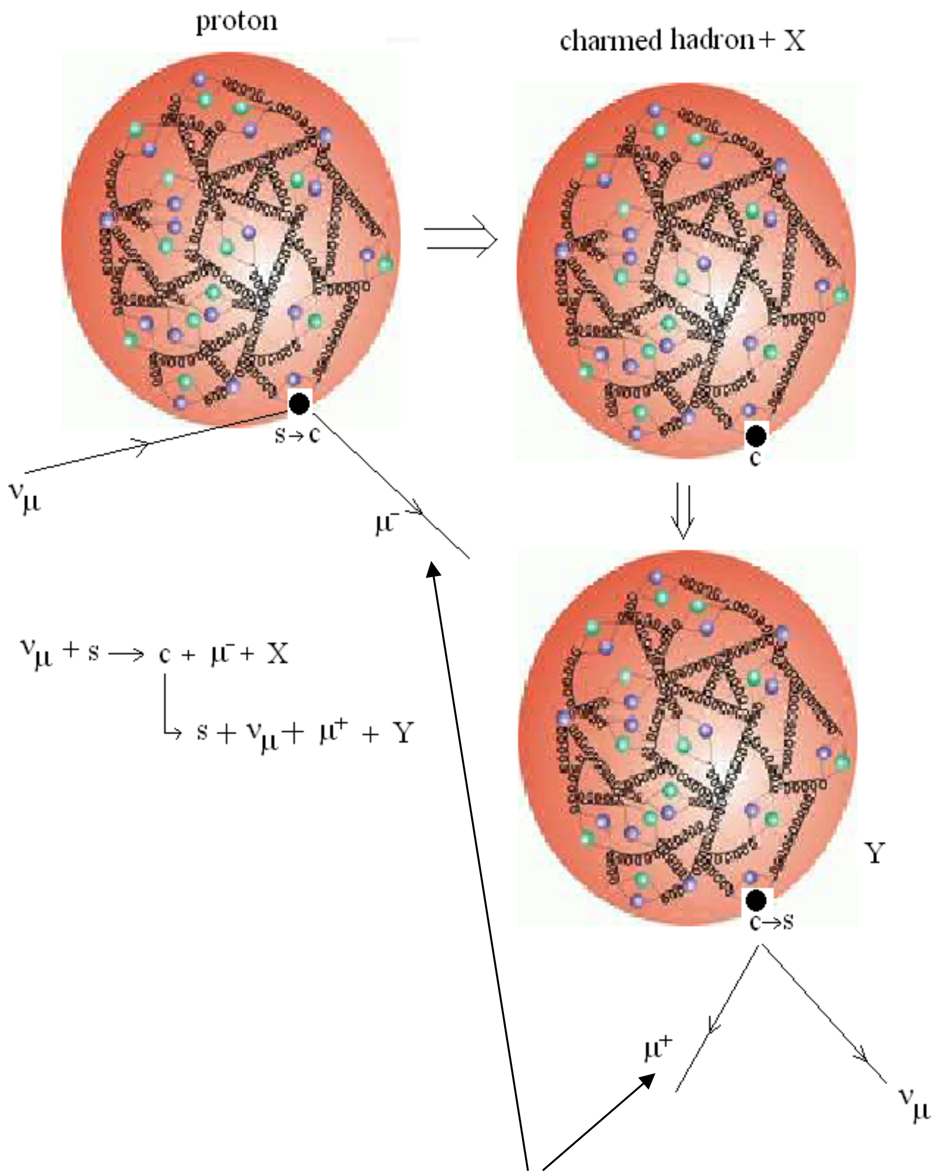
Gluons can also transform into q anti q pairs for a short time and then collapse back into a gluon. This produces evanescent electric dipoles inside the nucleon.

4)The strong gluon field supplies the nucleon mass and the quark-anti quark transitory pairs.

Why do we expect to find strange-anti strange, s - anti s, quarks in the nucleon?

The creation and propagation of q-anti q pairs depends on the masses of the quarks. The low mass quarks, u, d, s, are expected to be the principle products of the gluon “vacuum polarization” process.

The existence of the sea of strange-anti strange quarks is demonstrated by the production of particles with charm quarks when the proton is bombarded by muon neutrinos. An experimental signal is the production of simultaneous positive and negative muons.



$$\nu_\mu + s \longrightarrow c + \mu^- + X$$
$$\hookrightarrow s + \nu_\mu + \mu^+ + Y$$

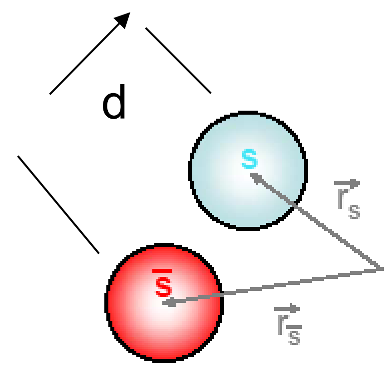
negative and
positive muons

The neutrino data tell us the sea exists. Can we measure some other effects of the strange quark sea?

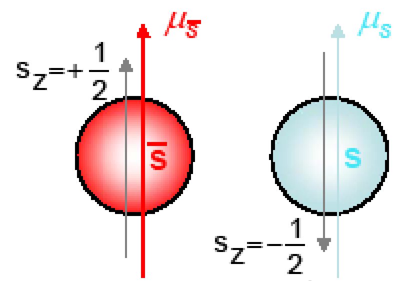
Electric dipole =d*q

q = -e/3

G_E^s, G_M^s Non-Zero?



- charge distribution
  - if s, $\bar{s}$ are separated, non-zero net contribution
- convection current
  - if s, $\bar{s}$ are separated, non-zero net contribution

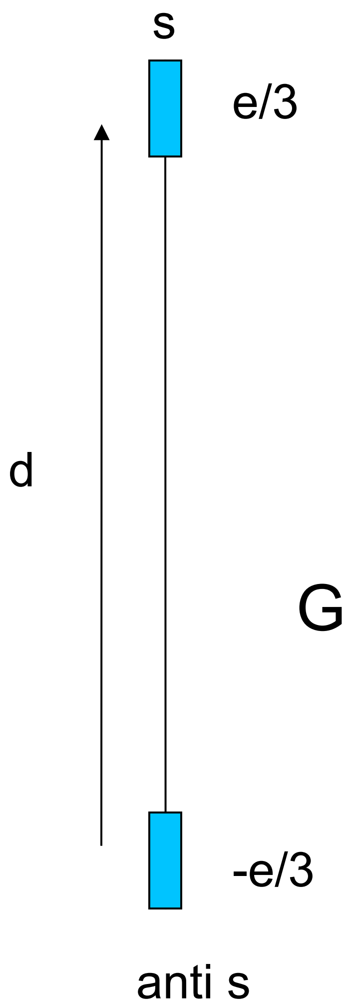


- spin current
  - spin triplet: moments cancel
  - spin singlet: zero net moment, zero net convection
  - *also requires separation*

From Doug Beck's talk

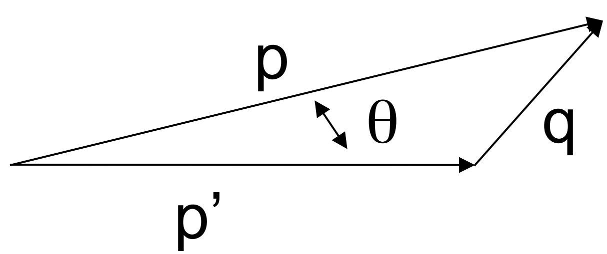
Magnetic dipole contributions from convection and quark spins.

Can we measure the contribution to the electric form factor (G_E) from the strange sea quarks?



We measure the elastic scattering of electrons on the proton at different values of momentum transfer, $\underline{q}$. This gives us $G_E(q)$ which is related to the electric charge distribution, $\rho(r)$.

$$G_E(q) = \int \rho(r)\exp(i\underline{q}.\underline{r}) \approx \frac{1}{2\pi}\sin(qd/2)$$



p = incident momentum

p'= scattered momentum

q = momentum transfer

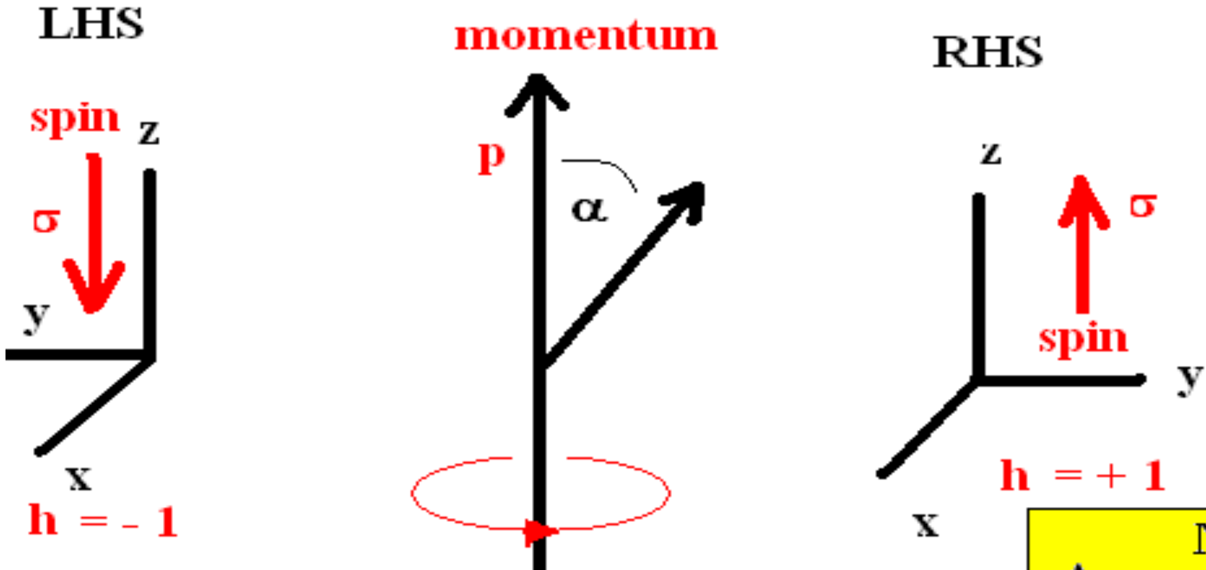
In the nucleon we have 3 sources of electric charge density, $\rho_{nucleon}$, from the u, d and s quarks.

$$\rho_{proton} = 2\rho_u + \rho_d + \rho_s$$

$$\rho_{neutron} = \rho_u + 2\rho_d + \rho_s$$

When the electron scatters off the nucleon it only senses the total charge density. How can we distinguish between the three sources, u, d, s, of charge density?

In order to extract all three charge distributions we need a third measurement. This is provided by scattering electrons off protons and looking for the effects due to the weak interaction.



$$A = \frac{N(h+) \; - N(h-)}{N(h-) \; + N(h+)}$$

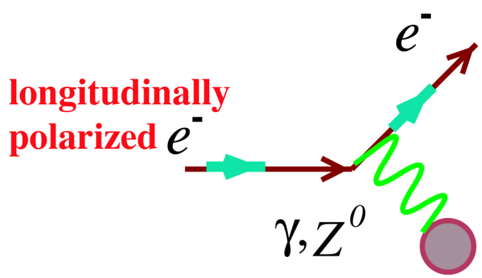
$$h = \frac{\vec{\sigma}\,.\vec{p}}{|\sigma|\,|p|} = \text{helicity}$$

Electrons are scattered from the target at an angle α . For the weak interaction the probability to scatter depends on the helicity, which depends on the orientation of the momentum and spin σ . The definition of the spin direction depends on the "handedness" of the coordinate system used. For electromagnetic scattering the probablity of scattering is independent of helicity.

Looking for a signal from the weak interaction.

Neutral Currents and Weak-Electromagnetic Interference

The weak boson Z^0 causes the cross section, σ, to depend on the helicity, h, of the scattered electron. h = spin·momentum.



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

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F\, Q^2}{4\,\pi\,\alpha}$$

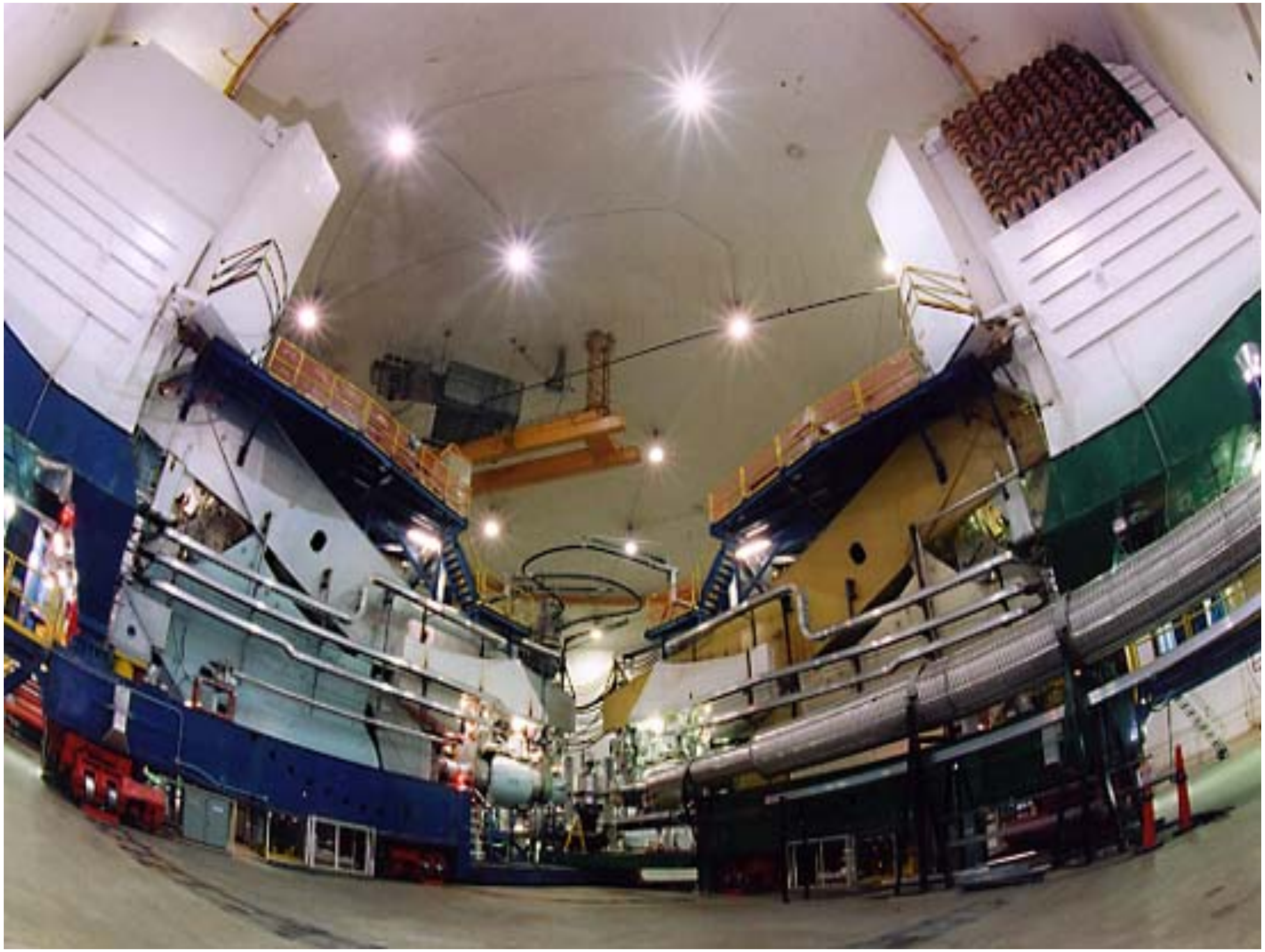
$$Q^2 \sim 0.01 - 1\ \mathrm{GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

The helicity asymmetry measurement demands precision control of the total electron transport and detection systems.

Lab/Expt	target	Q^2 GeV^2	A_{phys} ppm	Sensitivity	Status
MIT-Bates					
- SAMPLE	H_2	0.10	8.0	$\mu_s + 0.4 G_A^Z$	published
- SAMPLE-II	D_2	0.10	8.0	$\mu_s + 2.0 G_A^Z$	published
- SAMPLE-III	D_2	0.04	3.0	$\mu_s + 3.0 G_A^Z$	completed
JLab Hall A					
-HAPPEX	H_2	0.47	15.0	$G_E^s + 0.39 G_M^s$	published
-HAPPEXII	H_2	0.11	1.5	$\rho_s + \mu_p \mu_s$	published
-Helium-4	^4He	0.11	10.0	ρ_s	published
-Helium-4	^4He	0.60	50.0	G_E^s	published
-Lead-208	^{208}Pb	0.01	0.5	neutron skin	Ran in spring, 2010. Analysis in progress.
Mainz					
- A4	H_2, D_2	0.1-0.25	1.0-10.0	G_E^s, G_M^s	running
Jlab Hall C					
- G0	H_2, D_2	0.1-1.0	1.0-30.0	G_E^s, G_M^s	published
- Qweak	H_2	0.03	0.3	Qw	running

JLab, Hall A

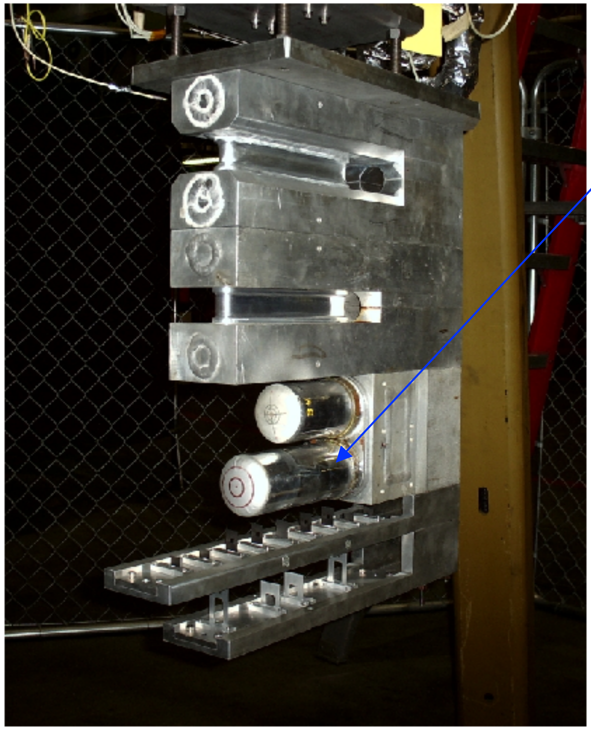
HAPPEX III, $Q^2 = 0.6$ GeV^2 ran in Fall 2009. The data are still being analyzed by the graduate students. We hope to have results by Christmas of 2010.



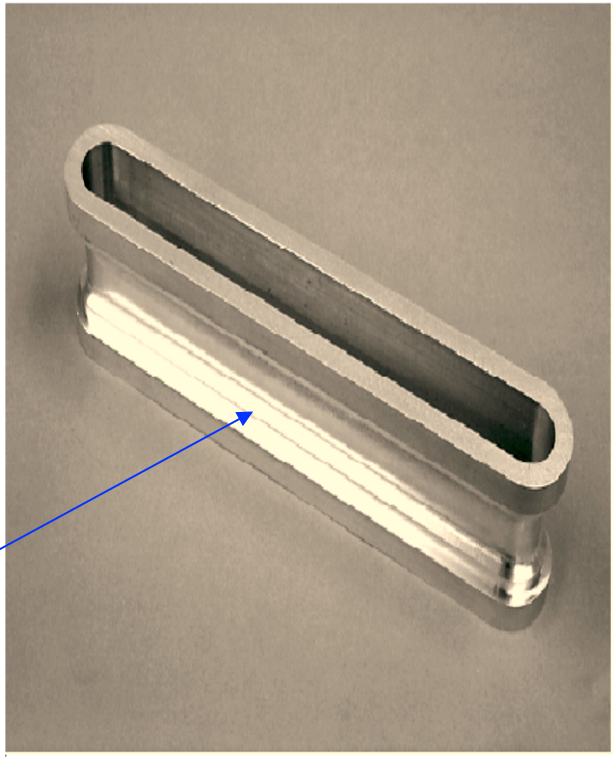
JLab, Hall A
high resolution
spectrometers

High Resolution Spectrometer, Hall A. Note man.

Target cells for HAPPEX

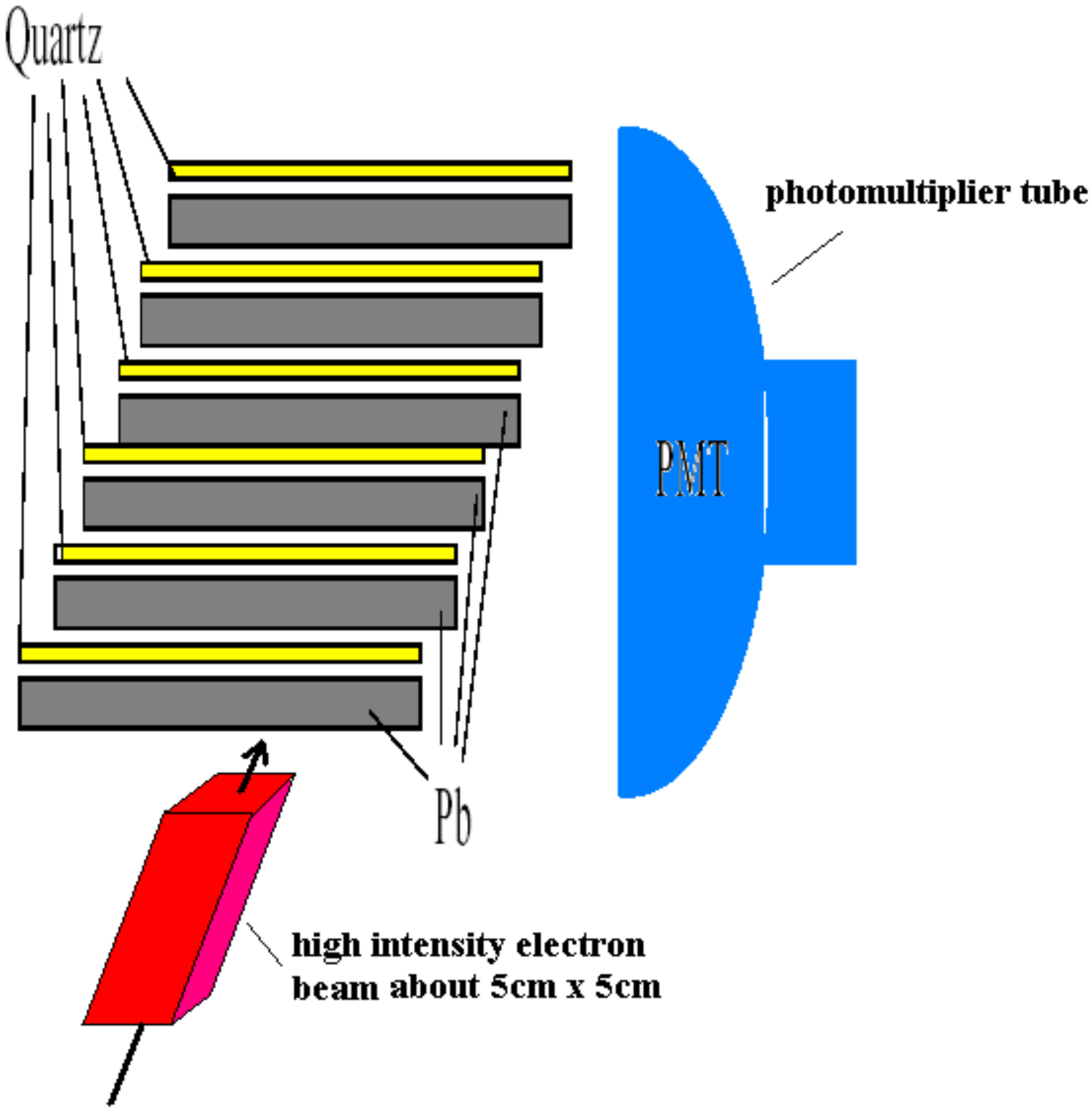


"Beer can", as used in HAPPEX-I

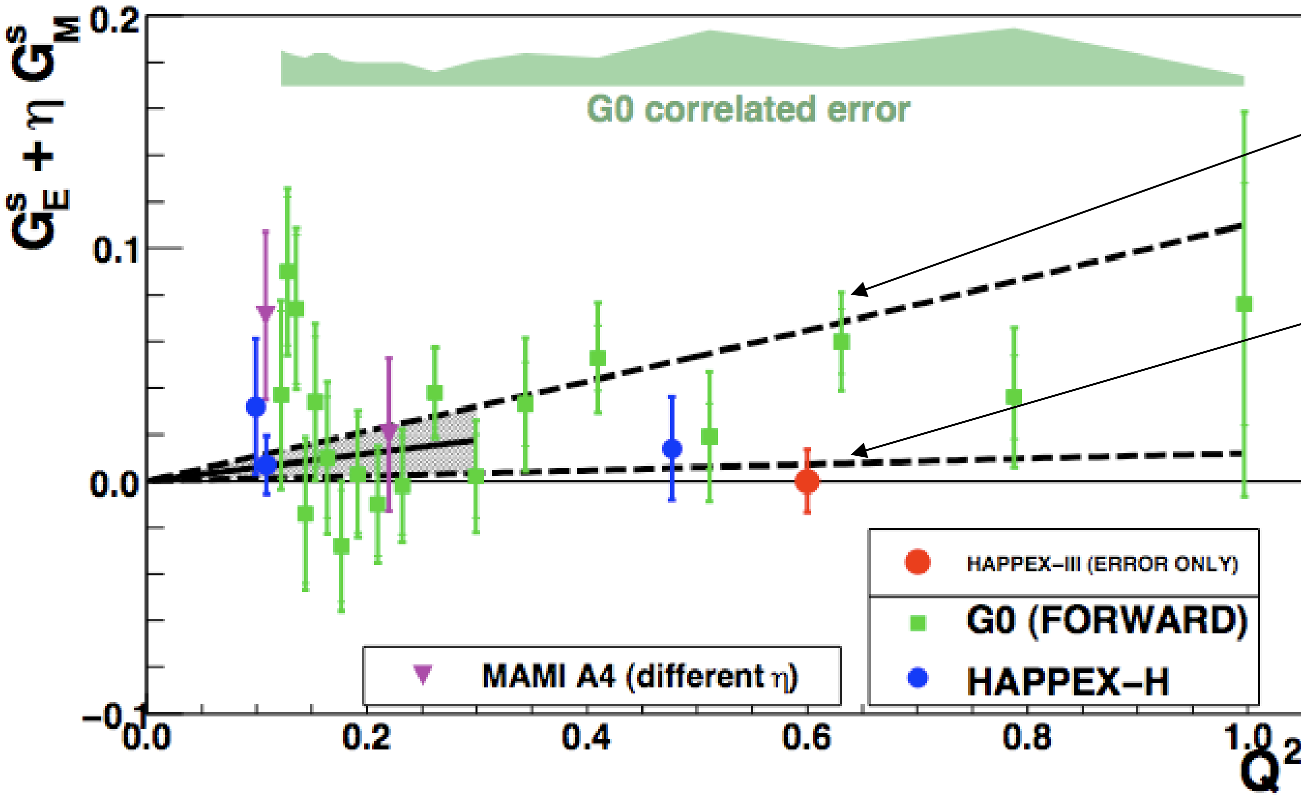


New "race track" design

Race track design and prototype done at CSULA by D. J. Margaziotis and R. Johnson.

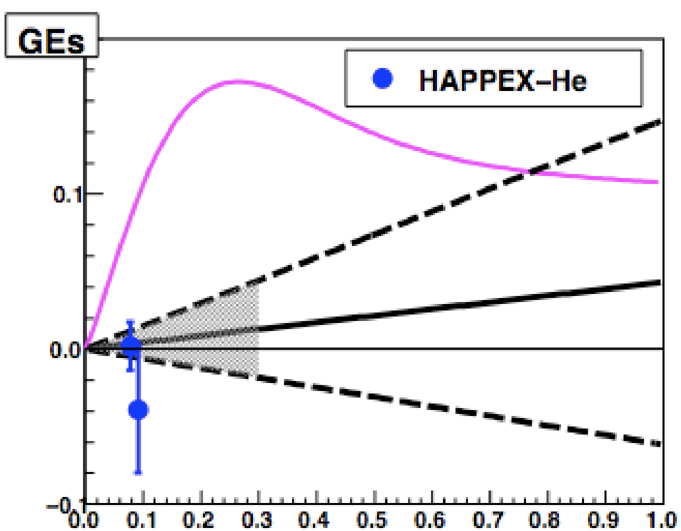


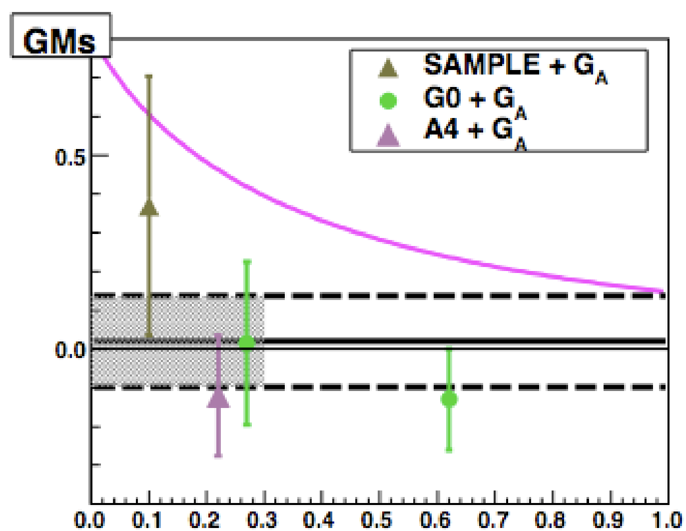
The very high rates of electron scattering at 6 degrees makes counting individually scattered electrons experimentally impossible. The HAPPEX collaboration measures the integrated rate of electrons by observing the light from the quartz rods.



Is the form factor this big?

Expected error bar from HAPPEX III.



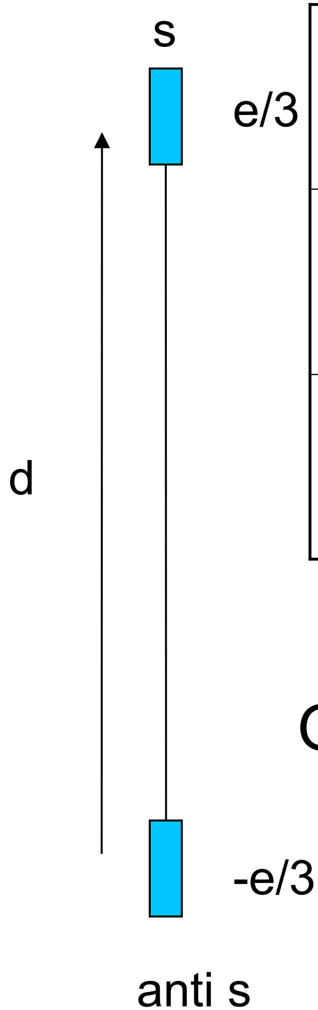


$\tau = Q^2/(4m_p{}^2)$ $\quad\quad$ $G_{Es,0} = -0.8 \pm 0.95$

$$G_{Es}(Q^2) = \frac{\tau}{(1 + 5.6\tau)} \frac{G_{Es,0}}{(1 + Q^2/(0.71)^2\ )^2}$$

D. Beck fit to world hydrogen data of strange quark contribution to the electric form factor of the proton

Simple Model
Can we measure the contribution to the electric form factor (G_E) from the strange sea quarks?



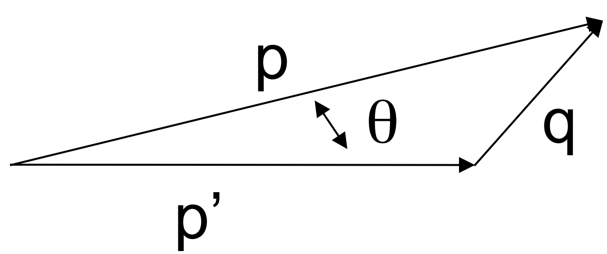
Q^2 $(GeV/c)^2$	G_E	d F(10^{-13}cm)
0.1	-0.002 ± 0.017	<0.016
0.6	-0.02 D. Beck fit	≈ 0.06

Size of proton ≈ 1F

HAPPEX II result

Mostly from G0

$$G_E(q) = \int \rho(r) \exp(i\underline{q}.\underline{r}) \approx \frac{1}{2\pi} \sin(qd/2)$$



p = incident momentum

p'= scattered momentum

q = momentum transfer

Strange Electric Form Factor of the Proton
Phys. Rev. Lett. 94 212001

D. B. Leinweber, S. Boinepalli, A. W. Thomas†, P. Wang,
A. G. Williams, R. D. Young†, J. M. Zanotti, and J. B. Zhang

By combining the constraints of charge symmetry with new chiral extrapolation techniques and recent low-mass quenched lattice QCD simulations of the individual quark contributions to the electric charge radii of the baryon octet, we obtain an accurate determination of the strange electric charge radius of the proton. While this analysis provides a value for $G_{sE}(Q^2 = 0.1\text{GeV}^2)$ in agreement with the best current data, the theoretical error is comparable with that expected from future HAPPEx results from JLab. Together with the earlier determination of G_{sM}, this result considerably constrains the role of hidden flavor in the structure of the nucleon.

$$G_{sE}(0.1\text{GeV}^2) = +0.001 \pm 0.004 \pm 0.004 \,.$$

experimental and statistical uncertainty

theoretical/lattice scale uncertainty

http://www.phys.anl.gov/theory/zfftr/08UND.pdf

Any strange quarks in there?

The search for strange quark effects in the nucleon ground state has:

a) Stretched the extreme capabilities of the electron accelerators and laboratories

b) Provided hard experimental data to test lattice QCD calculations of hadronic properties

c) Provided the experimental capabilities to challenge the Standard Model of particle physics.