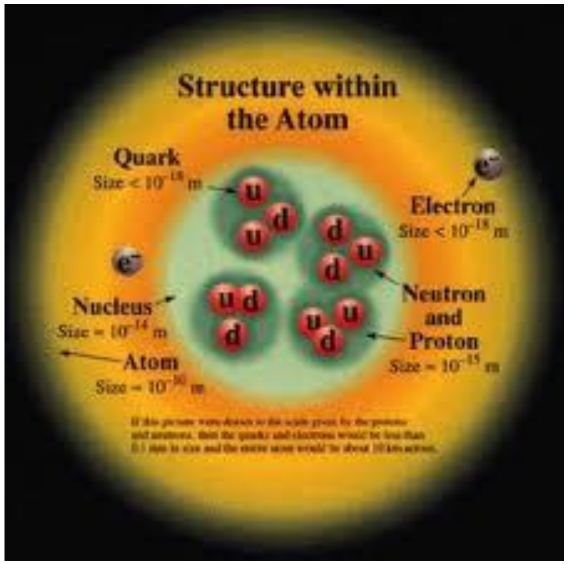
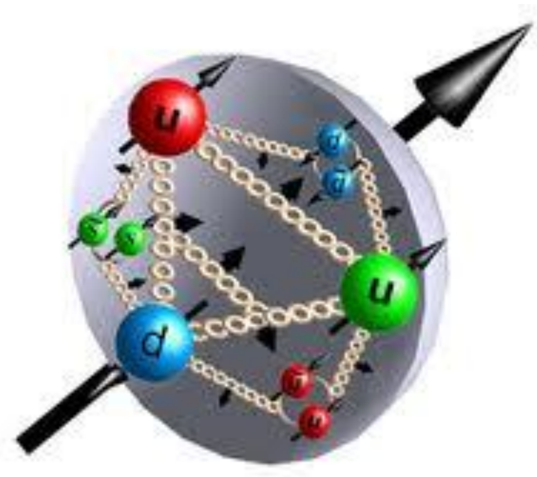
Nucleon Form Factors and the Nuclear Medium





Vincent Sulkosky

University of Virginia

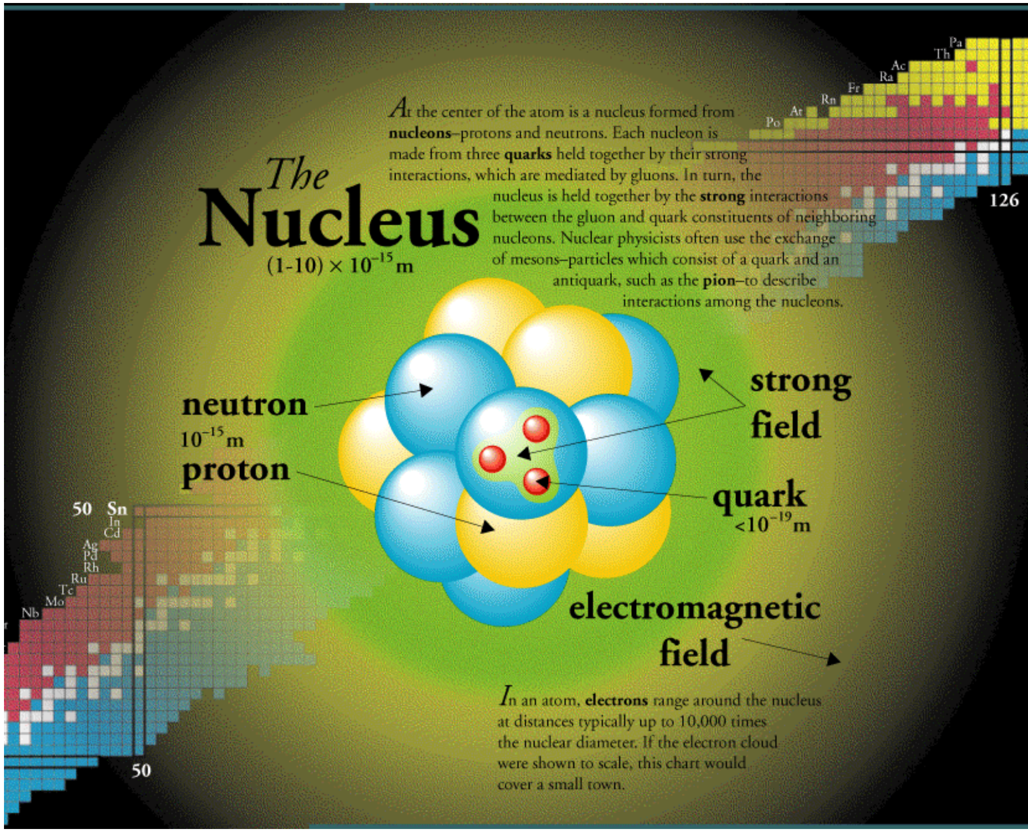
HUGS 2014, Lecture 1

June 11th, 2014

UNIVERSITY of VIRGINIA

Questions to Ponder

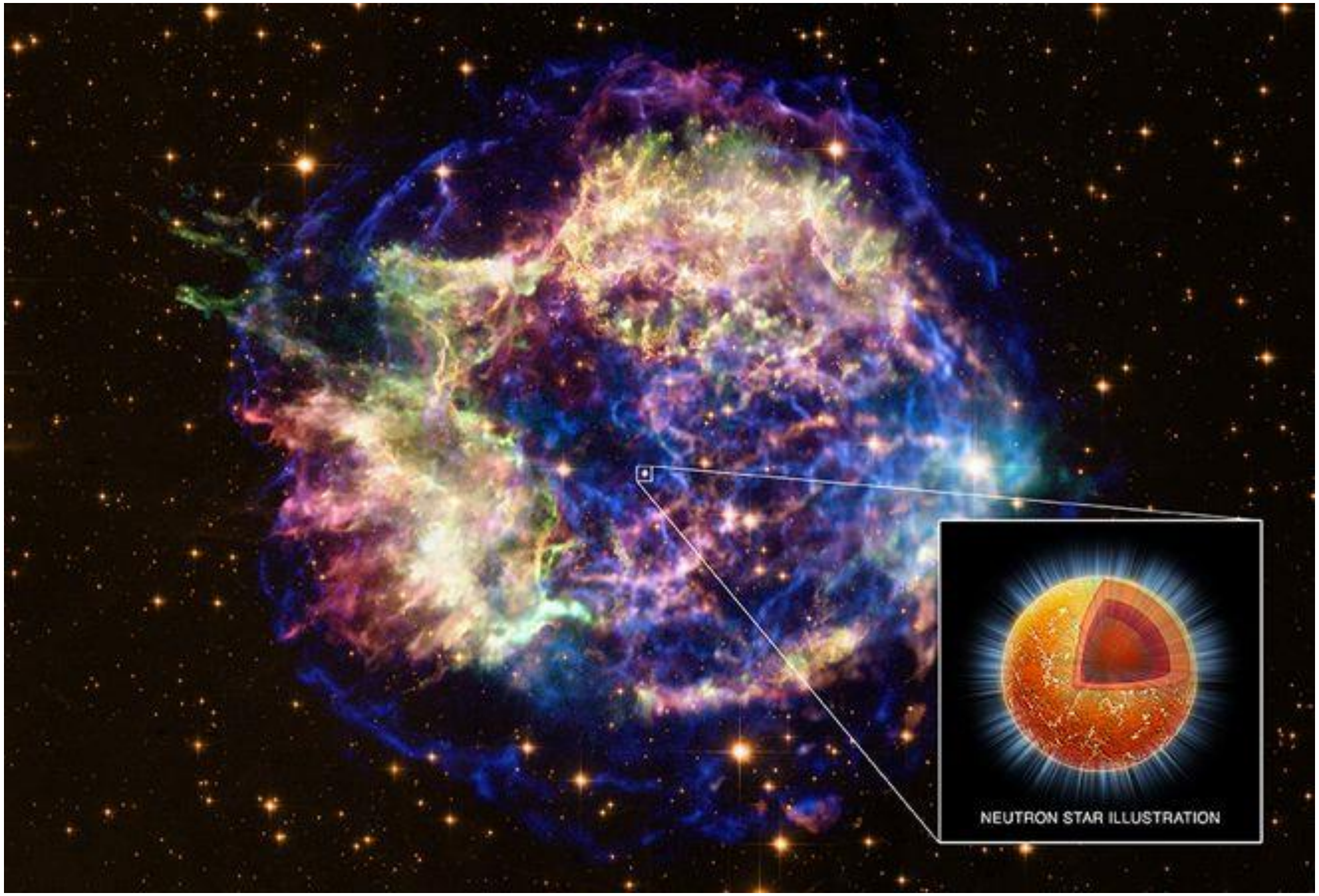
1) What are the building blocks of matter?
2) How do the building blocks interact with each other?
3) Why do we use electron scattering?
4) What do we know about the proton’s internal structure?
5) What can we learn from form factors?



What is the universe made of?

Macroscopic world:

Cassiopeia A



Scale: 10 ly ≈ 10^{17} m (across)

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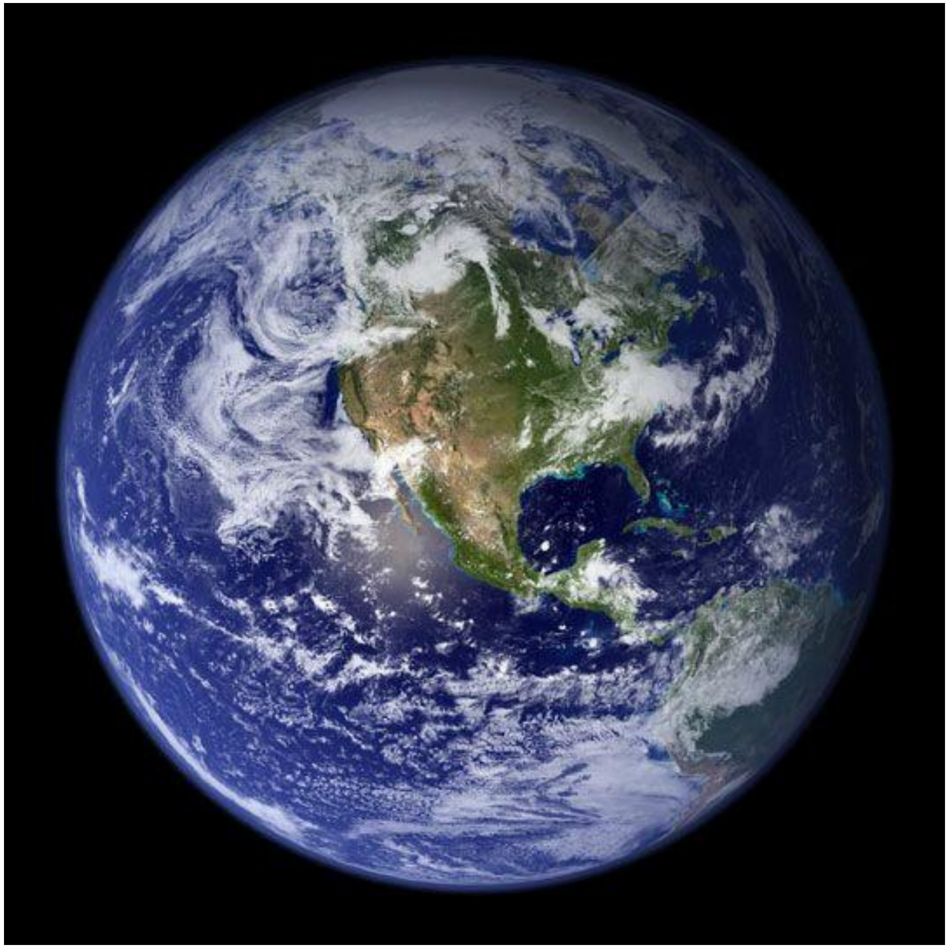
What is the earth made of?

Macroscopic world:

Earth



Scale: 10^7 m

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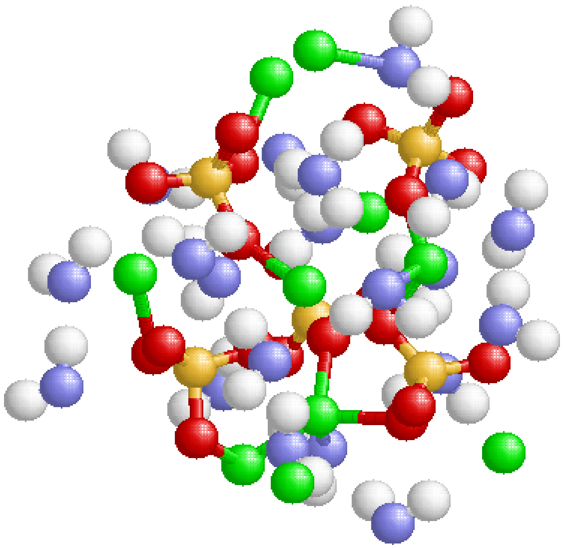
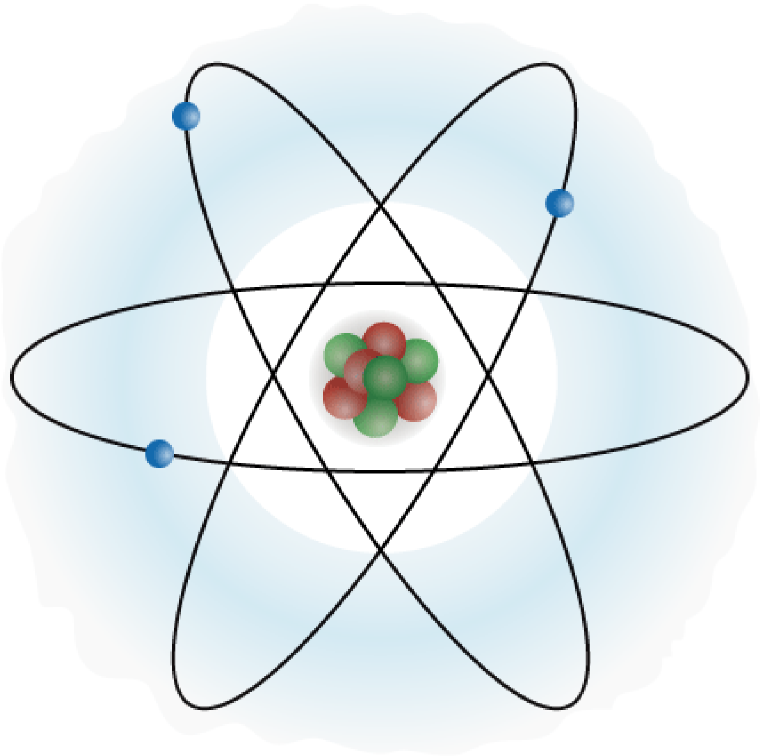
The Building Blocks of Matter

Atomic world:

Molecules



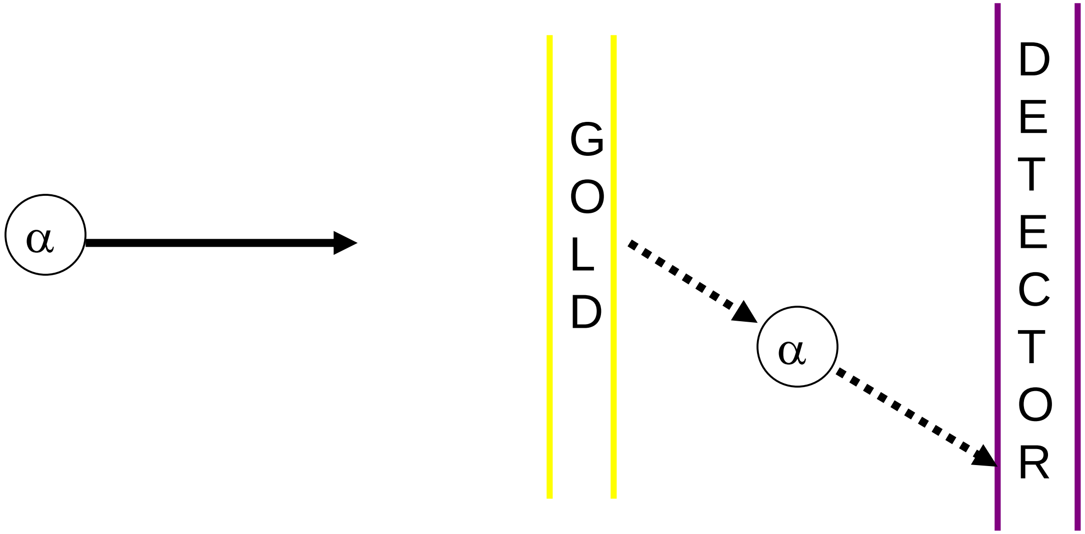
Atom

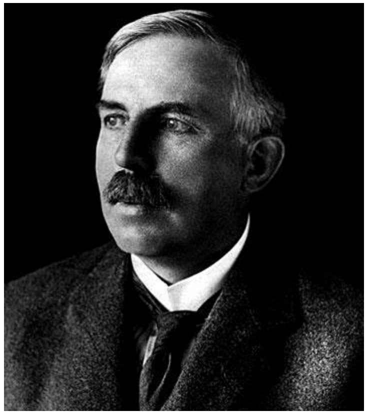


Scale: 10^{-10} - 10^{-9} m

Discovery of the Nucleus

- Ernest Rutherford and colleagues studied the scattering of **α-particles** (Helium-4 nucleus) from a thin gold foil.





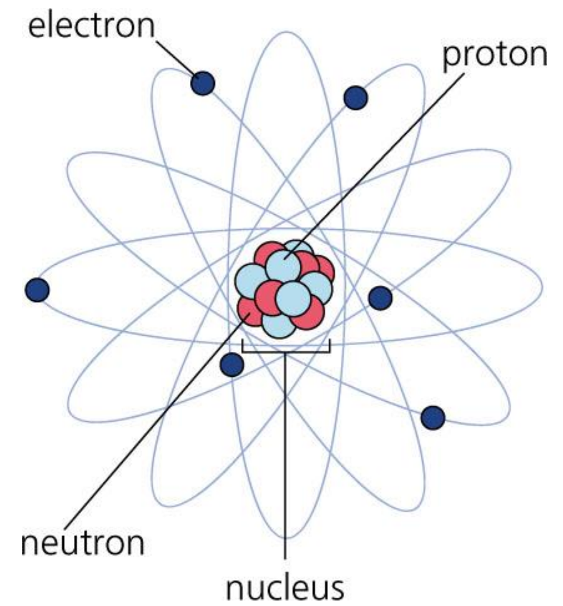
- α-particles scattered at large angles at high rates.
- First evidence that atoms have a small hard nucleus.
- Nucleus is comprised of proton(s) and/or neutron(s).

Periodic Table of Elements

Key: element name / atomic number / symbol / atomic weight (mean relative mass)

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*lanthanoids	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
**actinoids	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]



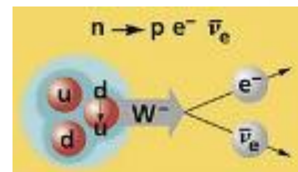
Protons, neutrons, and electrons <u>seem</u> like our fundamental particles.

Fundamental Forces in Nature

<u>Four Forces:</u>

- Strong Nuclear: short range (10^{-15} m)
- Electromagnetism: long range

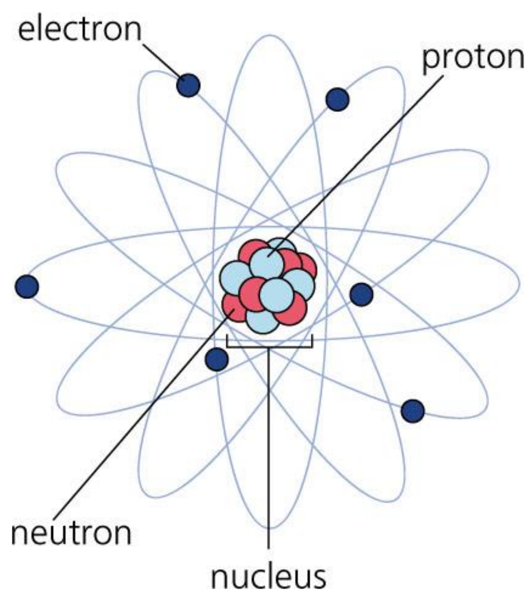
- Weak Nuclear: short range (10^{-18} m)



- Gravitation: long range

- Gravity, EM and weak: **adequate description** (within experimentally accessible range)
- Strong: **analytical description** only in a **small fraction of the experimentally accessible range**

Properties of Protons and Neutrons



Mass : ~ 940 MeV: majority of the visible mass in the universe (> 99%); neutron mass > proton mass (1.3 MeV)

1 MeV = 1.602 x 10^{-13} J

a 150-g baseball has a mass ~ 10^{28} MeV

Charge: proton, +1; neutron, 0

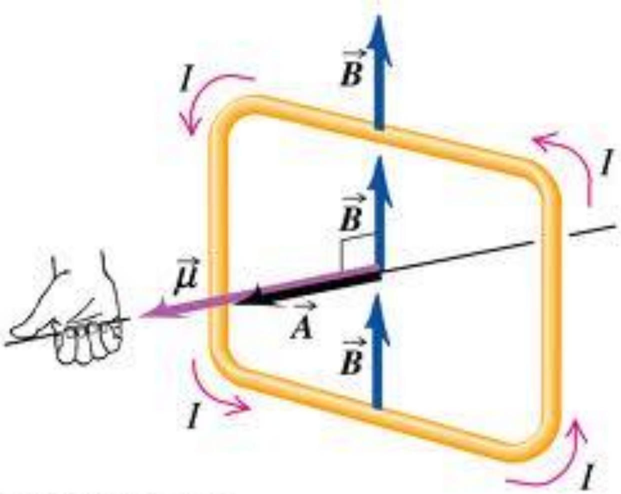
Magnetic moment

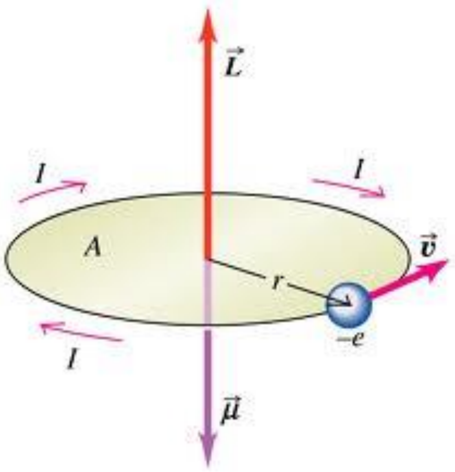
Spin-1/2

Magnetic Moments

- An electric current in a wire produces a magnetic field that curls around the wire.
- The **magnetic moment** ($\mu = IA$) quantifies the strength of the magnet; points from the south to the north pole of a magnet.
- An electron in a circular orbit around a nucleus has a magnetic moment that is proportional to its orbital angular momentum:

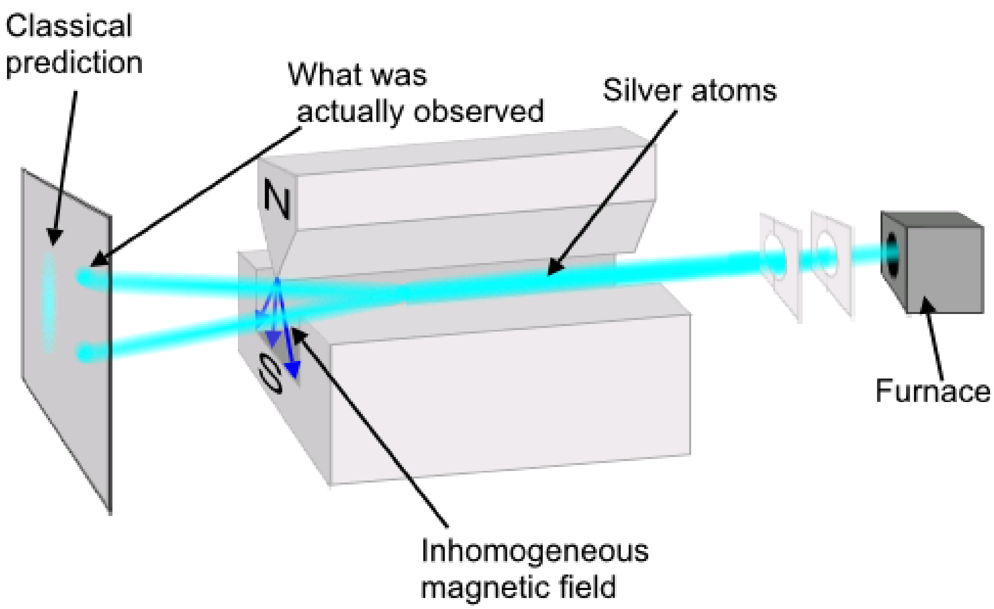
$$\mu = IA = \left(\frac{e}{2m}\right) L$$

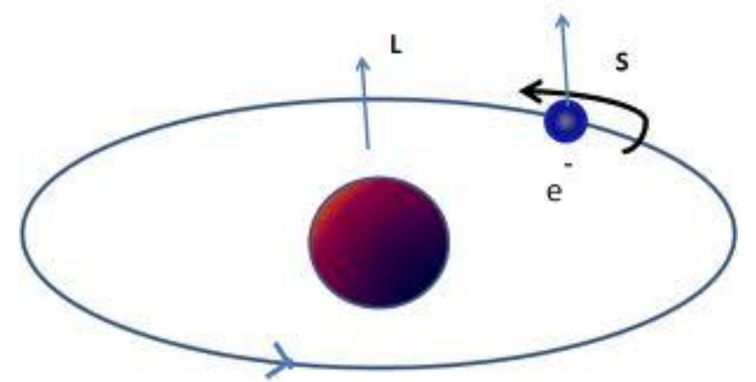




Spin

- In 1922, Stern and Gerlach discovered that the electron has an intrinsic property: **spin**, either up or down for electrons.





- Spin behaves like angular momentum.
- A particle's spin can be related to its **magnetic moment**:

$$\boldsymbol{\mu} = \frac{eQ}{M}\boldsymbol{S}$$

Nucleon Magnetic Moments

Nucleon is not a Dirac particle (*point-like* particle)

spin $\frac{1}{2}$ $\mu = \frac{e\hbar}{2mc}$

$\mu_p = +2.79\ \mu_N$ *Frisch and Stern (1933)*

$\mu_n = -1.91\ \mu_N$ should be 0

→ **per-se indication of internal structure**

$$\kappa_p = \frac{\mu_p - \mu_N}{\mu_N} = +1.79 \qquad \kappa_n = \frac{\mu_n - 0}{\mu_N} = -1.91$$

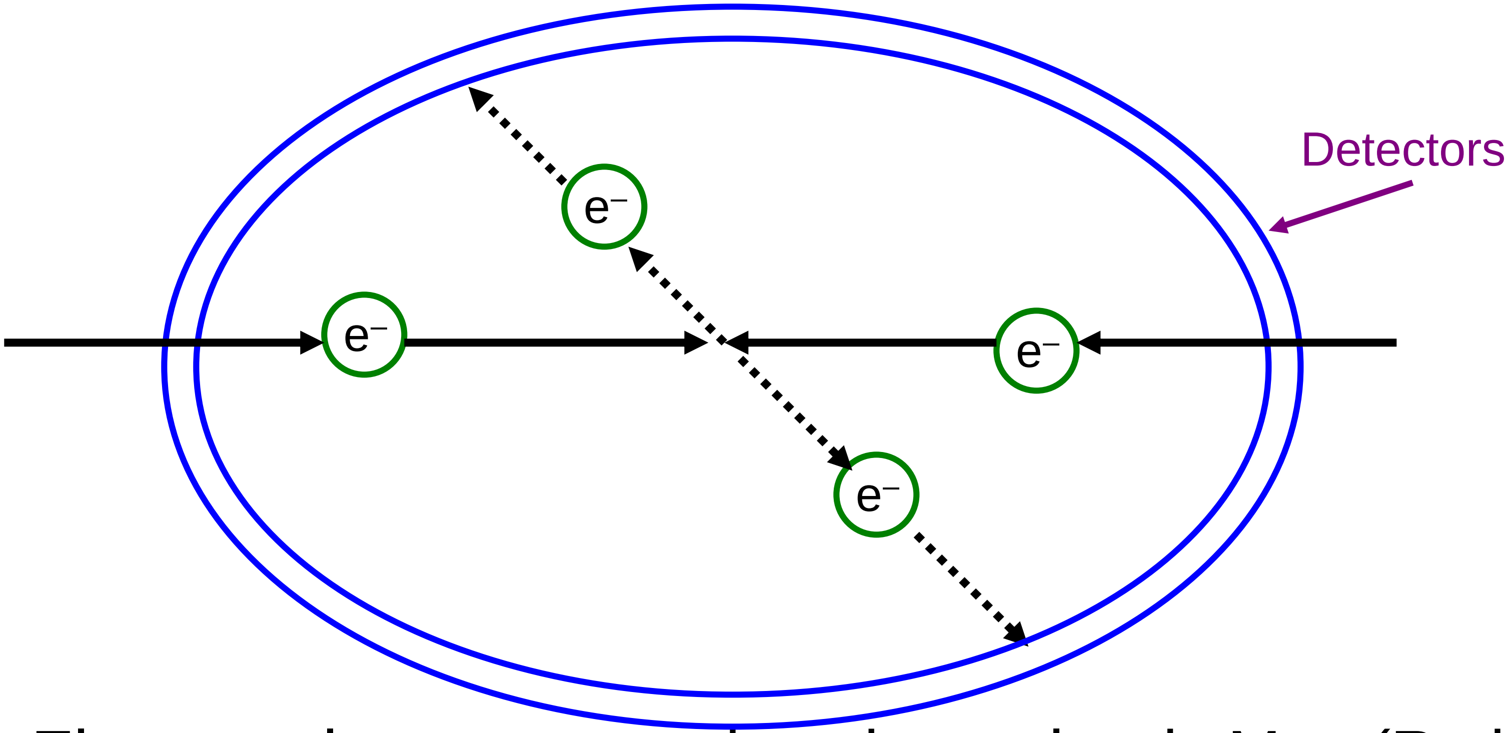
- First hint that the **proton and neutron are composite particles**.
- In 1933, Estermann and Stern discovered that the proton has a large **anomalous magnetic moment**: $\boldsymbol{\kappa}$.

Why use electron scattering?

1) Scattering experiments reveal the proton's and neutron's internal structure.
2) Electrons are point particles and their interactions are understood from the theory of electromagnetism (Quantum Electrodynamics).

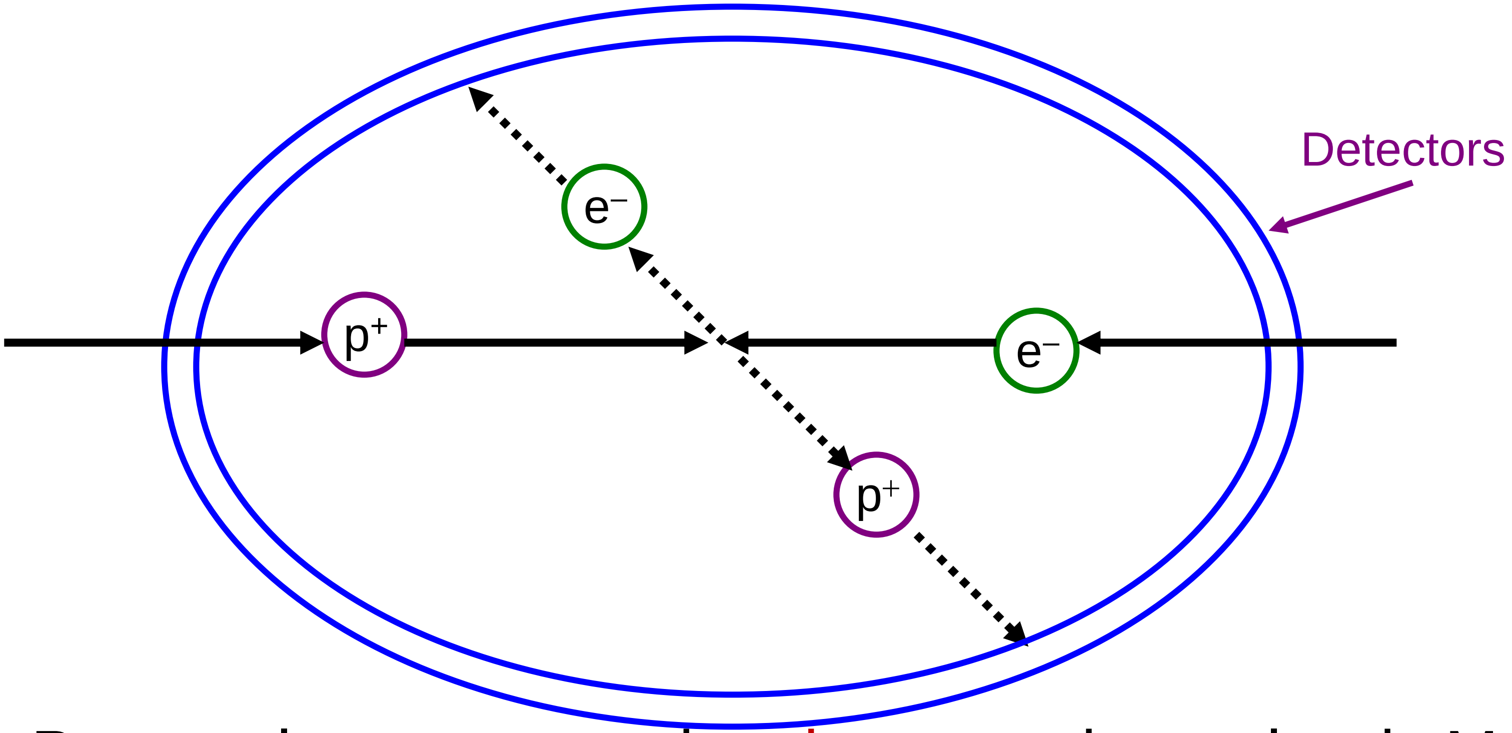
Electron scattering has proven to be a valuable tool to understand and investigate nucleon structure

Electron Scattering



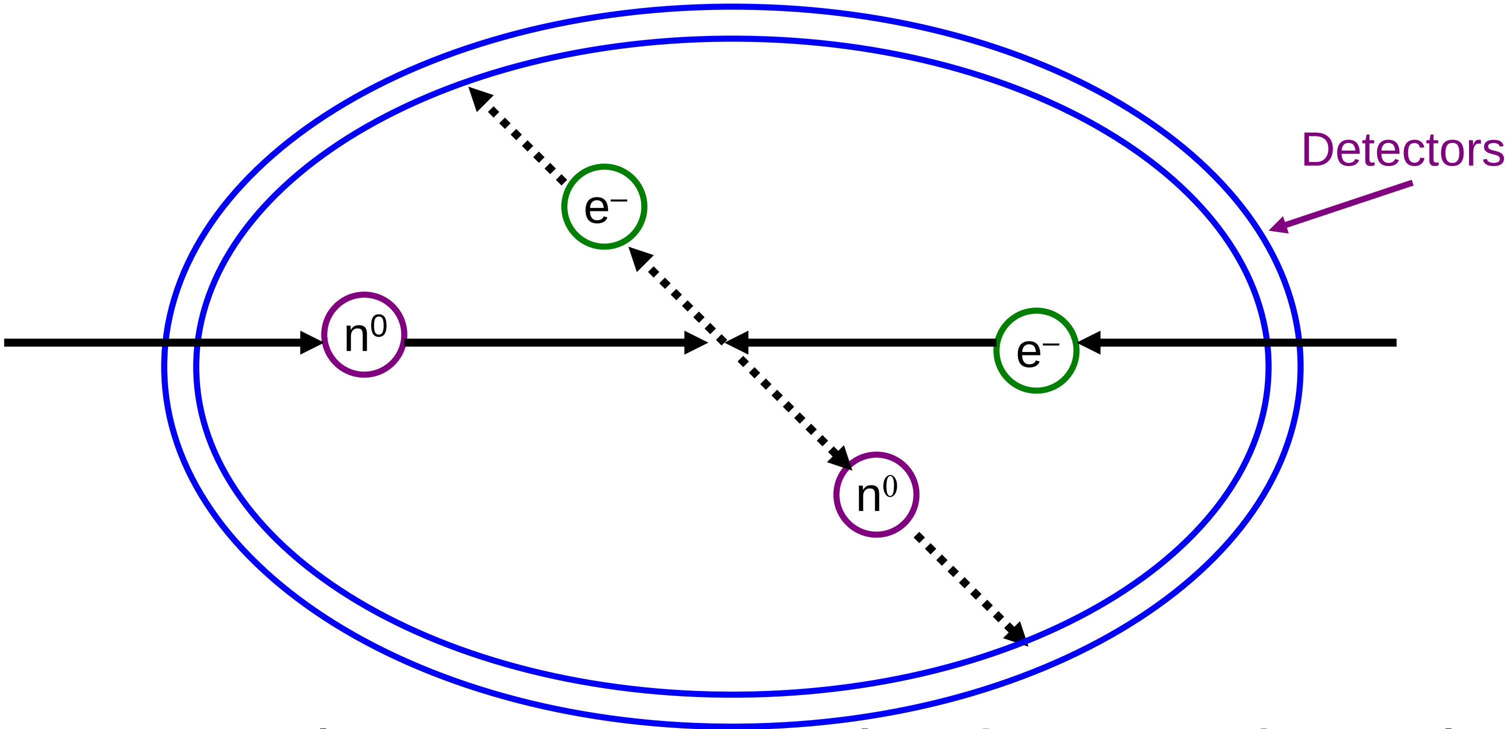
- Electron-electron scattering obeys classic Mott (Rutherford with spin) scattering.
- Electrons are point particles. They have no structure.

Proton-Electron Scattering



- Proton-electron scattering <u>does not</u> obeys classic Mott scattering.
- Proton are not point particles. They have structure.

Neutron-Electron Scattering



- Neutron-electron scattering <u>also does not</u> obeys classic Mott scattering.
- Neutron beams or targets are a challenge.

History of Electron Nucleon Scattering

- 1930s proton anomalous magnetic moment was discovered (O. Stern), direct indication of proton internal structure.
  - Nobel Prize 1943

$$\mu_p \approx 2.793(\mu_B) \neq 1(\mu_B)$$

- Pioneered by Hofstadter *et. al* at Stanford in 1950s, first proton form factor measurement reported in 1955.
  - Nobel Prize 1961
- DIS of electrons from protons by Friedman, Kendall and Taylor unravels the underlying quark structure of the proton at SLAC .
  - Noble Prize 1990
- While QCD has been tested well in the asymptotic region (David J. Gross, H. David Politzer, Frank Wilczek), understanding hadron structure in confinement region still challenging.
  - Noble Prize 2004

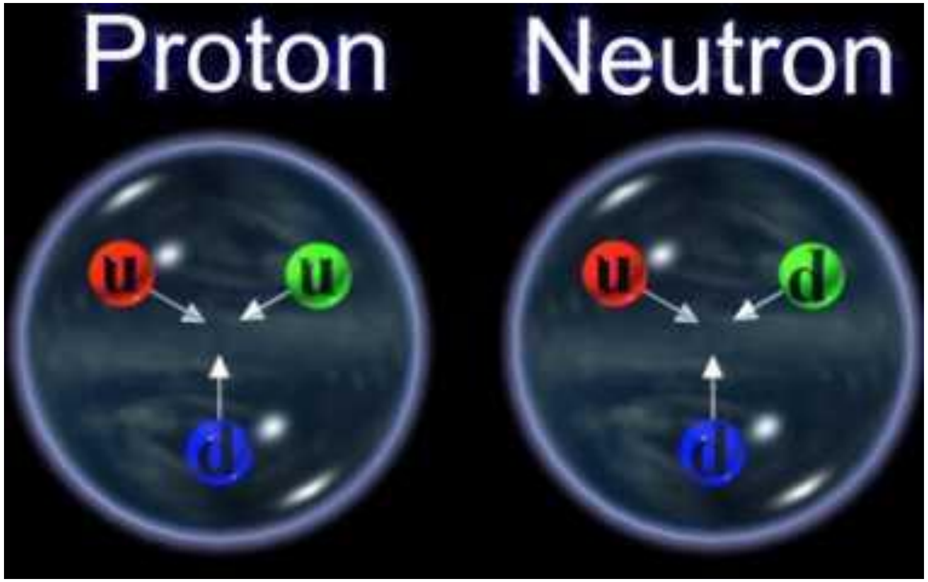
So what are we really made of?

Experimental results can be explained using quarks

- **Basic Quark model**:
  - Protons are made of two up quarks and one down quark
  - Neutrons are made of two down quarks and one up quark
- So it seems **we are made of up quarks, down quarks, and electrons**.

Subatomic world:

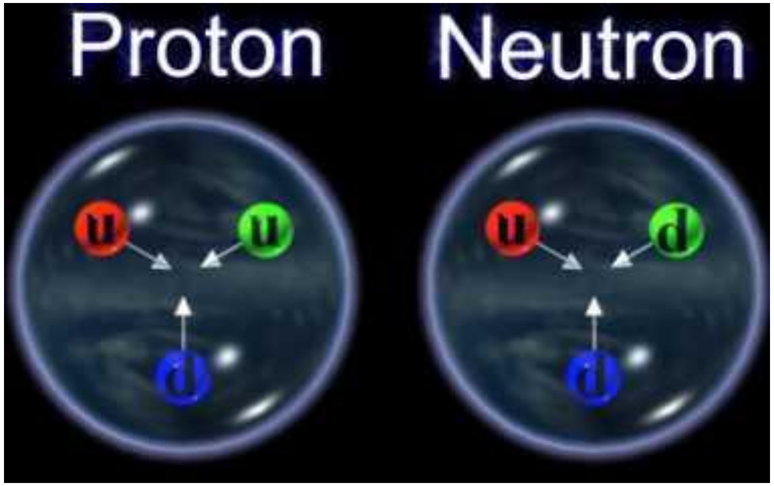
Scale: 10^{-15} m = 1 fm



Four forces describe all interactions:

gravity, **electromagnetism**, **weak nuclear** and **strong nuclear**

Building Nuclei from Quarks



Nucleons: (Protons and Neutrons)

Building blocks of visible matter

Composed of quarks (bricks) and gluons (mortar).

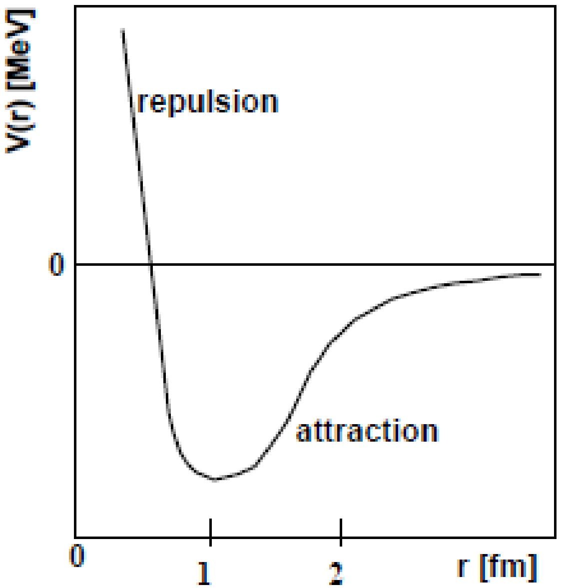
Structure mostly governed by the strong nuclear force, i.e., **nucleons are a "natural laboratory" to study this interaction**.

Strong Nuclear Force

- The theory is known as Quantum Chromodynamics (QCD)
- Holds nucleons and quarks together: **confinement**
- Difficult to solve mathematically, since gluons carry color charge and interact with themselves

- Options:
  - Model with a computer (Lattice QCD)
  - Make simplifications:
    High Energy (Perturbation theory)
    Low Energy (Chiral Perturbation theory)

- Theory should explain the internal dynamics of protons and neutrons and their global properties.



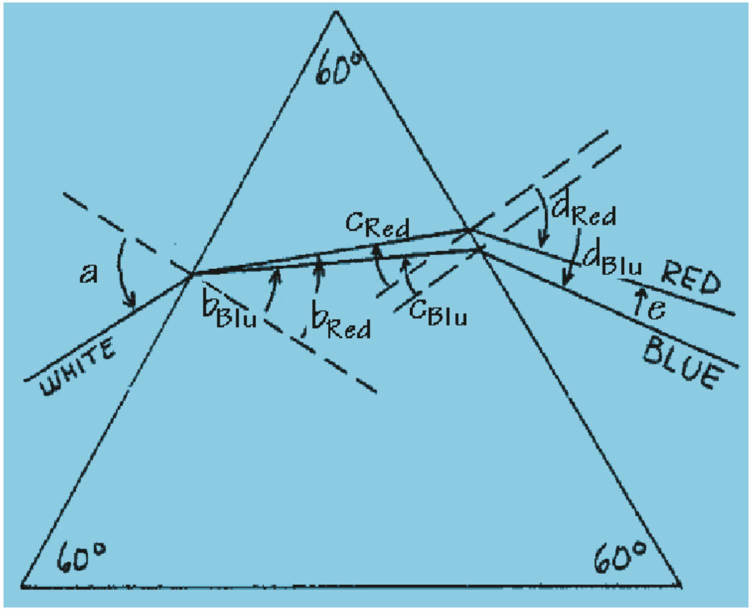
Effective Theories

When complexity makes the basic degrees of freedom too complicated to handle, effective theories can be used.

Legitimately a part of our description of Nature as long as connections with the fundamental theory are known.

A standard procedure in science:

e.g., geometric optics → electromagnetism,
thermodynamics → statistical mechanics



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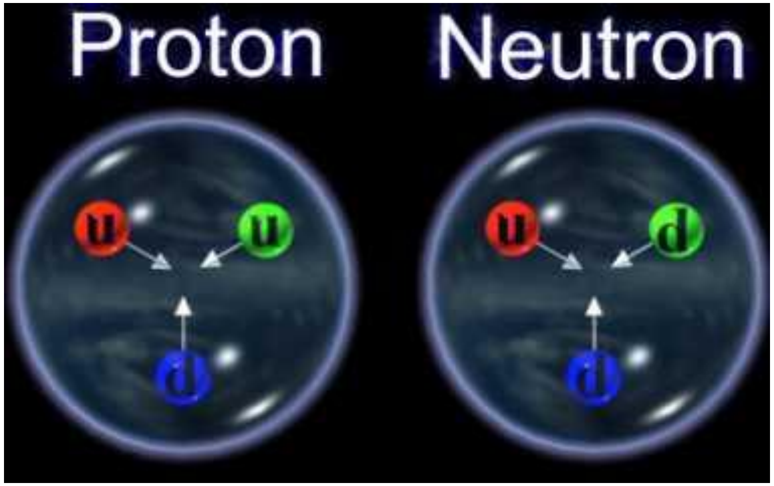
What do we know about their internal structure?



Mass: ~ 940 MeV, but u- and d-quark mass only a few MeV each!

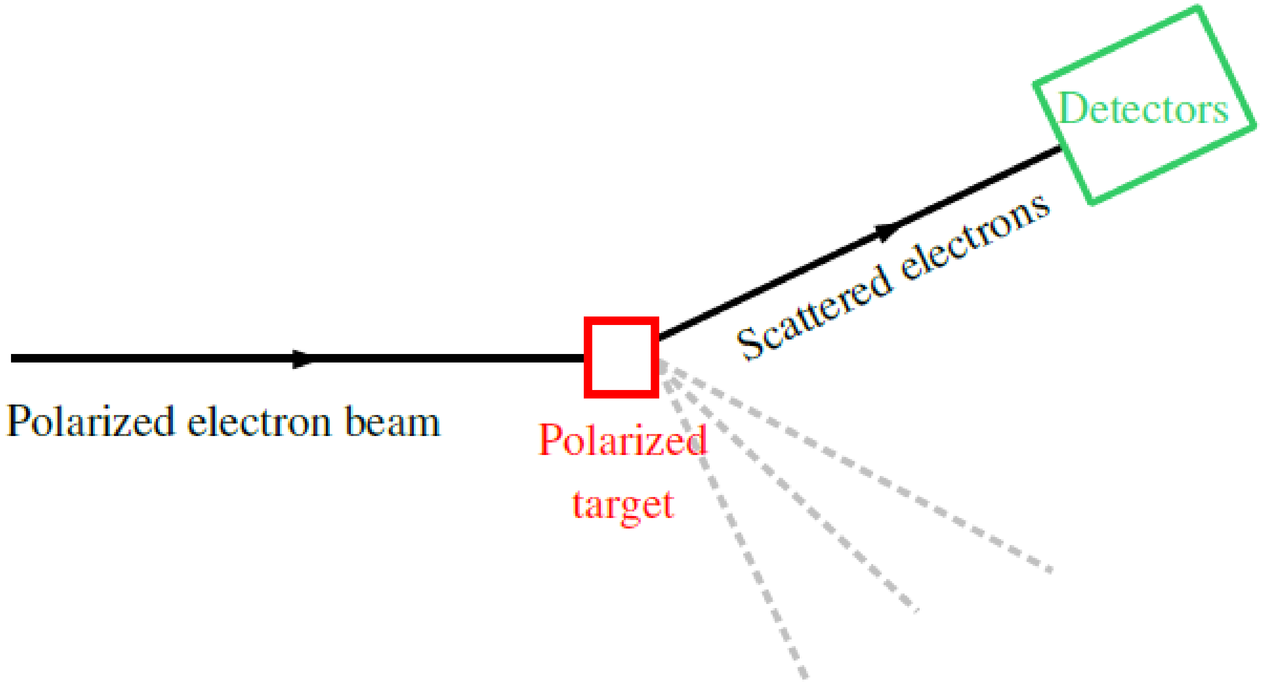
1 MeV = 1.602 x 10^{-13} J

Charge: proton, +1; neutron, 0
Magnetic moment: large part is anomalous, > 150%!
Spin-1/2: but total quark spin contributes only ~ 30%!

Sum of the parts is not equal to the whole!

Tools of the Trade

Electron Scattering



Target: electron, proton, or nucleus such as helium or carbon

Tools of the Trade

Electron Scattering Kinematics

Energy transfer:

$$\nu = E - E'$$

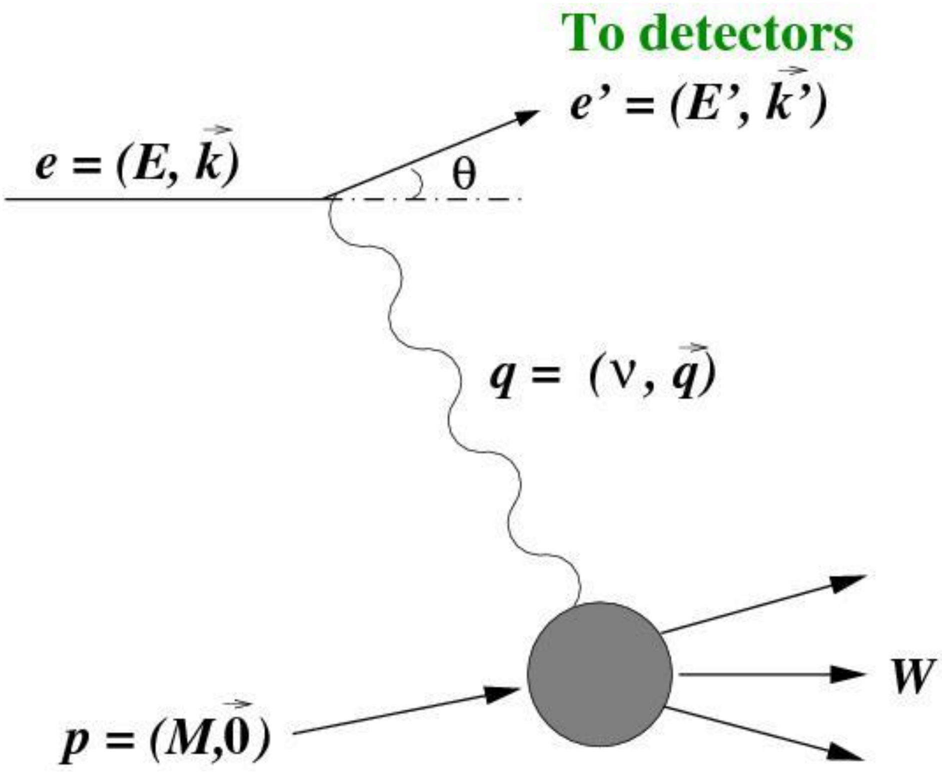
Momentum transfer:

$$\vec{q} = \vec{k} - \vec{k}'$$

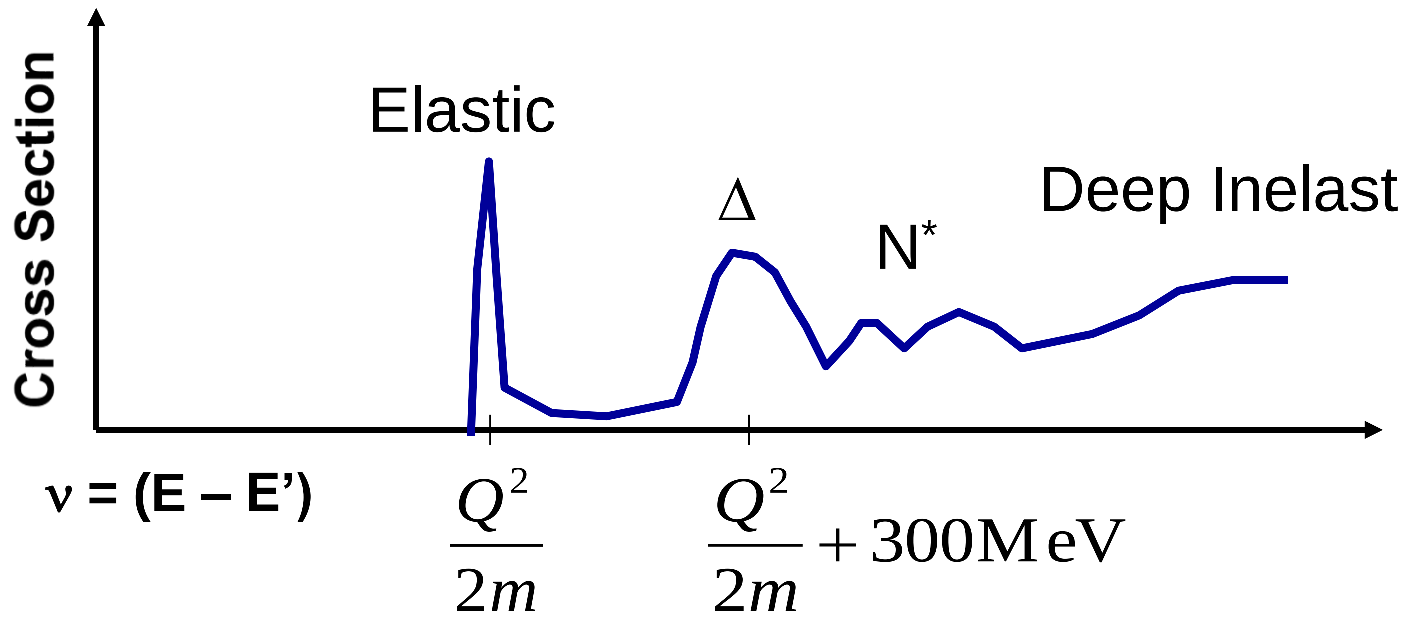
4-momentum transfer squared:

$$Q^2 = -q^2 = 4EE' \sin^2\frac{\theta}{2}$$

One-photon exchange (Born approximation) for e-p scattering



Electron-Proton Scattering at Fixed Momentum (Q^2)



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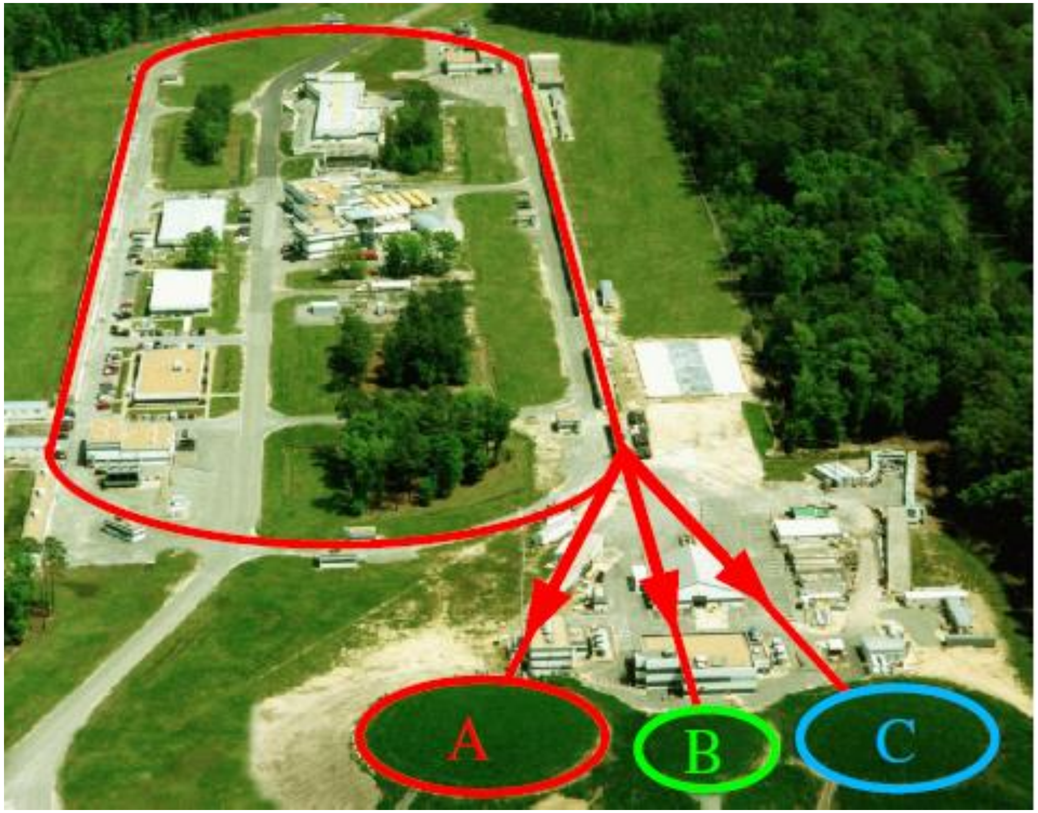
Jefferson Lab



In Newport News, VA
Continuous electron beam.
Energy: 0.3 to 6 GeV.
3 Experimental Halls.
Polarization: ~ 85–90%.
Beam energy being upgraded to 12 GeV!
International Collaboration
29 different countries representing 120 different institutions

The rest mass energy of an electron is 0.511 MeV.
At 6,000 MeV, the electron is traveling 0.999999996 times the speed of light, or eight 9's.

3 Experimental Halls

Hall A

Hall B

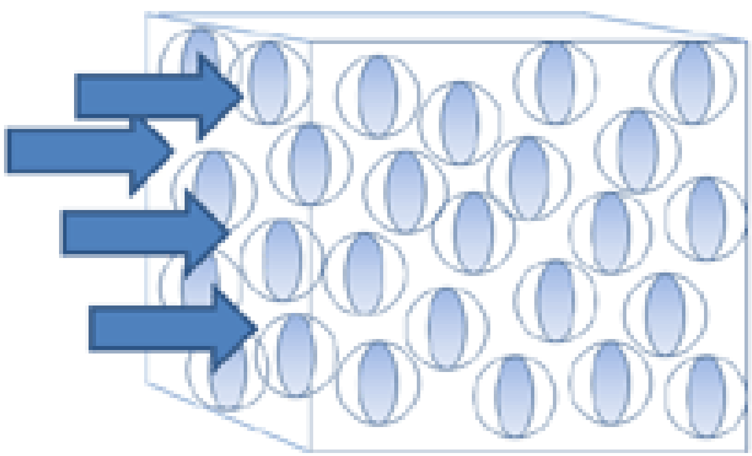
Hall C

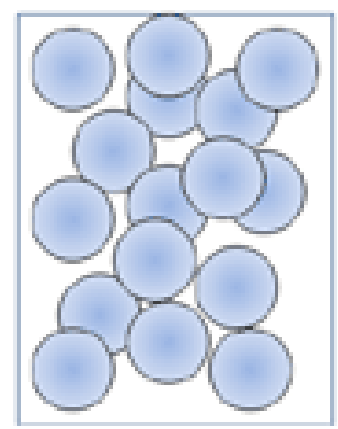
- All halls can take data at the same time.
- Different detectors allow for different types of experiments.

Cross Section in Particle Physics

Cross section: the likelihood of an interaction between particles

- In our case, between the incoming electrons and the protons in the target.
  - N_e is the number of incident electrons on the target
  - N_p is the number of protons in the target
  - N_s is the number of electrons scattered from the target
  - The cross section is related to $\dfrac{N_s}{N_e \cdot N_p}$





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Elastic Nucleon Form Factors

Electron elastic scattering from nucleons:

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\frac{1}{1+\tau}[G_E^2 + \frac{\tau}{\varepsilon}G_M^2]$$

$$J^{\mu}_{hadronic} = e\bar{N}(p')[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)]N(p)$$

$$(\tau = \frac{Q^2}{4M^2}, \varepsilon = [1+2(1+\tau)\tan^2\frac{\theta_e}{2}]^{-1})$$

Sachs Form Factors (FFs):

Electric: $G_E(Q^2)$ $\quad G_E \equiv F_1 - \tau F_2$

Magnetic: $G_M(Q^2)$ $\quad G_M \equiv F_1 + F_2$

Q^2=0

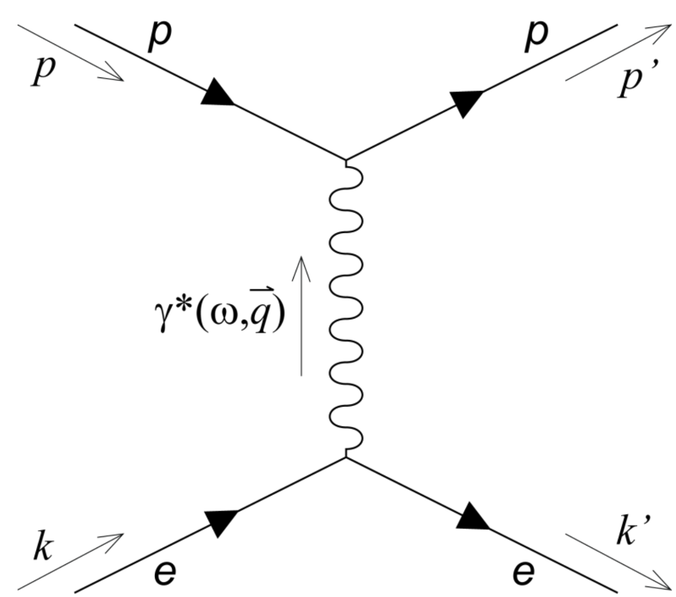
$G_{Ep}(0) = 1 \quad G_{Mp}(0) = \mu_p$

$G_{En}(0) = 0 \quad G_{Mn}(0) = \mu_n$

Dipole form

$$G_D(Q^2) = (1 + \frac{Q^2}{0.71 GeV^2})^{-2}$$

$$\mu_P \frac{G_E}{G_M} = 1$$

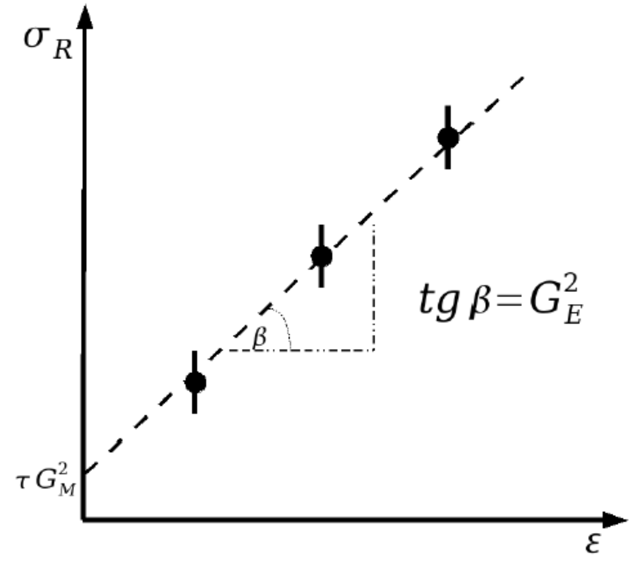


Lowest order perturbation theory in QED
(single photon exchange)

Rosenbluth Separation

$$\sigma_R \equiv \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

- No interference between G_E and G_M



Method: Vary ε at fixed Q^2, fit σ_R, linearly
Slope $\longrightarrow$ G^2_E
Intercept $\longrightarrow$ G^2_M

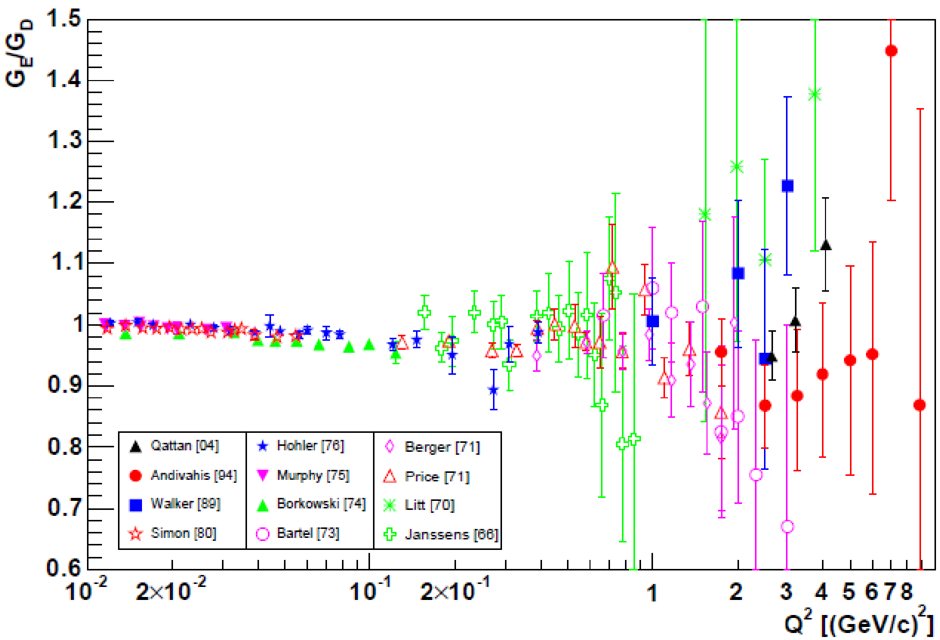
Difficulties:

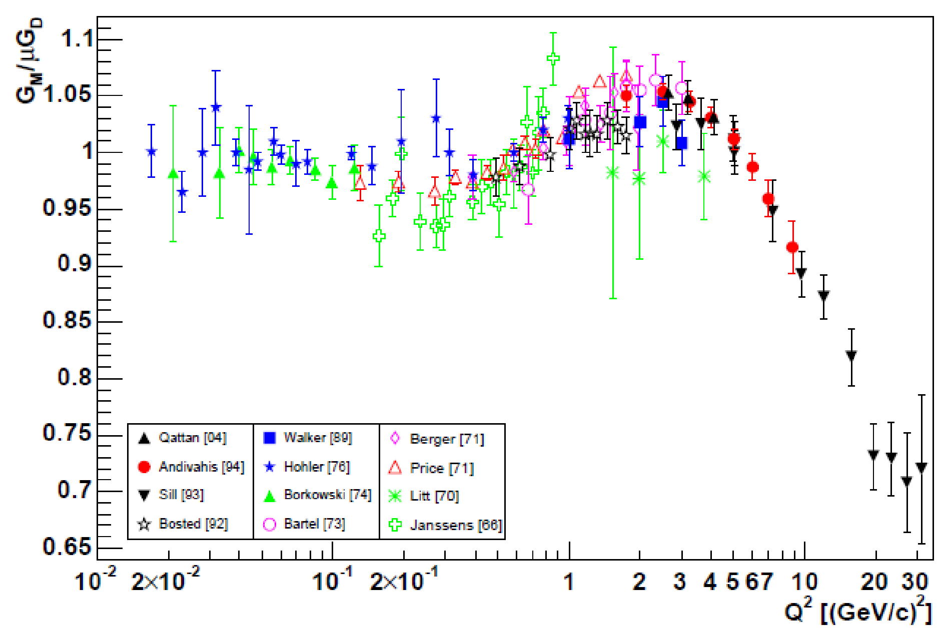
- σ is not sensitive to G_E at large Q^2 and to G_M at small Q^2
- Limited by accuracy of cross section measurement at different settings
- Radiative correction 10-30%, 2-γ exchange (ε dependent)

Existing Data: Proton FFs

G_{Ep} and G_{Mp} Rosenbluth Data:

$G_E \sim G_M/\mu \sim G_D$





Cross Section is not sensitive to G_E at large Q^2 and to G_M at small Q^2

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The Rise of Polarization

Polarization provides an extra handle in testing theories and models:

J. D. Bjorken: "*Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self protection.*"

Spin degrees of freedom provide a more complete understanding of theory.

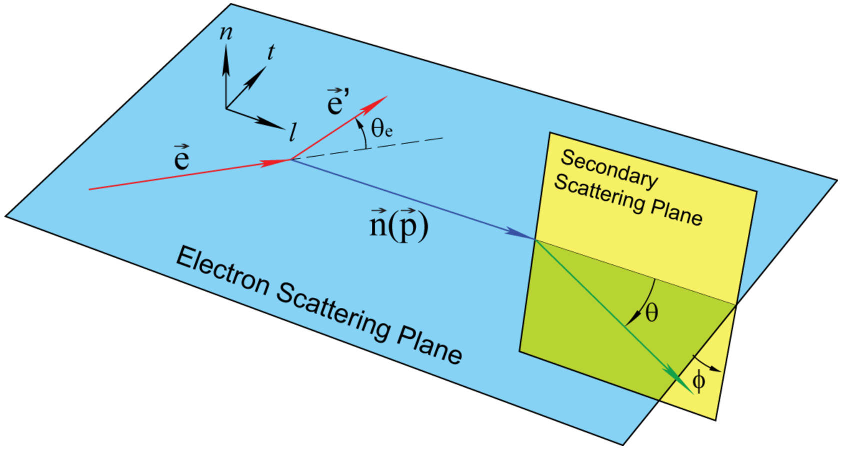
Recoil Polarimetry

- Direct measurement of form factor ratios by measuring the ratio of the transferred polarization P_t and P_l .

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

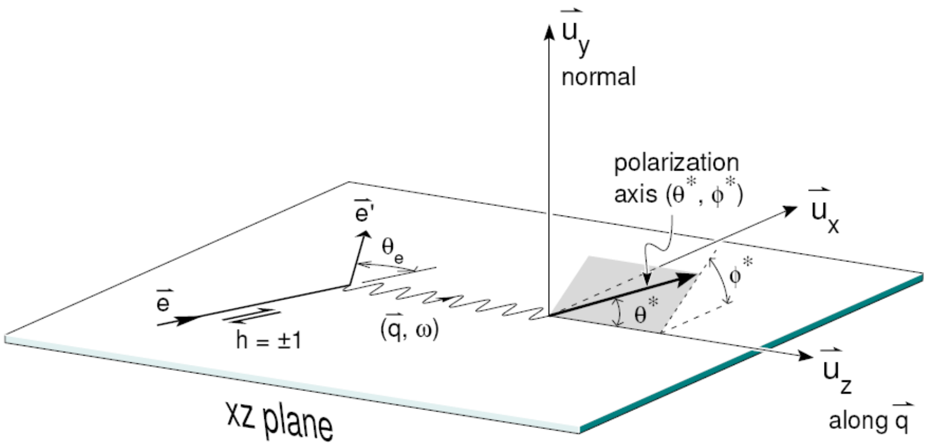
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\frac{\theta_e}{2}$$

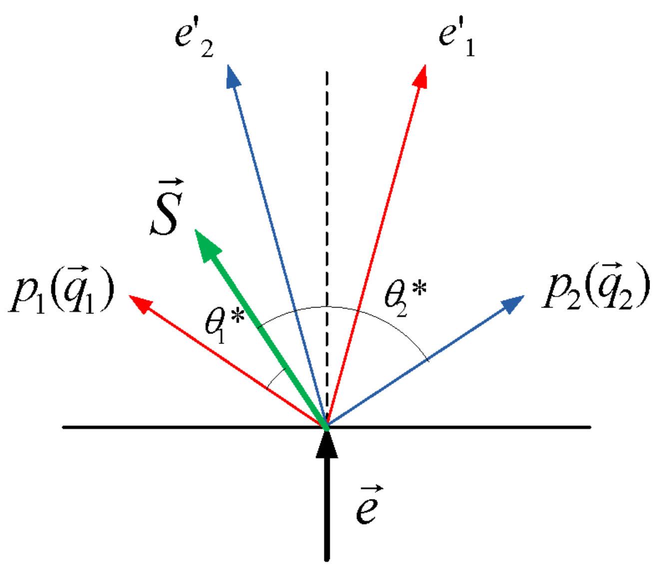


Advantages:

- Only one measurement is needed for each Q^2.
- Much better precision than a cross section measurement.
- Complementary to XS measurements.

Beam Target Asymmetry





- Polarized cross section:

$$\sigma = \Sigma + h\Delta$$

- Beam helicity h=$\pm$1:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$

- Super ratio of asymmetries:

$$\mu_p \frac{G_E^p}{G_M^p} = -\mu_p \frac{a(\tau,\theta)\cos\theta_1^* - \frac{f_2}{f_1}\Gamma a(\tau,\theta)\cos\theta_2^*}{\cos\phi_1^* \sin\theta_1^* - \frac{f_2}{f_1}\Gamma \cos\phi_2^* \sin\theta_2^*}$$

$$a(\tau,\theta) = \sqrt{\tau(1+(1+\tau)\tan^2(\theta_e/2))},$$

$$\Gamma = \frac{A_1}{A_2}$$

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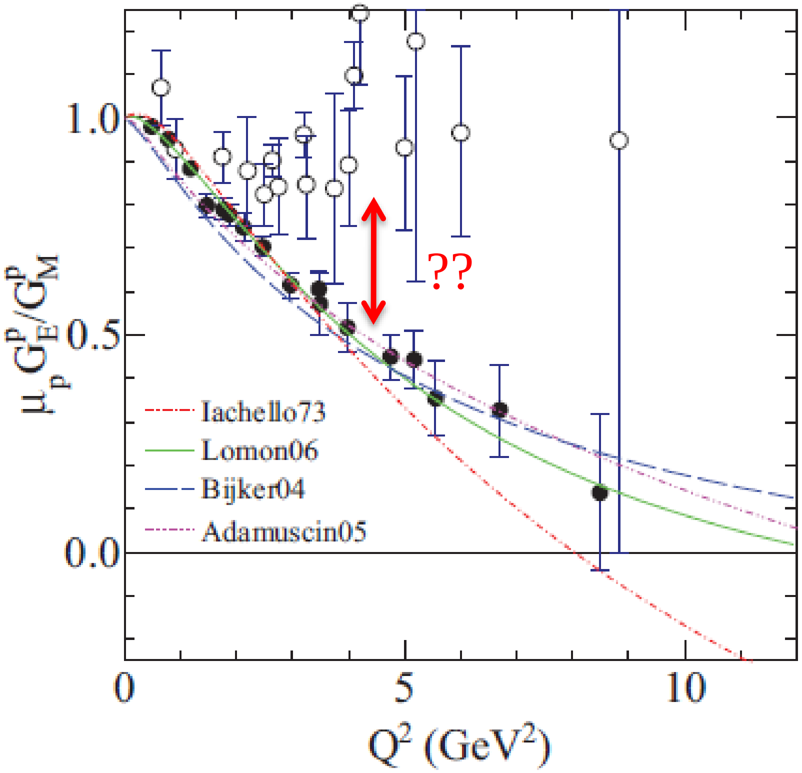
Rosenbluth vs. Polarization Transfer

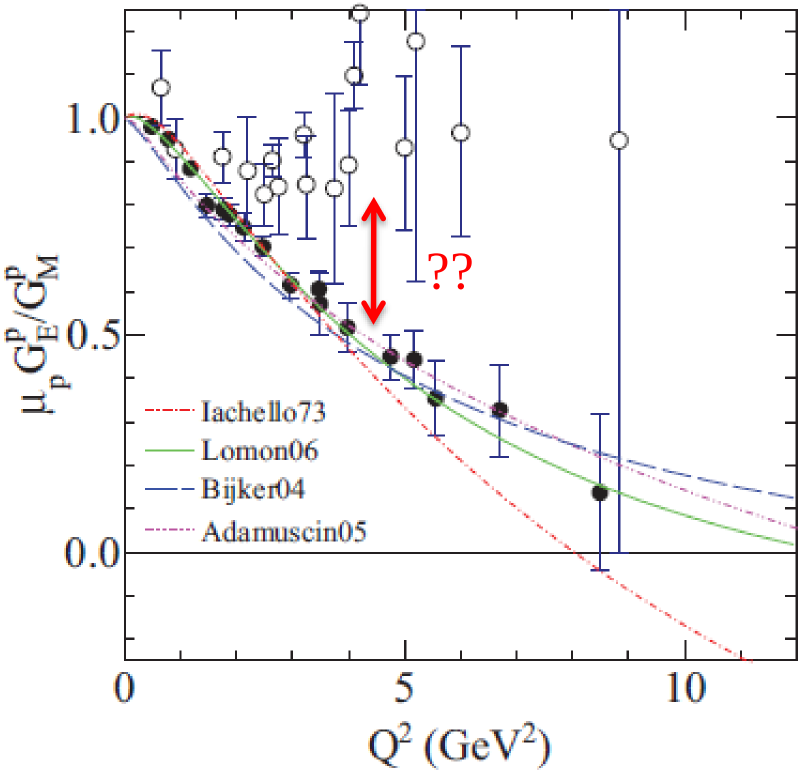
A. J. R. Puckett et al., PRC 85 045203 (2012)

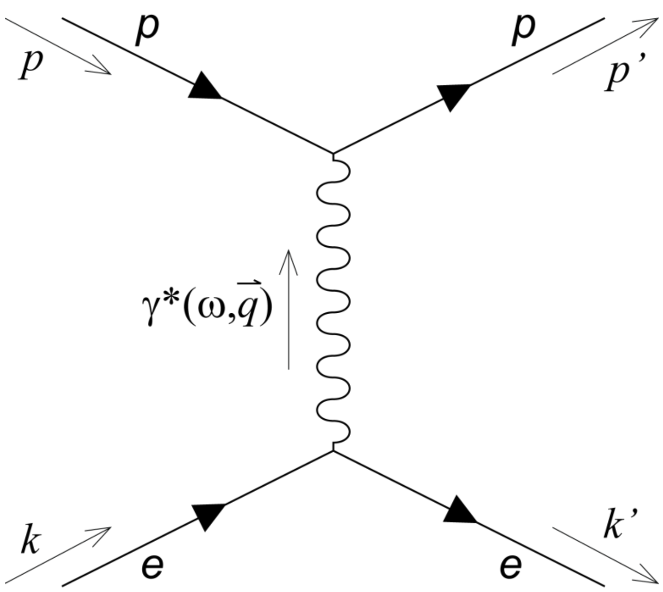


Guichon and Vanderhaeghen, PRL 91, 142303 (2003): "This discrepancy is a serious problem as it generates confusion and doubt about the whole methodology of lepton scattering experiments."

Rosenbluth vs. Polarization Transfer

A. J. R. Puckett et al., PRC 85 045203 (2012)

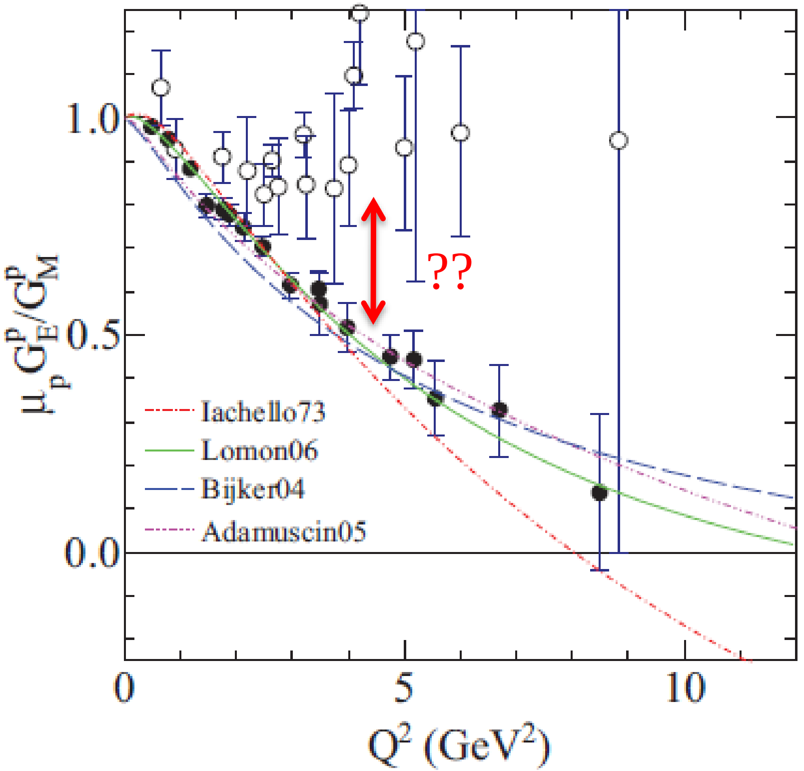




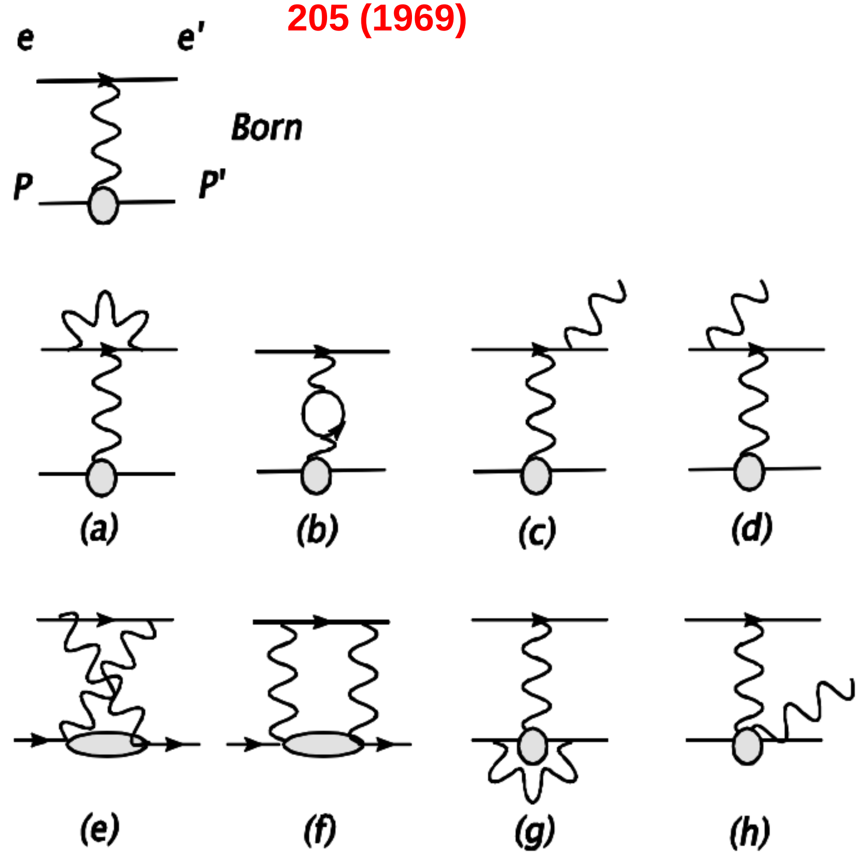
Lowest order perturbation theory in QED
(single photon exchange)

Rosenbluth vs. Polarization Transfer

A. J. R. Puckett et al., PRC 85 045203 (2012)

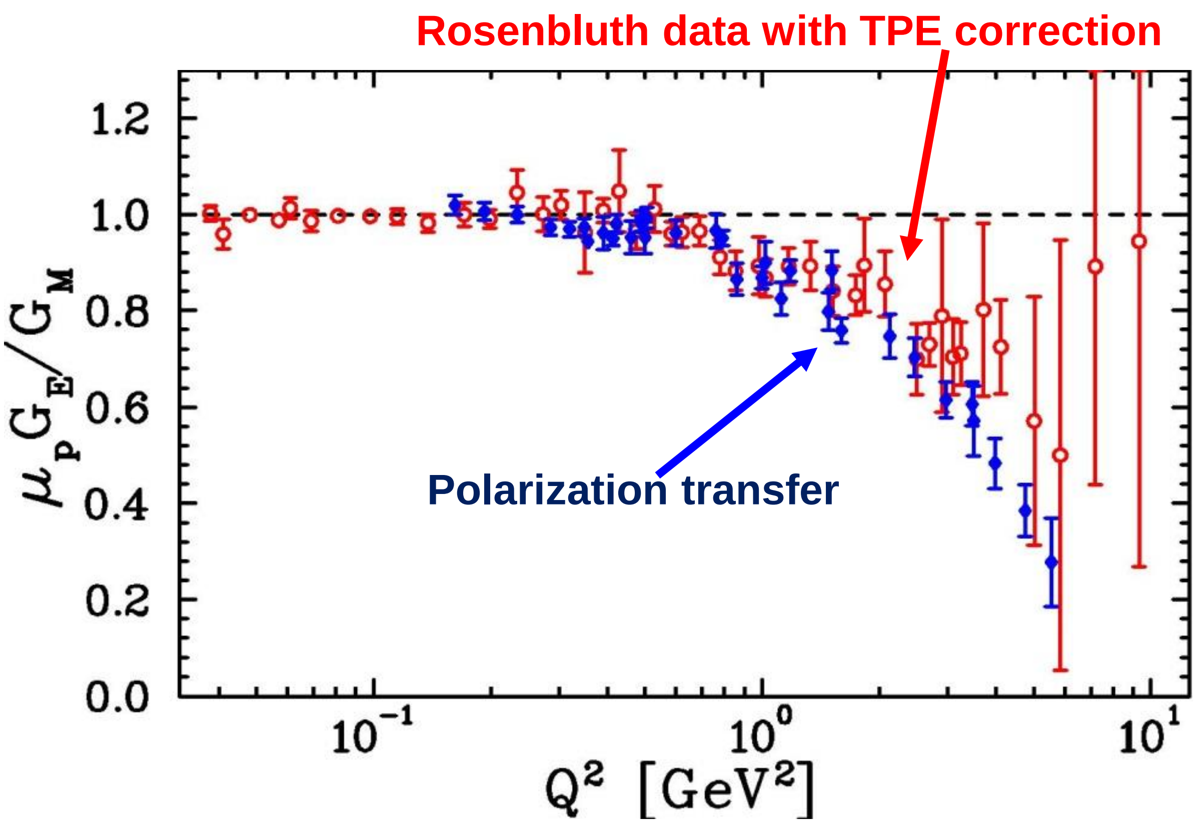


L. W. Mo and Y.-S. Tsai, Rev. Mod. Phys. 41, 205 (1969)



Two photon exchange partially included by using infrared (IR) divergent part. An IR-finite contribution is neglected and has a significant ε dependence.

Rosenbluth vs. Polarization Transfer



J. Arrington, W. Melnitchouk, and J. Tjon, PRC 76, 035205 (2007)

Models of two photon exchange (TPE) largely resolve the difference, moving the Rosenbluth results towards the polarization results

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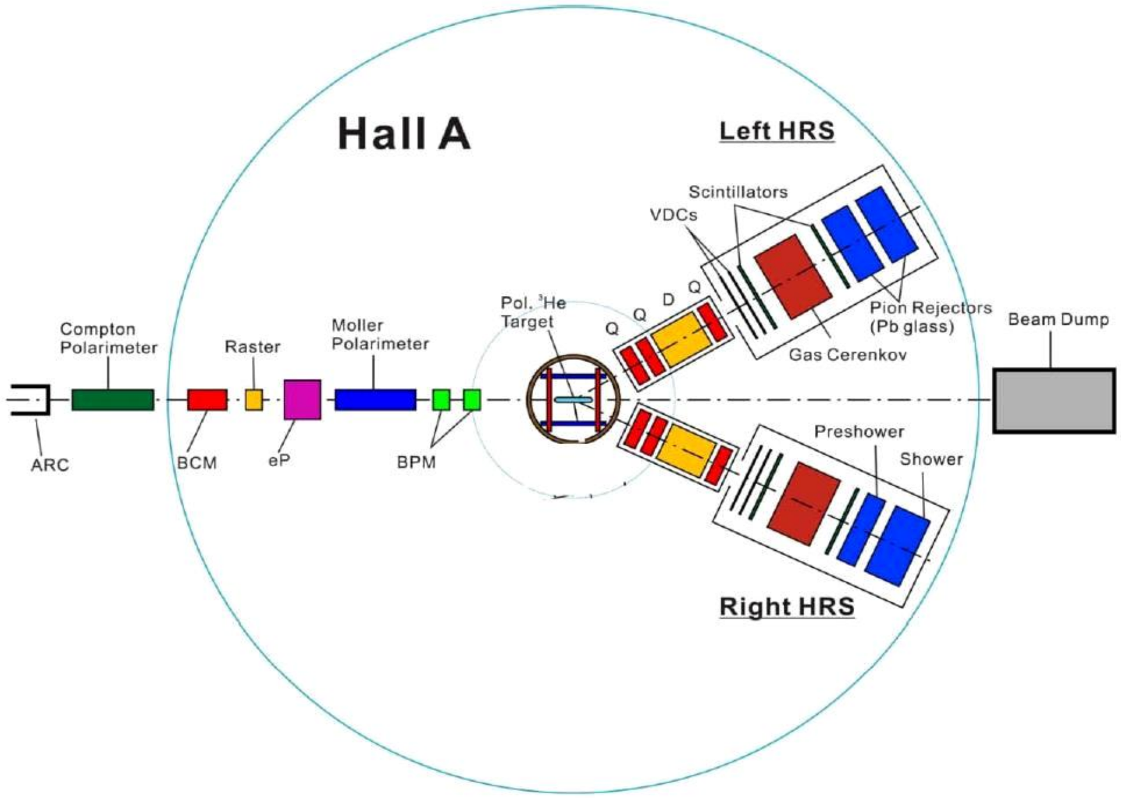
E05-015: Search for TPE Effects

Measurements of Target Single-Spin Asymmetries in the Quasi-elastic $^3He^{\uparrow}(e, e')$ reaction



Nucleon Analyzing Power:

$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$= \frac{N_e^{\uparrow} - N_e^{\downarrow}}{N_e^{\uparrow} + N_e^{\downarrow}}$$

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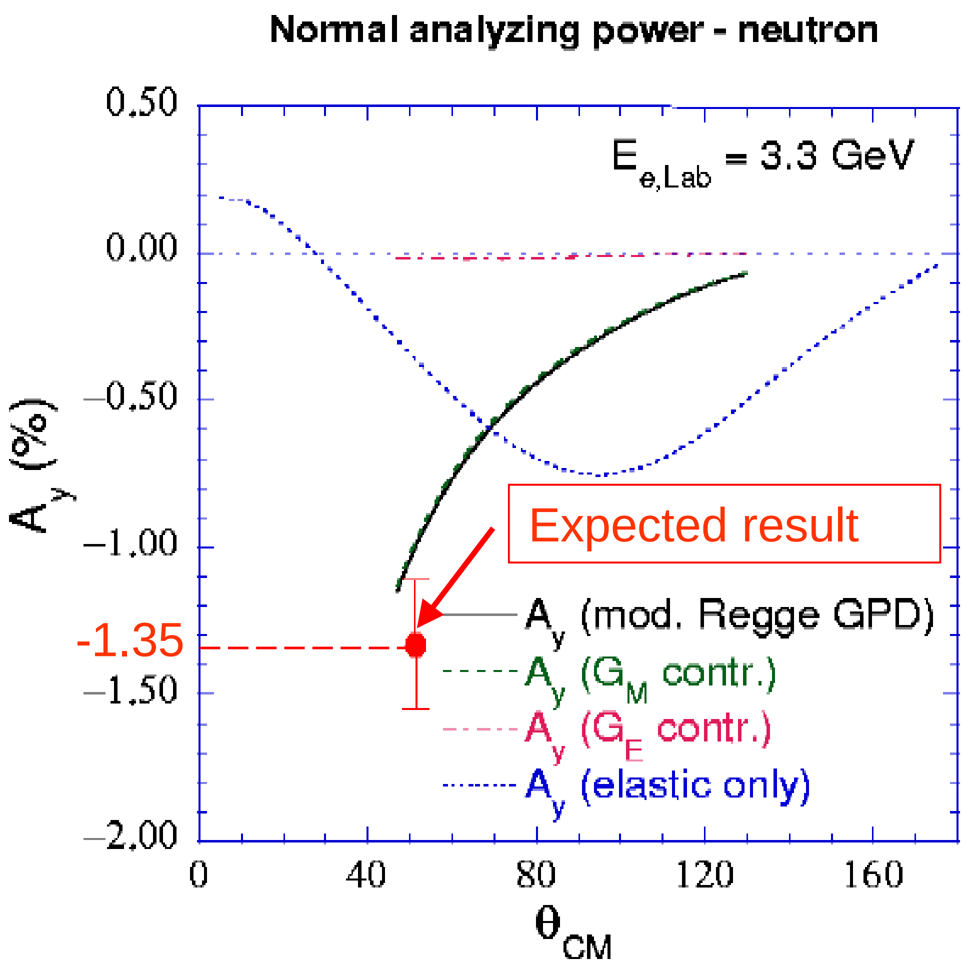
Theoretical Prediction



A. Afanasev *et al.*, PRD **72**, 013008 (2005)

$$A_y \propto \frac{\mathrm{Im}\left(T_{1\gamma} T_{2\gamma}^{*}\right)}{\left|T\right|^2}$$

A. DeRujula *et al.*, *Nuc. Phys. B* **35** (1971) 365

Born Approximation:

$T_{2\gamma} = 0$, $T_{1\gamma}$ = real ➡ $A_y = 0$

Include 2γ exchange:

$T_{2\gamma}$ has an imaginary part

➡ $A_y \neq 0$

N. Christ and T.D. Lee, Phys. Rev. 143, 1310 (1966)

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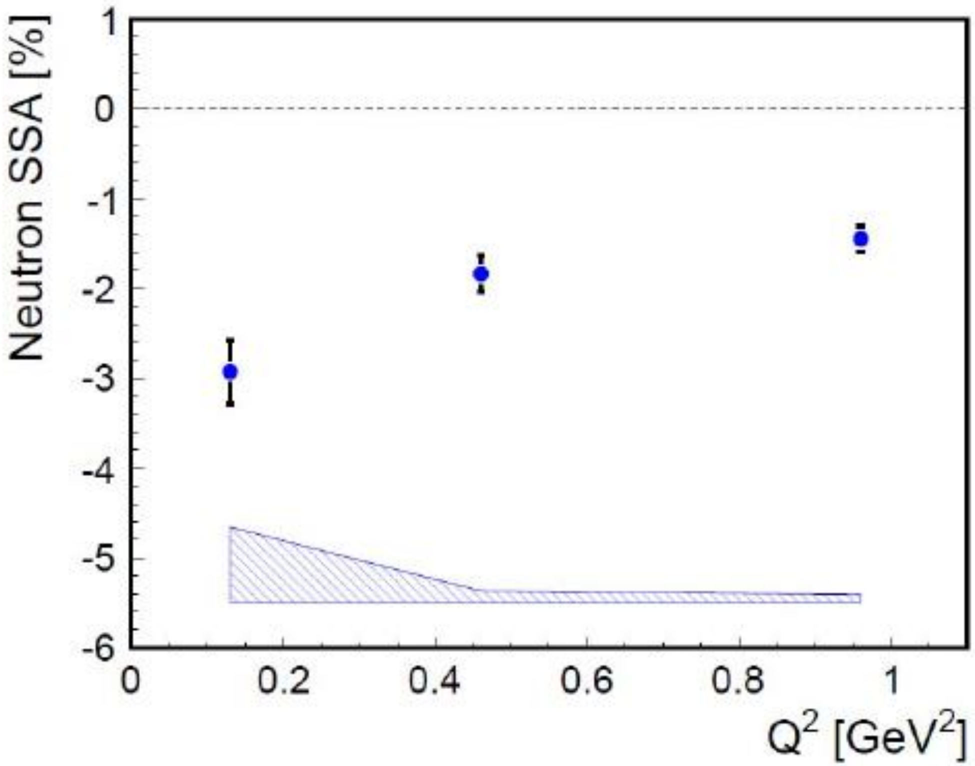
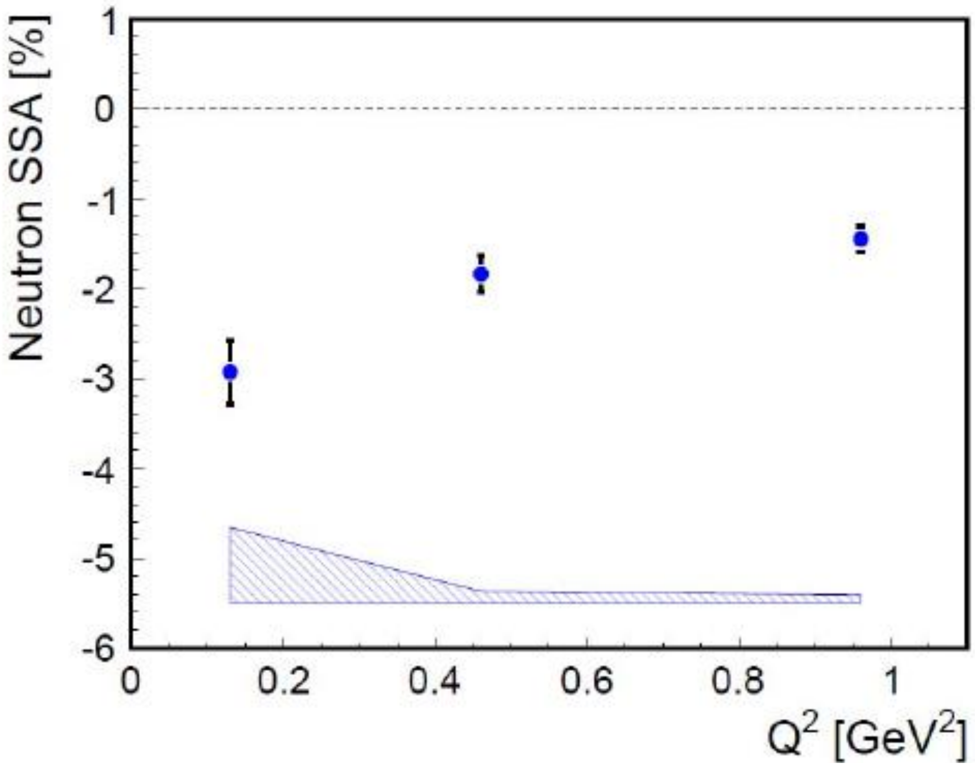
Experimental Results



- Extracted neutron asymmetries from the measured ^{3}He results
- First time a non-zero A_y with high-precision (~10^{-4} level) was measured.

Experimental Results

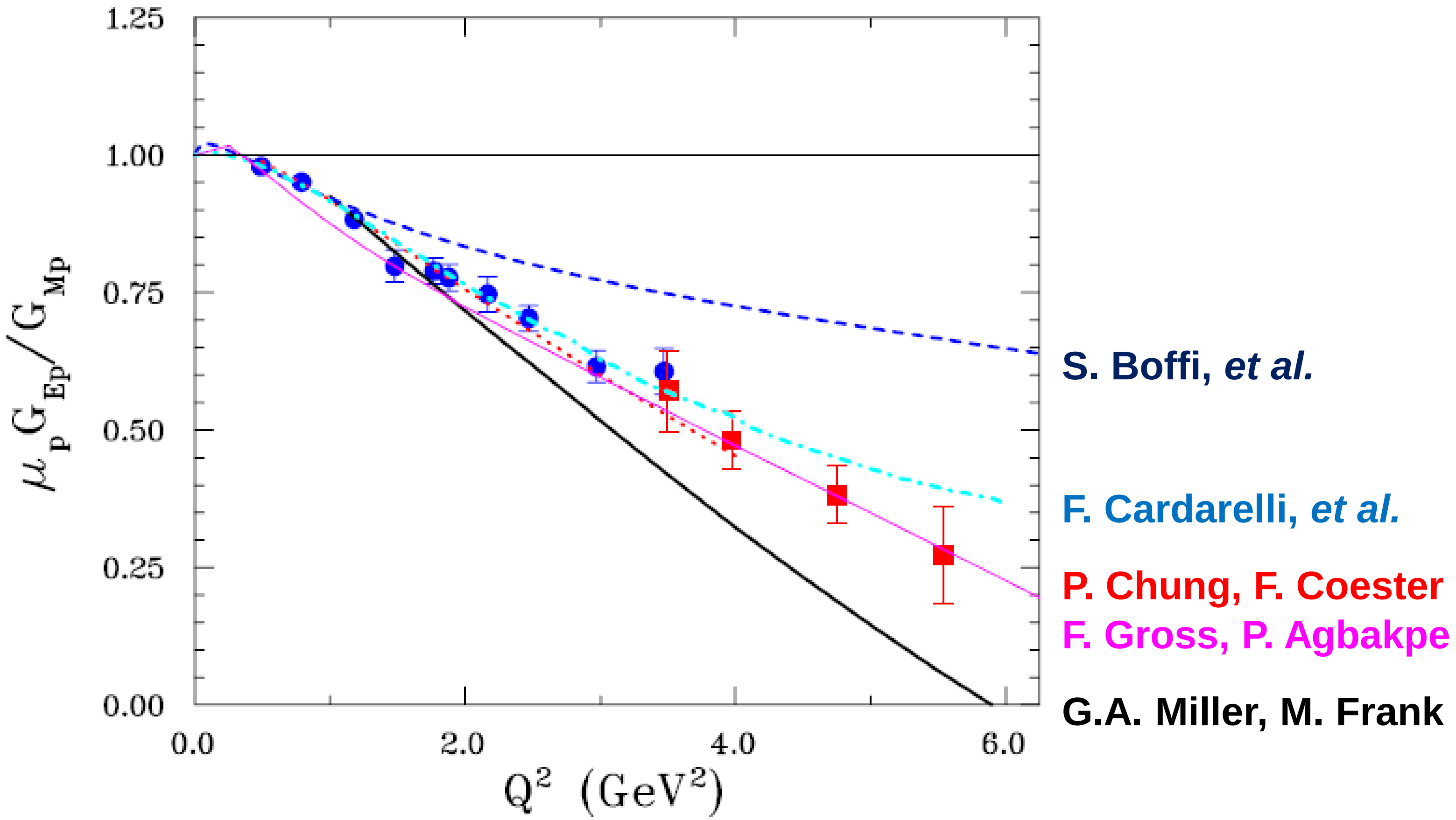


Q^2 [GeV^2]	Prediction [%] [5]	Experiment [%]
0.13	0.16	$-2.93 \pm 0.35 \pm 0.84$
0.46	-0.15	$-1.84 \pm 0.20 \pm 0.13$
0.97	-1.35	$-1.45 \pm 0.14 \pm 0.09$

Quark Orbital Angular Momentum

Calculations reproduce recently observed falloff in G_E/G_M

- Descriptions differ in details, but nearly all were directly or indirectly related to quark angular momentum



C. Perdrisat, V. Punjabi, and M. Vanderhaeghen, PPNP 59 (2007)

What can we learn from form factors?

- At small $Q^2 \rightarrow$ larger length scale, closely related to the proton size.
- In the non-relativistic limit:

$$\left\langle r_{E,M}^2 \right\rangle = \frac{-6}{G_{E,M}(0)} \left[\frac{d}{dQ^2} G_{E,M}(Q^2) \right]_{Q^2=0}$$

- The slope of the form factors versus Q^2 is related to the charge and magnetic radius of the proton.