Spin Structure of the Nucleon?

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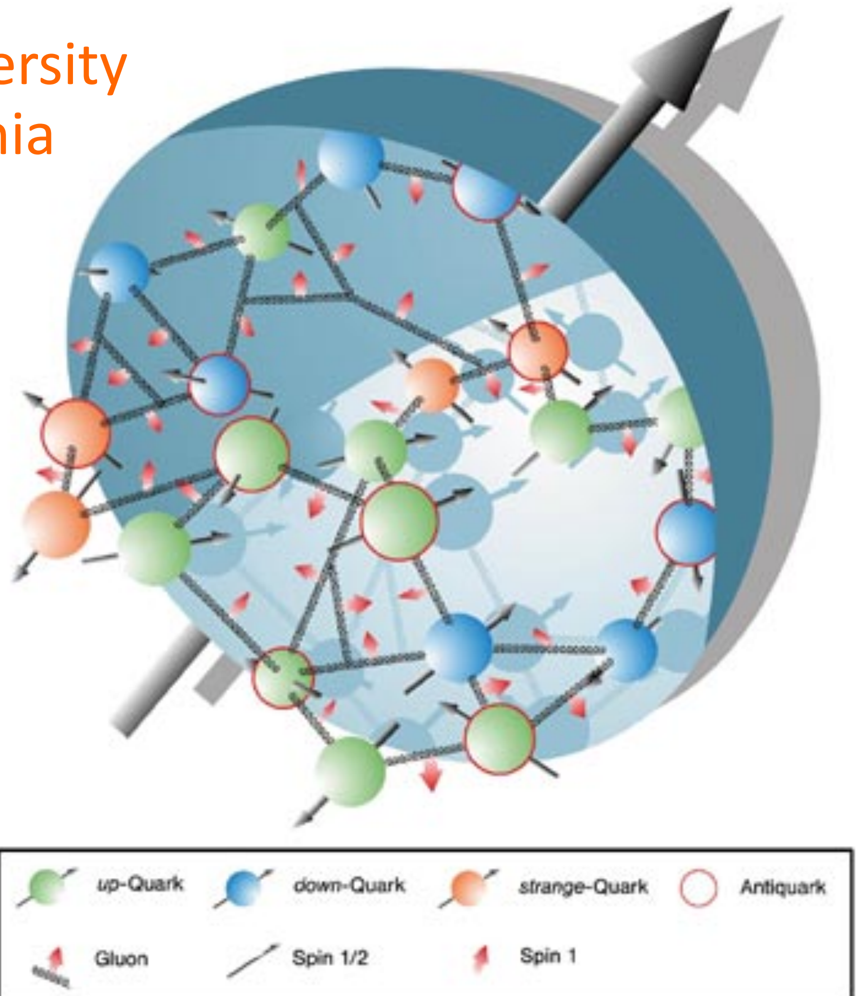
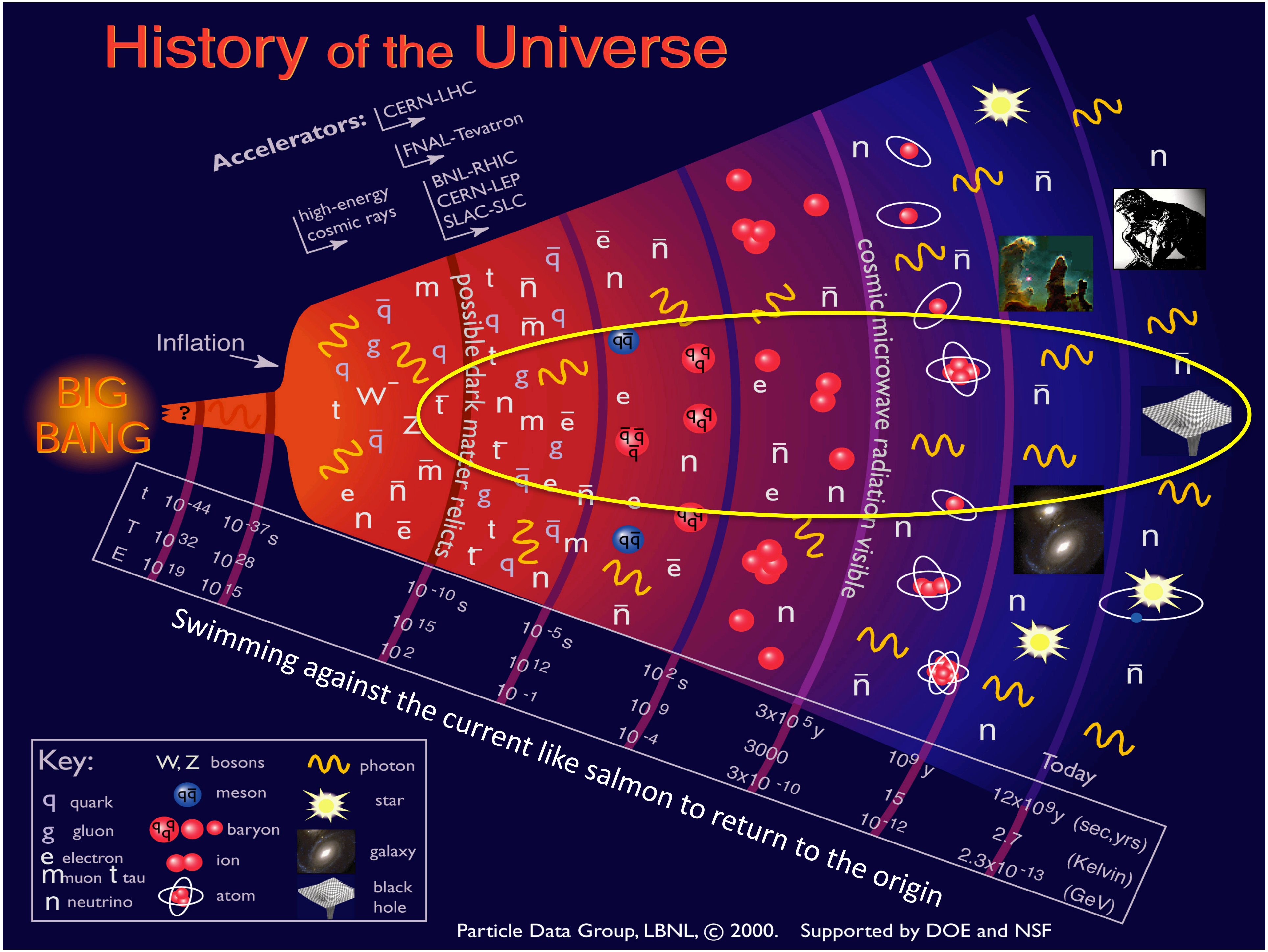


Coutesy of CERN Courier

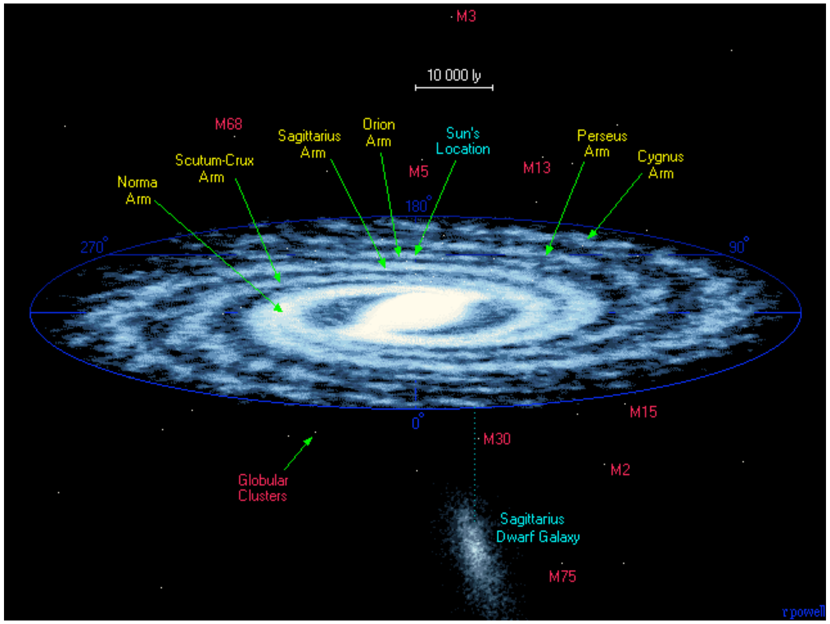
Outline

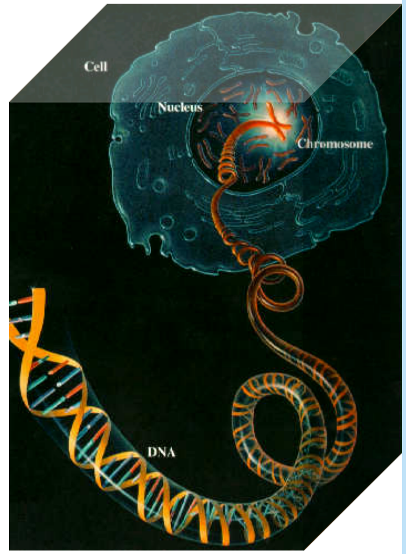
- Lecture 1
  - Introduction to scattering and spin
  - Spin of the proton from the basic constituents
- Lecture 2:
  - Spin at low energy scale, moments polarizabilities
  - Spin at large x, moments, quark-gluon correlations
- Lecture 3:
  - Nucleon Tomography and Orbital Angular Momentum
    - Generalized parton Distributions
    - Transverse momentum Distributions



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10 -44 10 -37 s 10 -10 s 10 -5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Swimming against the current like salmon to return to the origin
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

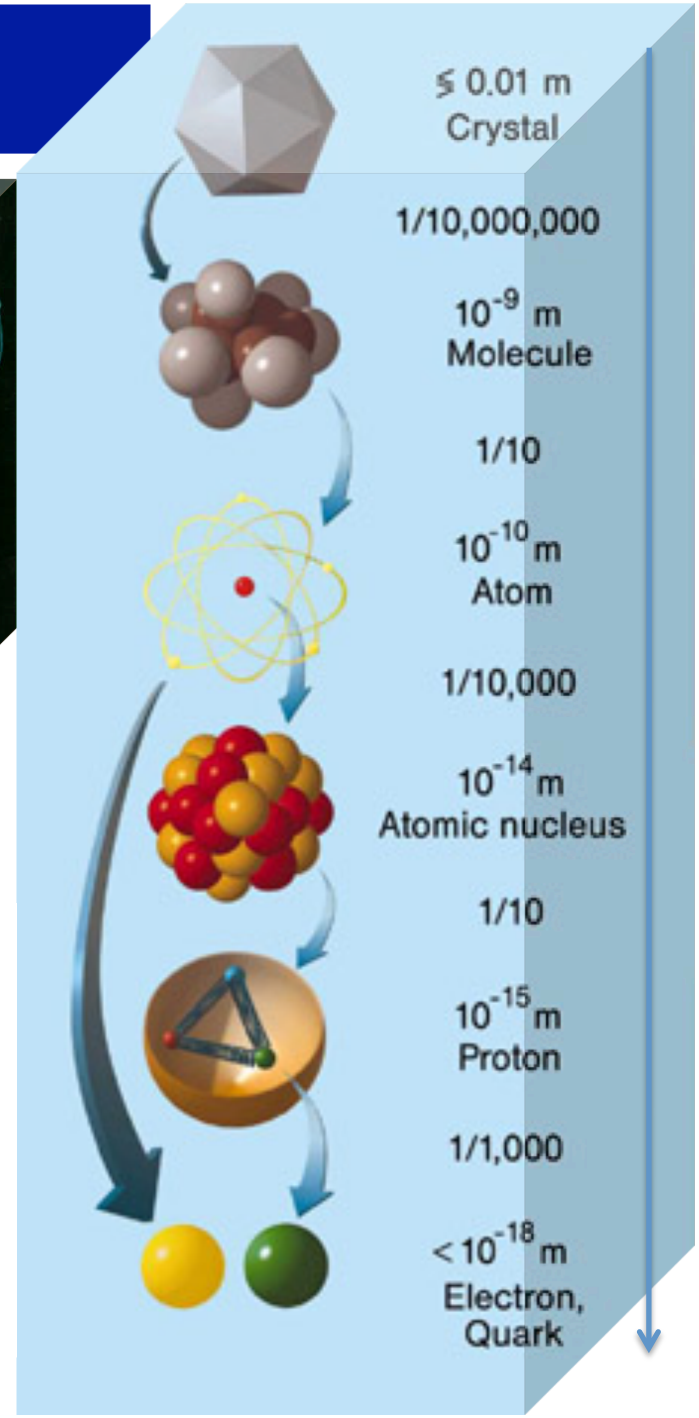
Of fundamental importance in science: The structure of matter at all distances



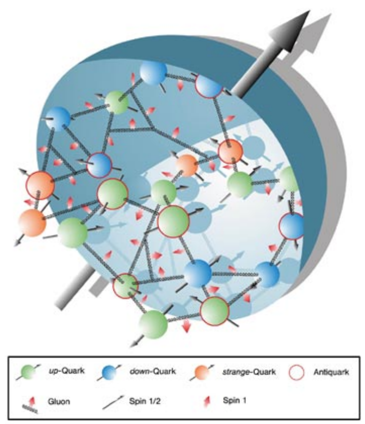


Cell +DNA

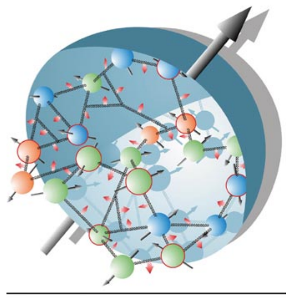
Our Galaxy



The focus of these lectures is the nucleon, a system made out of strongly interacting particles, quarks and gluons, and its spin



Spin in everyday Life



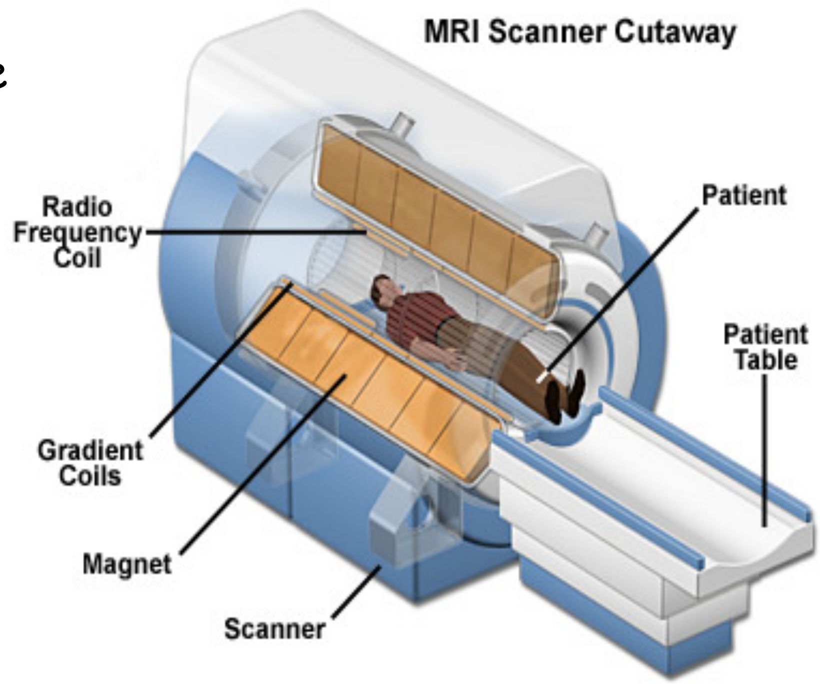
Proton spins are used to image the structure and function of the human body using the technique of Magnetic Resonance Imaging (MRI)

Paul C. Lauterbur

Sir Peter Mansfield

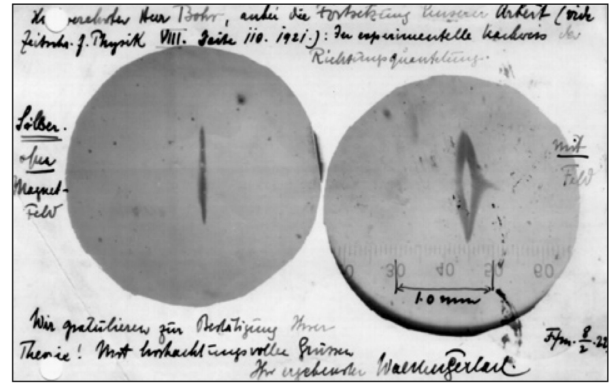
Nobel Prize Medicine 2003:

“for their discoveries concerning Magnetic Resonance Imaging"



Historical Perspective

- Spin an "intrinsic property" emerges during development of quantum mechanics;
  - Stern-Gerlach experiment 1922



Postcard from Gerlach to Bohr. Image courtesy of Niels Bohr Archive, Copenhagen.

- Spin (magnetic moment) hinted that the nucleon is not point like
  - Otto Stern (1933) measured the magnetic moment of the proton to be

$$\mu_p = e\hbar/2m_p c(1+\kappa_p) \qquad \kappa_p = 1.7928$$

- Quantum Statistics: According to Pauli (1940) "particles of half integer spin obey Fermi-Dirac statistics and those of integer spin obey Bose-Einstein statistics.

Nature: http://www.nature.com/milestones/milespin/index.html

Spin Milestones Timeline According to a recent Nature Article.

Despite its success, the standard model is unsatisfactory for a number of reasons. First, although the electromagnetic and weak forces have been unified into a single force, a 'grand unified theory' that brings the strong interaction into the fold remains elusive. Second, the origins of mass are not fully understood. Third, gravity is not included.

Although it is difficult to explain supersymmetry through analogies to classical physics, its consequences are dramatic — it predicts that every fundamental particle has a superpartner with half a unit of spin less. The electron, for instance, has a spin of a half, so its superpartner (which is known as a selectron) has zero spin. This means that the superpartner of a boson is always a fermion and vice versa.

1896	Zeeman effect (1)
1922	Stern–Gerlach experiment (2)
1925	The spinning electron (3)
1928	Dirac equation (4)
	Quantum magnetism (5)
1932	Isospin (6)
1940	Spin–statistics connection (7)
1946	Nuclear magnetic resonance (8)
1950s	Development of magnetic devices (9)
1950–1951	NMR for chemical analysis (10)
1951	Einstein–Podolsky–Rosen argument in spin variables (11)
1964	Kondo effect (12)
1971	Supersymmetry (13)
1972	Superfluid helium-3 (14)
1973	Magnetic resonance imaging (15)
1975–1976	NMR for protein structure determination (16)
1978	Dilute magnetic semiconductors (17)
1988	Giant magnetoresistance (18)
1990	Functional MRI (19)
	Proposal for spin field-effect transistor (20)
1991	Magnetic resonance force microscopy (21)
1996	Mesoscopic tunnelling of magnetization (22)
1997	Semiconductor spintronics (23)

Zoom-zoom| Dreamstime.com

Nucleon Spin; Why should we / you care?

- Has been a laboratory for Quantum Chromodynamics (QCD) the theory of strong interactions in the last 30 years
  - Example: Test of the Bjorken Sum Rule, described by Feynman as one that would have a decisive influence on the future of high-energy physics
- The nucleon is a strongly interacting many body confined system
- Turns out to be an important window into QCD dynamics too

Force carriers (Fields) and matter constituents within the Standard Model

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

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

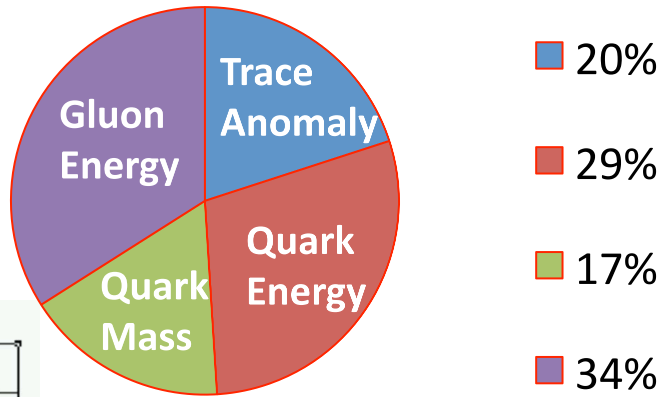
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

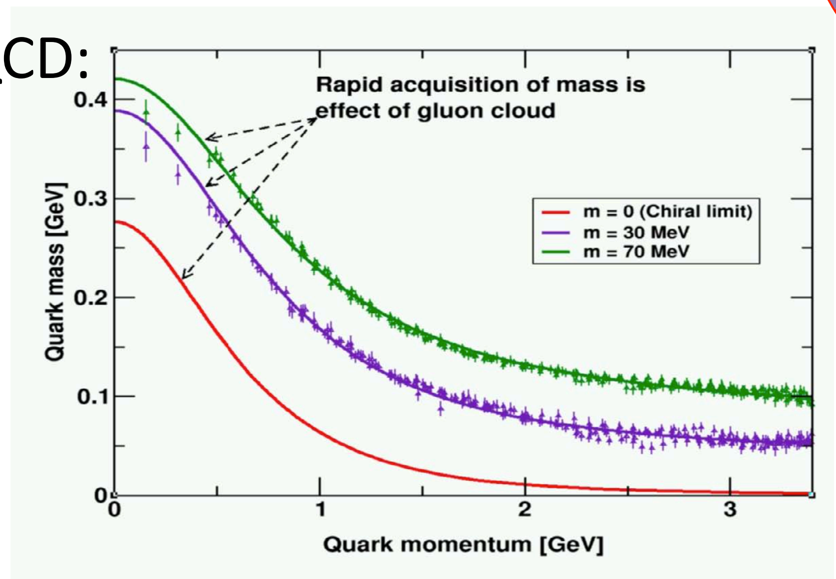
Nucleon Mass- Where does it come from?

- Naive expectation
  - quark masses (current quarks not constituent quarks) but not enough to generate the proton mass
- Ji's Decomposition of the proton mass
  X. Ji PRL 74 (1995) 1071

$$M = \frac{\langle P|H_{\rm QCD}|P\rangle}{\langle P|P\rangle}|_{\rm rest\ frame} \quad H_{\rm QCD} = \int d^3\vec{x}\, T^{00}(0,\vec{x})$$



- Lattice QCD:



Current quark mass
Grows into a constituent quark mass

Gluon dynamics dominates
The mass of QCD bound states

Quantum Chromodynamics (QCD)

A quantum field theory of quarks and gluons

- **Fields:** $\psi_i^f(x)$ — **Quark fields:** spin-½ Dirac fermion (like electron)
  - **Color triplet:** $i = 1, 2, 3 = N_c$
  - **Flavor:** $f = u, d, s, c, b, t$

  $A_{\mu,a}(x)$ — **Gluon fields:** spin-1 vector field (like photon)
  - **Color octet:** $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f - \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc} A_{\mu,b} A_{\nu,c} \right]^2 + \text{gauge fixing} + \text{ghost terms}$$

- **QED Lagrangian density – force to hold atoms together:**

$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f \right] \psi^f - \frac{1}{4} \left[\partial_\mu A_\nu - \partial_\nu A_\mu \right]^2$$

QCD is much richer in dynamics than QED

Gluons are dark, but, interact with themselves, NO free quarks and gluons

Courtesy of J. W. Qiu

The Science Problem in relation to Nucleon Structure?

Quantum Chromodynamics (QCD) and confinement

What do we know?

QCD works well in the perturbative (weak) regime

Many experimental tests led to this conclusion

But

Confinement in QCD is still a puzzle and among the 10 top problems in Physics! (Gross, Witten,….)

Strings 2000

Lattice QCD, AdS/CFT correspondence…….?!

AdS/CFT: anti de Sitter/Conformal field theory

STRINGS MICHIGAN THEORY

July 10-15, 2000 University of Michigan Ann Arbor

"Millennium Madness"

Physics Problems for the Next Millennium

In 1900 the world-renowned mathematician David Hilbert presented twenty-three problems at the

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature?
   Louise Dolan, University of North Carolina, Chapel Hill
   Annamaria Sinkovics, Spinoza Institute
   Billy & Linda Rose, San Antonio College

8. What is the resolution of the black hole information paradox?
   Tibra Ali, Department of Applied Mathematics and Theoretical Physics, Cambridge
   Samir Mathur, Ohio State University

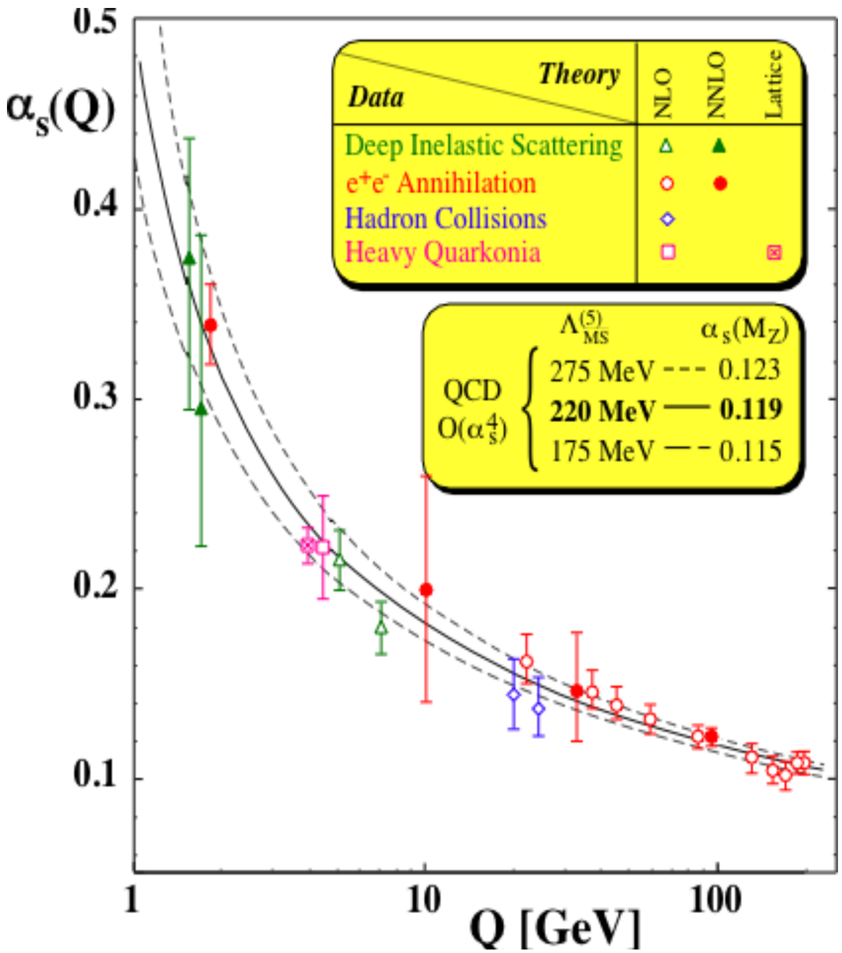
9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?
   Matt Strassler, Institute for Advanced Study, Princeton

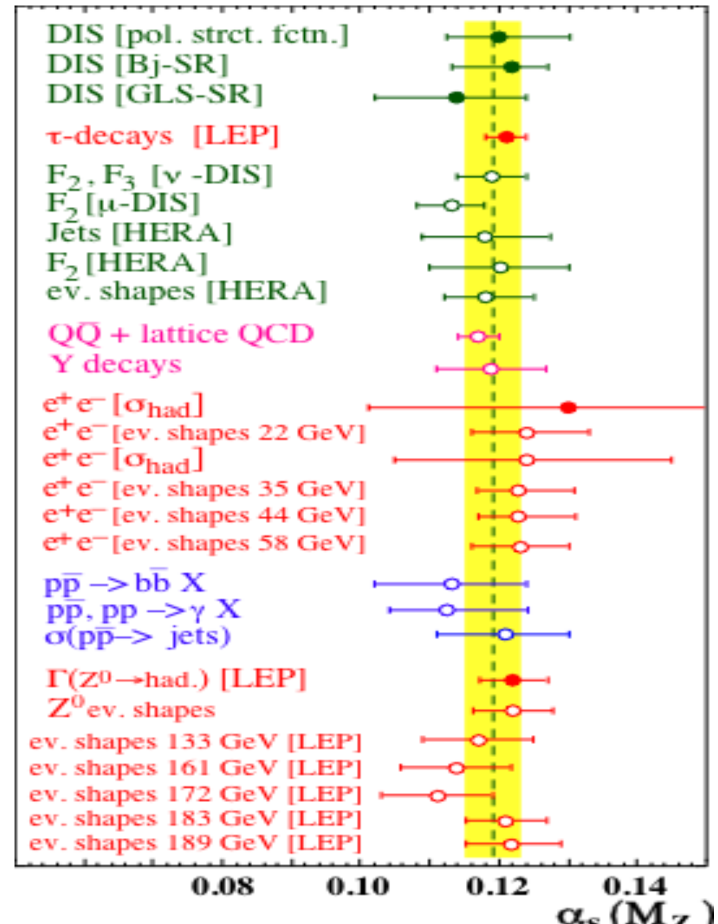
10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap?
    Igor Klebanov, Princeton University
    Oyvind Tafjord, McGill University

These ten questions were presented by David Gross at the closing of the conference on Saturday July 15, 2000.

QCD: asymptotic freedom

Gross,Wilczek, Politzer





$$\alpha_S(Q^2) = \frac{12\pi}{(11\,N_c - 2\,n_f)\ln\left(\frac{Q^2}{\Lambda^2_{\rm QCD}}\right)}\left[1 - \frac{6(153-19n_f)}{(11N_c-2n_f)^2}\frac{\ln(\ln(Q^2/\Lambda^2_{\rm QCD}))}{\ln(Q^2/\Lambda^2_{\rm QCD})}\right] + \cdots$$

Coupling grows weaker with increasing momentum transfer (shorter distances)

Resolution of the probe and scale of the theory tools

Models

10 ∞

Q^2

OPE *pQCD*

QCD

theory

expansion

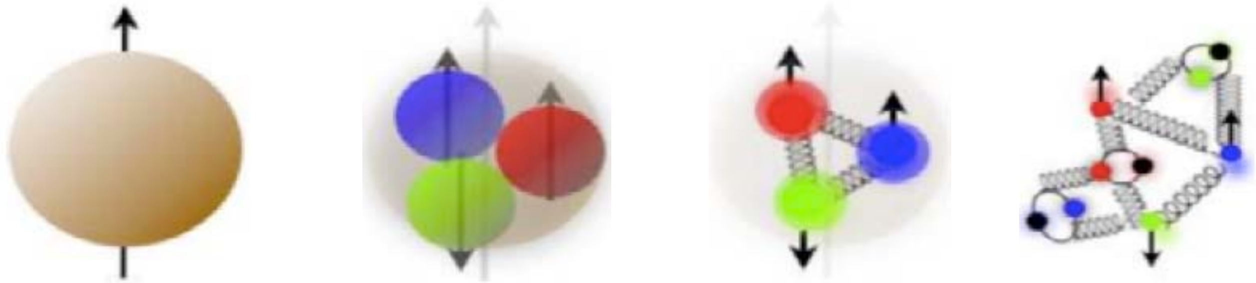
antum Chromodynami

Nucleon Spin

- In QCD- the Nucleon Spin is a window into a complex nucleon state

$$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) = \frac{1}{2}\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

$$S(\mu) = \frac{1}{2}$$



$$\mu \Rightarrow \infty$$

- In a Quark Model $S_p \equiv \langle p \uparrow | \, S \, | p \uparrow \rangle = \frac{1}{2}, \qquad S = \sum_i S_i$

$$|p \uparrow\rangle = \sqrt{\frac{1}{18}} [u \uparrow u \downarrow d \uparrow -2 \ u \uparrow u \uparrow d \downarrow +\text{perm.}]$$

- Asymptotic Limit

Ji

$$J_q(\mu \to \infty) \Rightarrow \frac{1}{2} \frac{3N_f}{16 + 3N_f} \sim \frac{1}{4} \qquad J_g(\mu \to \infty) \Rightarrow \frac{1}{2} \frac{16}{16 + 3N_f} \sim \frac{1}{4}$$

- Spin Structure?

Role of partons' intrinsic spin vs partons' dynamical motion

Studying the structure of hadrons

How?

⇨ Rutherford tradition of scattering experiments

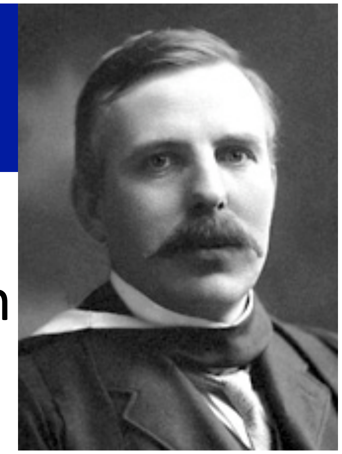
⇨ Using a super high resolution transmission electron (lepton) microscopes

SLAC, CERN, DESY, Jefferson Lab

⇨ Using hadronic probes

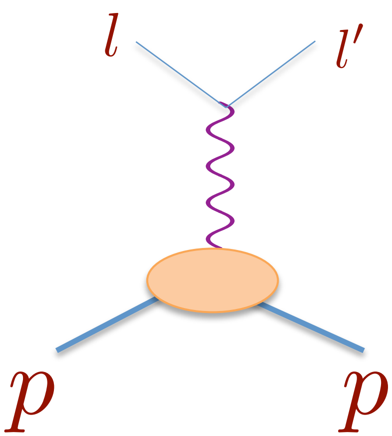
RHIC

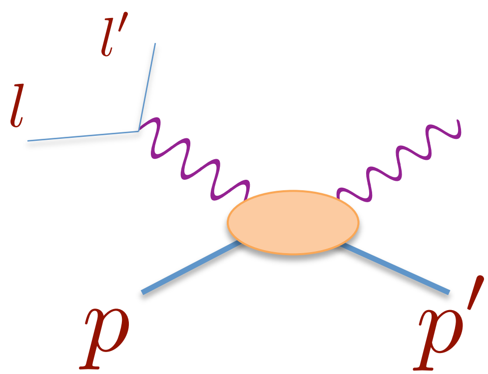
Experimental tools to investigate Spin by Scattering

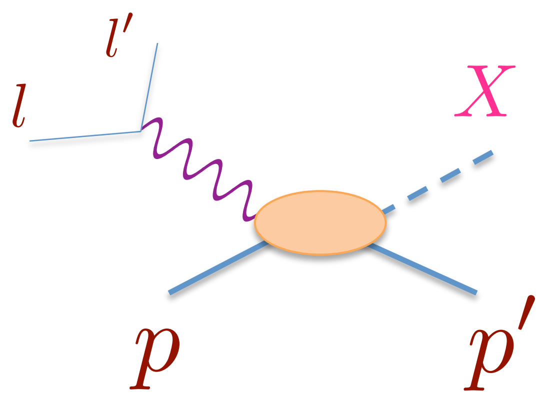


Rutherford,
1908, Chem. N.P.

- Use of lepton or hadron beams to scatter on the nucleon
  - ➡ Polarized beams of e-, e+, μ+, μ-, p
- Use of proton and nuclei targets that are polarized
  - ➡ Targets in many cases are polarized p, D, NH_3, ND_3, ^3He,)
- Electromagnetic probe as a microscope: Compton scattering, real and virtual
  - ➡ Exclusive, semi-inclusive or inclusive (elastic scattering, inelastic scattering)







Compton,
1927, Phys. N.P.

How to get Information about the nucleon structure in terms of the constituents, quarks and gluons?

- Elastic scattering
  - Charge distribution
  - Magnetization distribution

- Deep Inelastic Scattering (DIS)
  - Inclusive DIS: detect scattered lepton
  - Semi-inclusive DIS: detect scattered lepton + one leading hadron (pion, kaon,..)
    - Momentum distribution among the different constituents
    - Spin distribution among the different constituents

Proton

Mass:
$1.672\ 621\ 71(29) \times 10^{-27}$ kg
938.272 029(80) MeV/c^2
Electric Charge:
$1.602\ 176\ 53(14) \times 10^{-19}$ C
Diameter:
About 1.6×10^{-15} m
Spin:
1/2
Quark Composition:
1 down, 2 up

Some Tools to Study Nucleon Structure and understand QCD

Generalized Parton Distributions (GPDs)

Since 1998

Inclusive

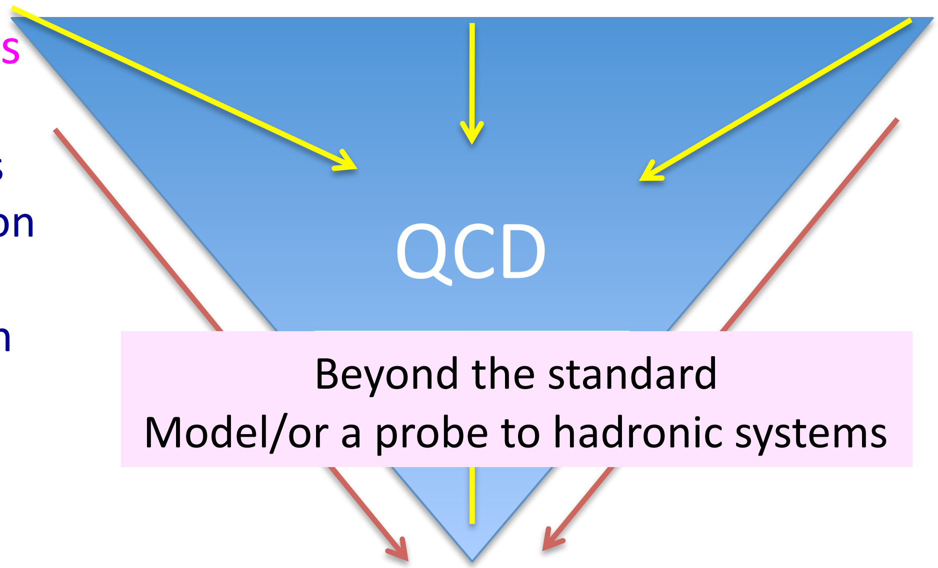
Sum rules and polarizabilities

Transverse Momentum Distributions (TMDs)

Since 2002

Exclusive reactions

Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production



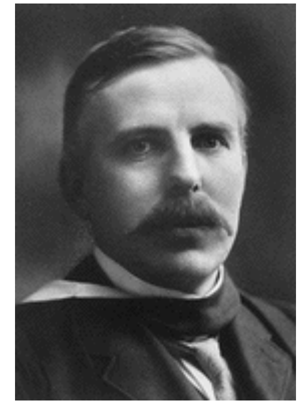
Semi-Inclusive DIS

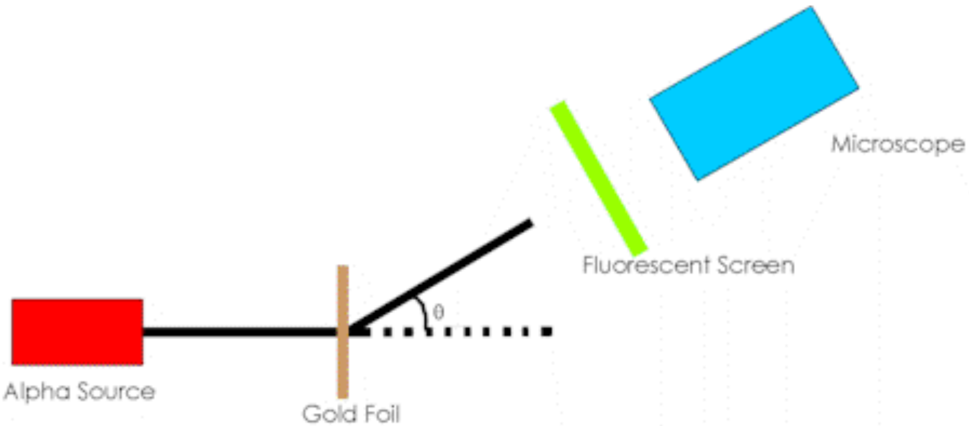
Distributions and Fragmentation functions

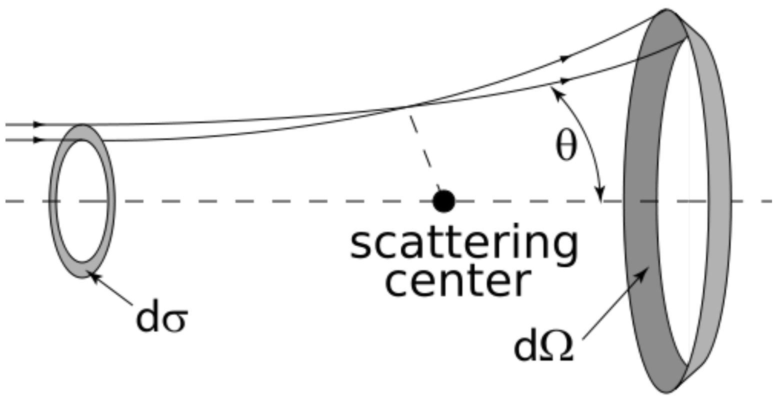
Beyond the standard Model/or a probe to hadronic systems

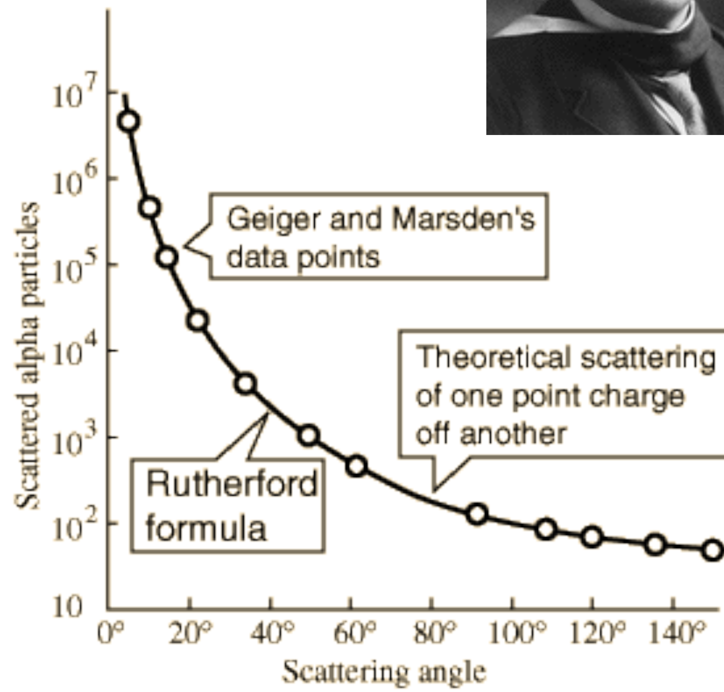
GPDs and TMDs in Nuclei
Exclusive
Semi-inclusive
Initial and final medium effects

Rutherford scattering







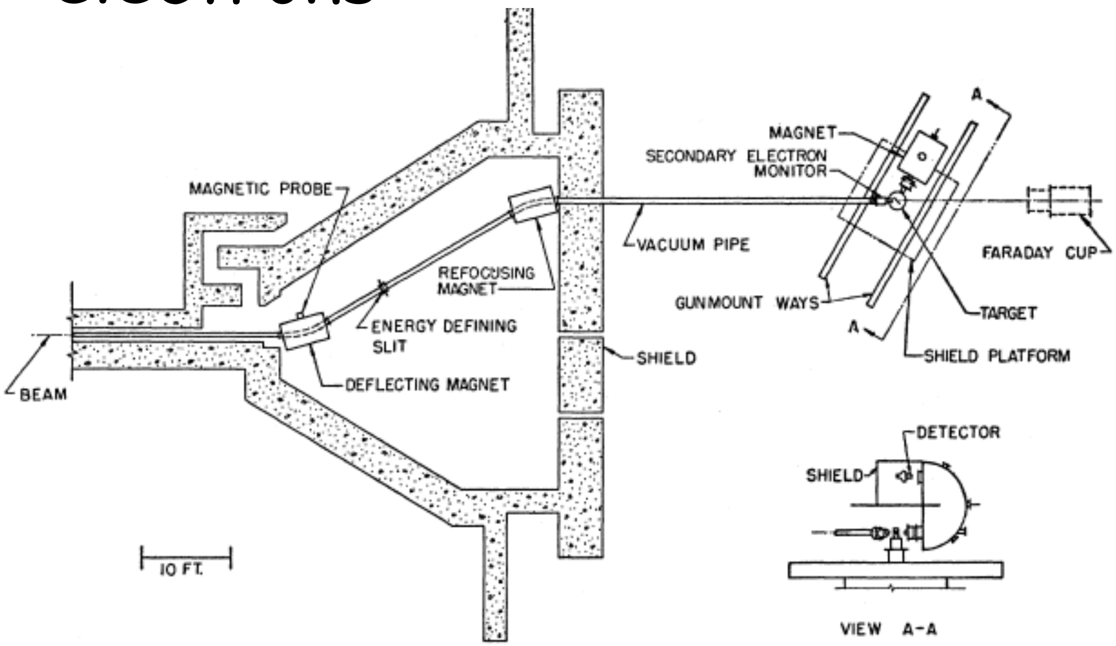


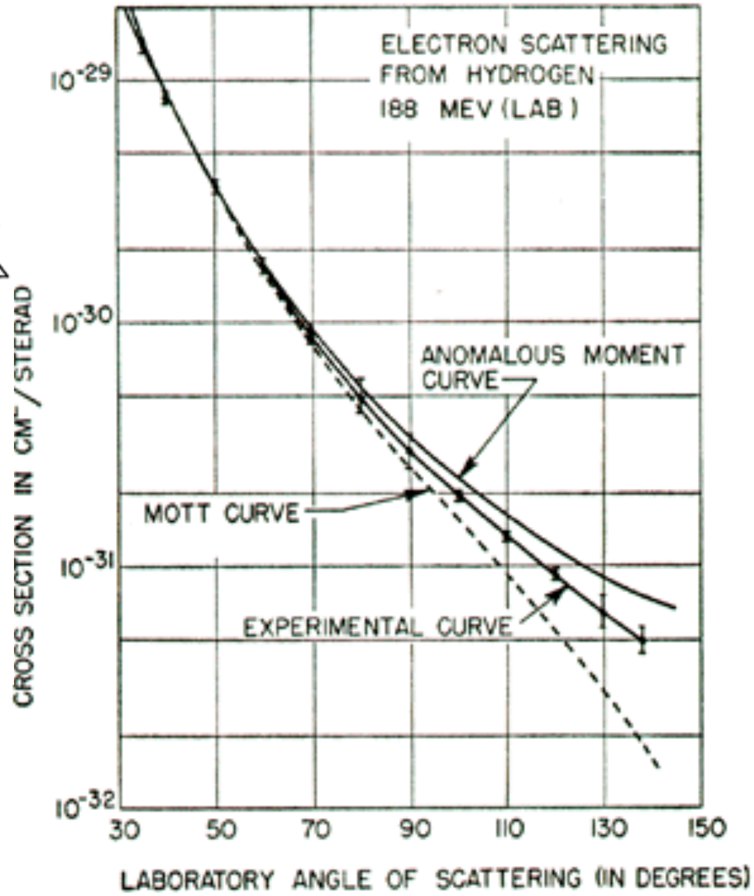
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha\hbar c}{2mv_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

Finite size of proton

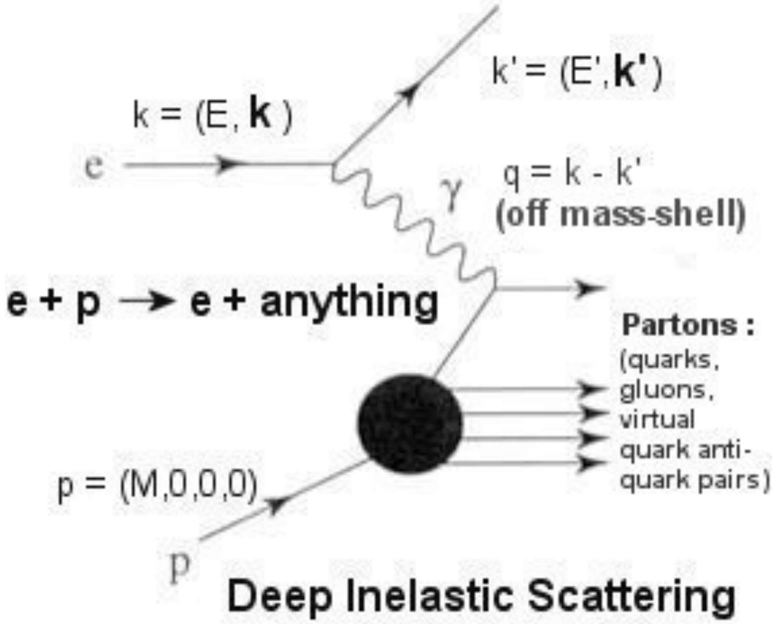
Hofstadter

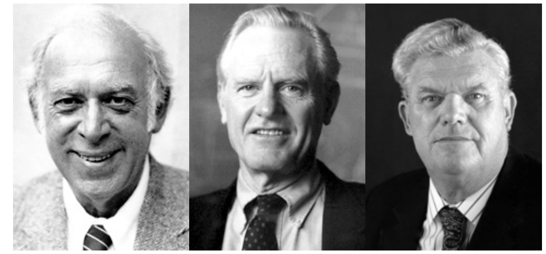
- Rutherford (elastic) scattering with electrons



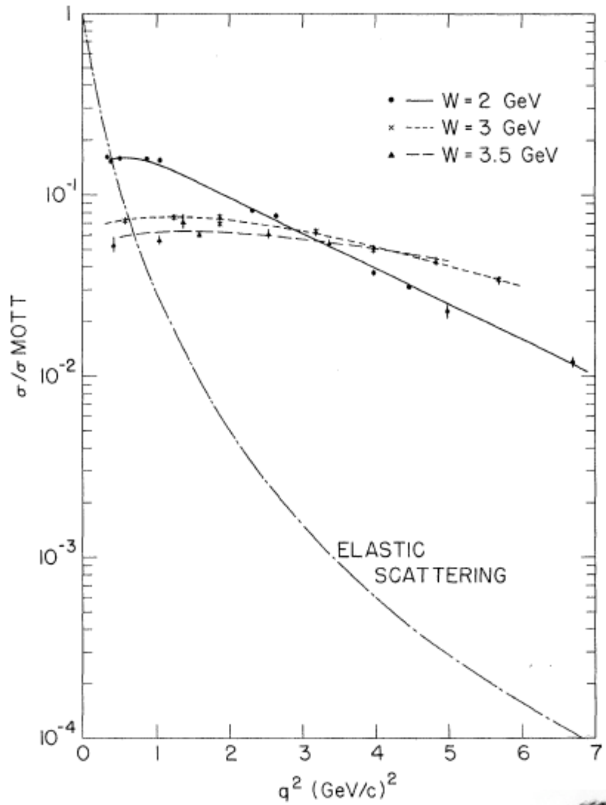


Deep Inelastic Scattering





Friedman Kendall Taylor



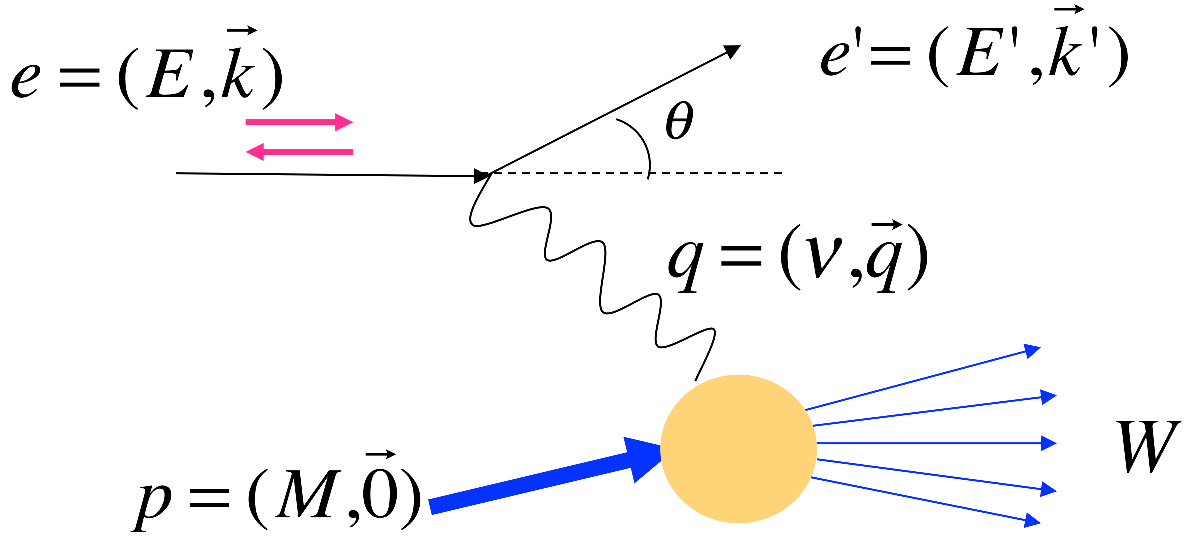
Bjorken Scaling: $Q^2 \rightarrow$ Infinity

Feynman Parton Model

Feynman

Inclusive lepton scattering

The one photon exchange approximation



$$W^2 = M^2 + 2M\nu - Q^2$$

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

$$x = \frac{Q^2}{2M\nu}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$$

Leptonic tensor:

$$L_{\mu\nu} = L^S_{\mu\nu} + iL^A_{\mu\nu} = 2\left[k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu}\left(k \cdot k' - m^2\right) + im\epsilon_{\mu\nu\rho\sigma} q^\rho s^\sigma\right]$$

Hadronic Tensor:

$$W^{\mu\nu} = W^{\mu\nu}_S + iW^{\mu\nu}_A = \frac{1}{2\pi}\int d^4x\; e^{iq\cdot x} < P, S|[J_\mu(x), J_\nu(0)]|P, S >$$

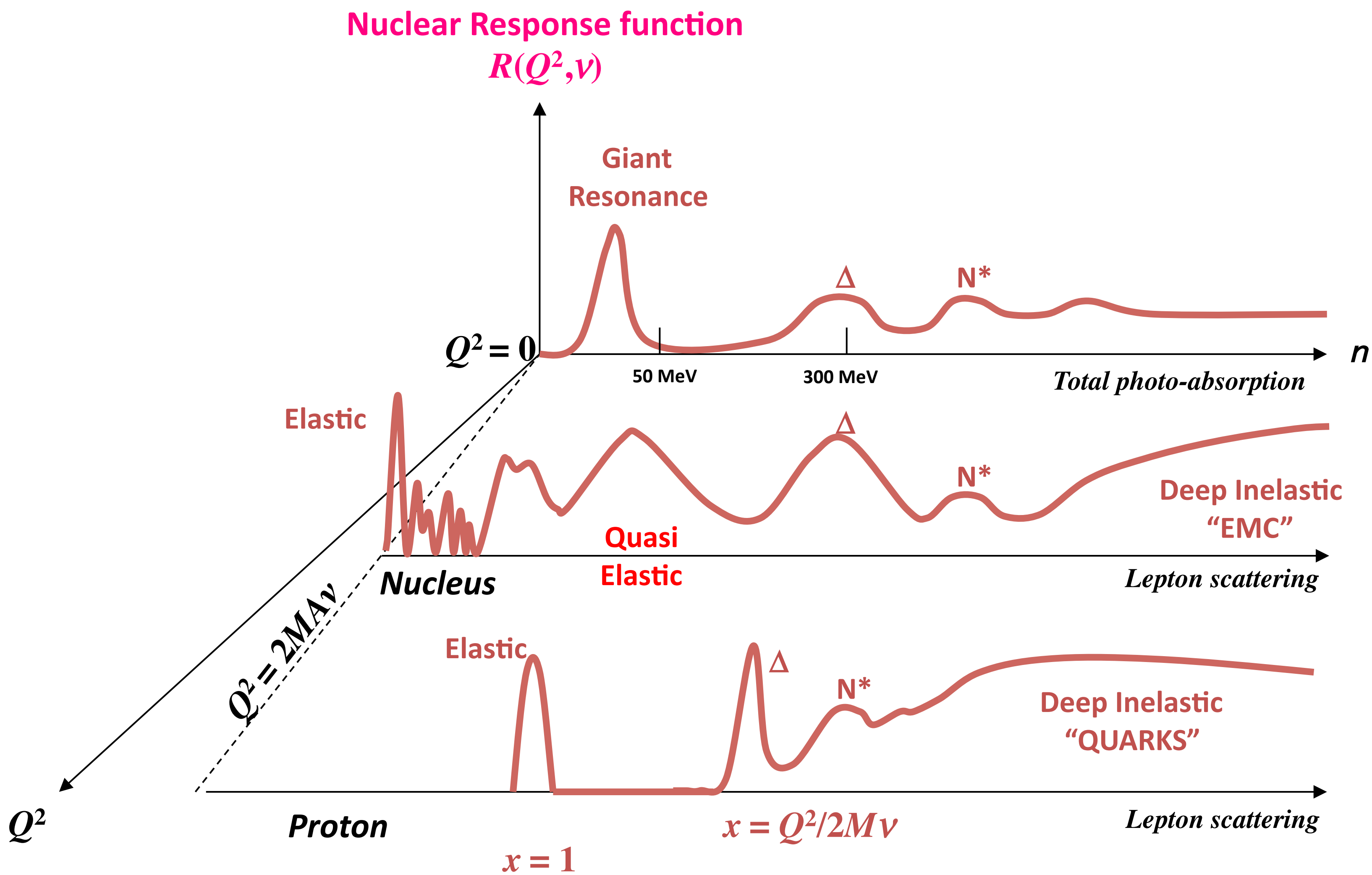
Quantum Electrodynamics

Feynman diagrams → Matrix element → Fermi's Golden Rule → Transition probability → Cross section

Example of inclusive electron scattering

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

Nucleus/nucleon response to electromagnetic scattering



Inclusive lepton scattering (continued)

- The symmetric part of the tensor is written in terms of two spin-independent structure functions $W_1(x,Q^2)$ and $W_2(x,Q^2)$:

$$W_S^{\mu\nu} = -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) W_1 + \frac{1}{M^2}\left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left((P^\nu - \frac{P\cdot q}{q^2}q^\nu\right) W_2$$

- The *antisymmetric* part of the tensor is similarely written in terms of two spin dependent structure functions $G_1(x,Q^2)$ and $G_2(x,Q^2)$

$$W_A^{\mu\nu} = WM\epsilon^{\mu\nu\rho\sigma} q_\rho s_\sigma G_1(\nu,Q^2) + \frac{1}{M}\epsilon^{\mu\nu\rho\sigma} q_\rho \left[(P\cdot q)S_\sigma - (S\cdot q)P_\sigma\right] G_2(\nu,Q^2)$$

- This decomposition is possible because the form of the tensor is constrained to be invariant under parity and time reversal. It must be hermitian: $W^{\mu\nu} = W^{\nu\mu *}$ and satisfy current conservation:

$$q_\mu W^{\mu\nu} = q_\nu W^{\mu\nu} = 0$$

Inclusive electron scattering cross sections

Unpolarized beam and target

$$\frac{1}{2}\left(\frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega}+\frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\left[2W_1(x,Q^2)\sin^2(\theta/2)+W_2(x,Q^2)\cos^2(\theta/2)\right]$$

Longitudinally polarized target and longitudinally polarized beam

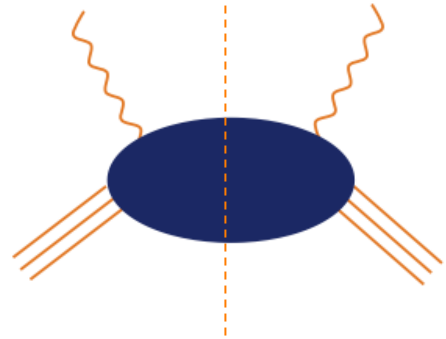
$$\left(\frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega}-\frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\frac{E}{E'}\left[(E+E'\cos\theta)G_1(x,Q^2)-Q^2G_2(x,Q^2)\right]$$

Transversely polarized target and longitudinally polarized beam

$$\left(\frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega}-\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\frac{E'^2}{E}\sin\theta\left[MG_1(x,Q^2)+2EG_2(x,Q^2)\right]$$

Virtual Photoabsorption Cross Section

$$\gamma^* + N \rightarrow \gamma^* + N$$



Compton scattering amplitude

$$\sigma_{\pm 1,0} = \frac{4\pi^2\alpha}{K}\epsilon^{\mu *}_{\pm 1,0} W_{\mu\nu}\epsilon^{\nu}_{\pm 1,0}$$

$$K = \nu - Q^2/2M$$

$$\epsilon_{\pm 1} = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)$$

Polarization vectors

$$\epsilon_0 = \frac{1}{\sqrt{Q^2}}(\sqrt{Q^2+\nu^2}, 0, 0, \nu)$$

$$\mathrm{Im}T_{[1,\frac{1}{2}\rightarrow 1,\frac{1}{2}]} \propto \sigma_{3/2} = \frac{4\pi^2\alpha}{K}[W_1 + M\nu G_1 - Q^2 G_2]$$

$$\mathrm{Im}T_{[1,-\frac{1}{2}\rightarrow 1,-\frac{1}{2}]} \propto \sigma_{1/2} = \frac{4\pi^2\alpha}{K}[W_1 - M\nu G_1 + Q^2 G_2]$$

$$\mathrm{Im}T_{[0,\frac{1}{2}\rightarrow 0,\frac{1}{2}]} \propto \sigma_L = \frac{4\pi^2\alpha}{K}[W_2(1+\nu^2/Q^2) - W_1]$$

$$\mathrm{Im}T_{0,-\frac{1}{2}\rightarrow 1,\frac{1}{2}} \propto \sigma_{TL} = \frac{4\pi^2\alpha}{K}\sqrt{Q^2}[MG_1 + \nu G_2]$$

Virtual Photoabsorption Cross Section

$$\sigma_T \equiv \frac{1}{2}(\sigma_{1/2} + \sigma_{3/2}) = \frac{4\pi^2\alpha}{K} W_1(\nu, Q^2)$$

$$\sigma_L \equiv \sigma_0 = \frac{4\pi^2\alpha}{K}\left[\left(1 + \frac{\nu^2}{Q^2}\right) W_2(\nu, Q^2) - W_1(\nu, Q^2)\right]$$

The unpolarized differential deep inelastic cross section can be expressed in terms of the virtual photo-absorption cross sections

$$\frac{d\sigma}{dE' d\Omega}|_{lab} = \Gamma\left(\sigma_T + \epsilon\sigma_L\right)$$

$$\Gamma = \frac{\alpha K}{2\pi^2 Q^2}\frac{E'}{E}\frac{1}{1-\epsilon} \qquad \epsilon = \left(1 + 2\frac{\nu^2 + Q^2}{Q^2}\tan^2\frac{\theta}{2}\right)^{-1}$$

Scaling of structure functions

First measurements of the unpolarized cross section show that at large Q^2 the cross section was independent of Q^2

At large Q^2 and large ν but finite x the structure functions depend only one variable, x

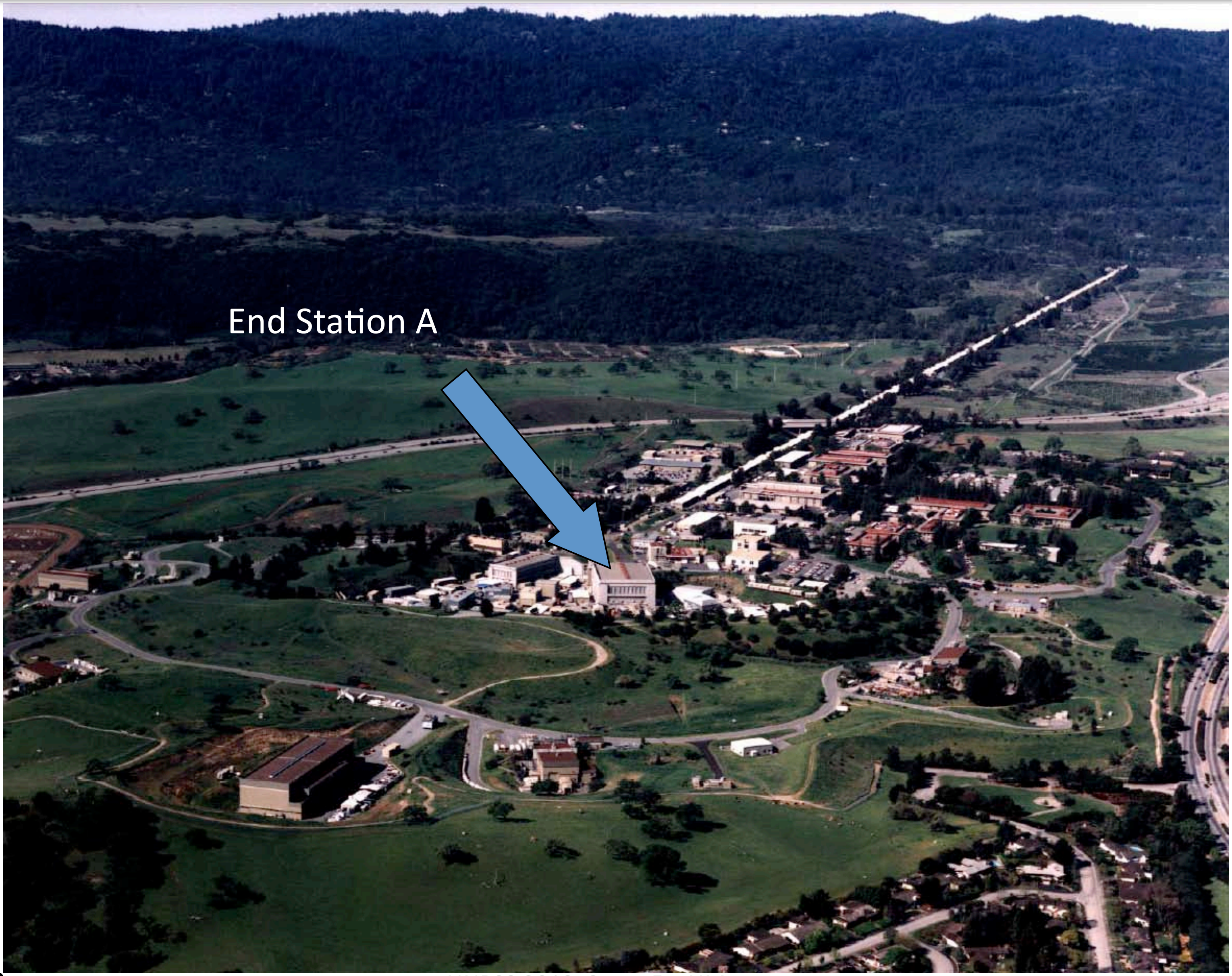
$$\begin{aligned} MW_1(\nu, Q^2) &\rightarrow F_1(x) \\ \nu W_2(\nu, Q^2) &\rightarrow F_2(x) \\ M^2\nu G_1(\nu, Q^2) &\rightarrow g_1(x) \\ M\nu^2 G_2(x, Q^2) &\rightarrow g_2(x) \end{aligned}$$

$$x = \frac{Q^2}{2M\nu}$$

The typical notation found in many papers is to write the cross sections in terms of

$$F_1(x, Q^2), F_2(x, Q^2), g_1(x, Q^2) \text{ and } g_2(x, Q^2)$$

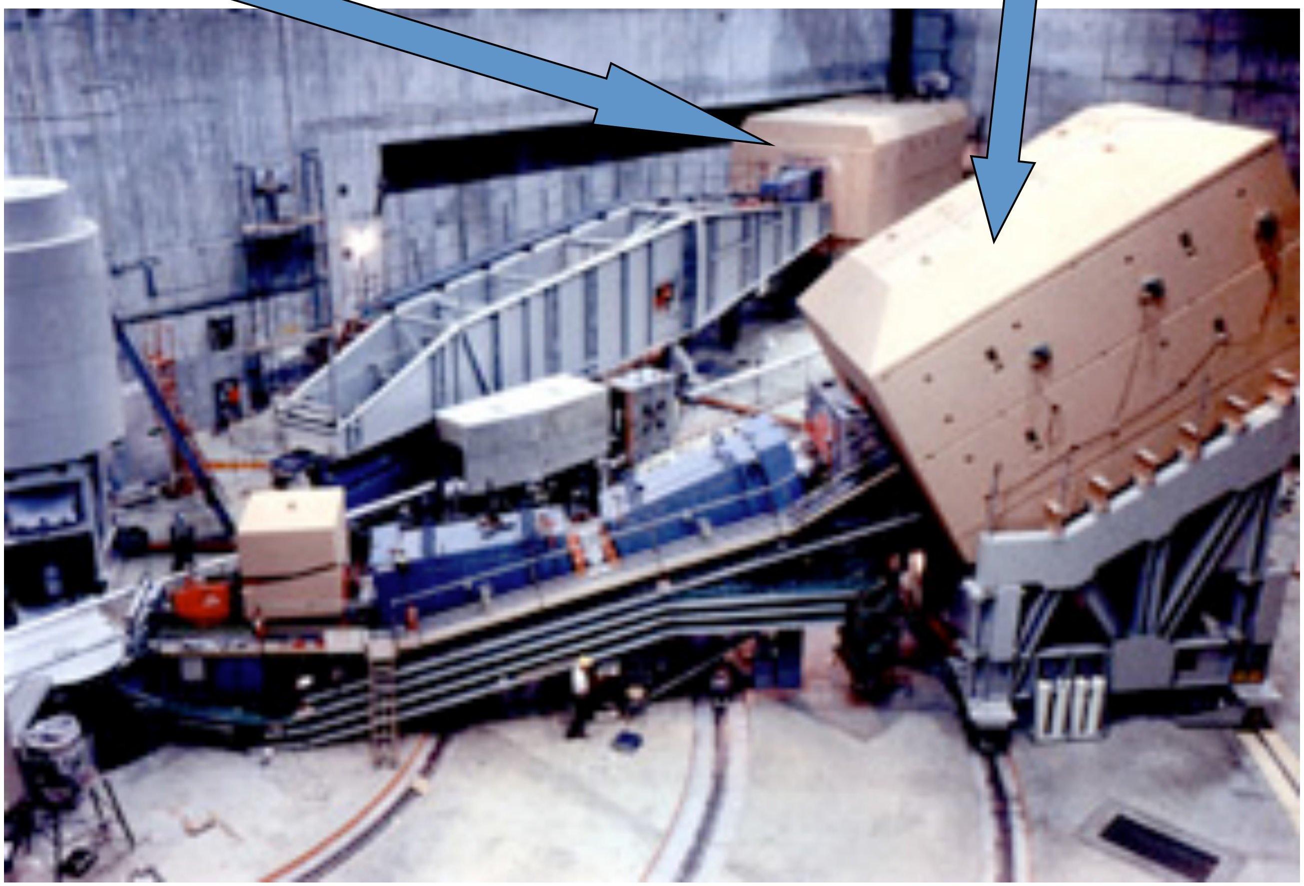
SLAC



SLAC End Station A Spectrometers

20 GeV maximum momentum spect.

8 GeV maximum momentum spect.



Scaling of F_2 Structure Function

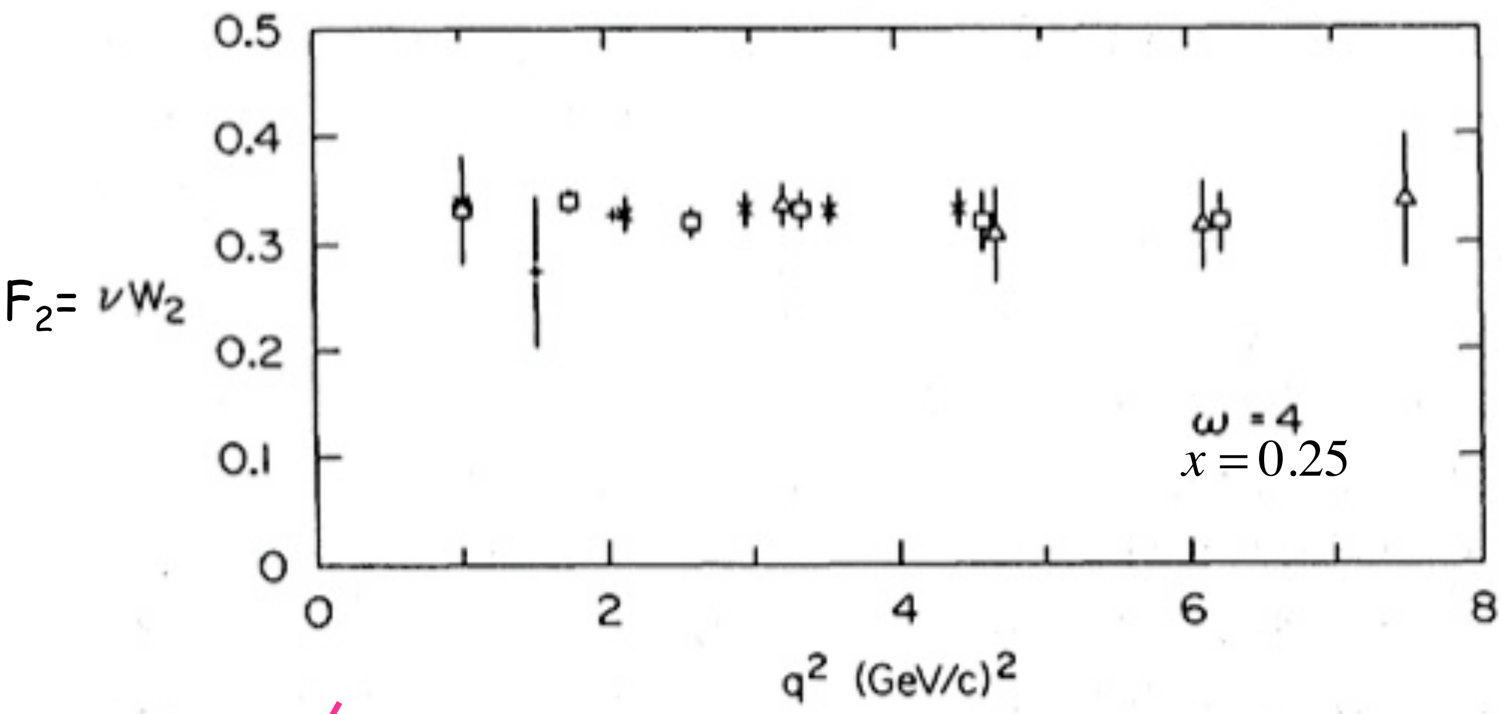
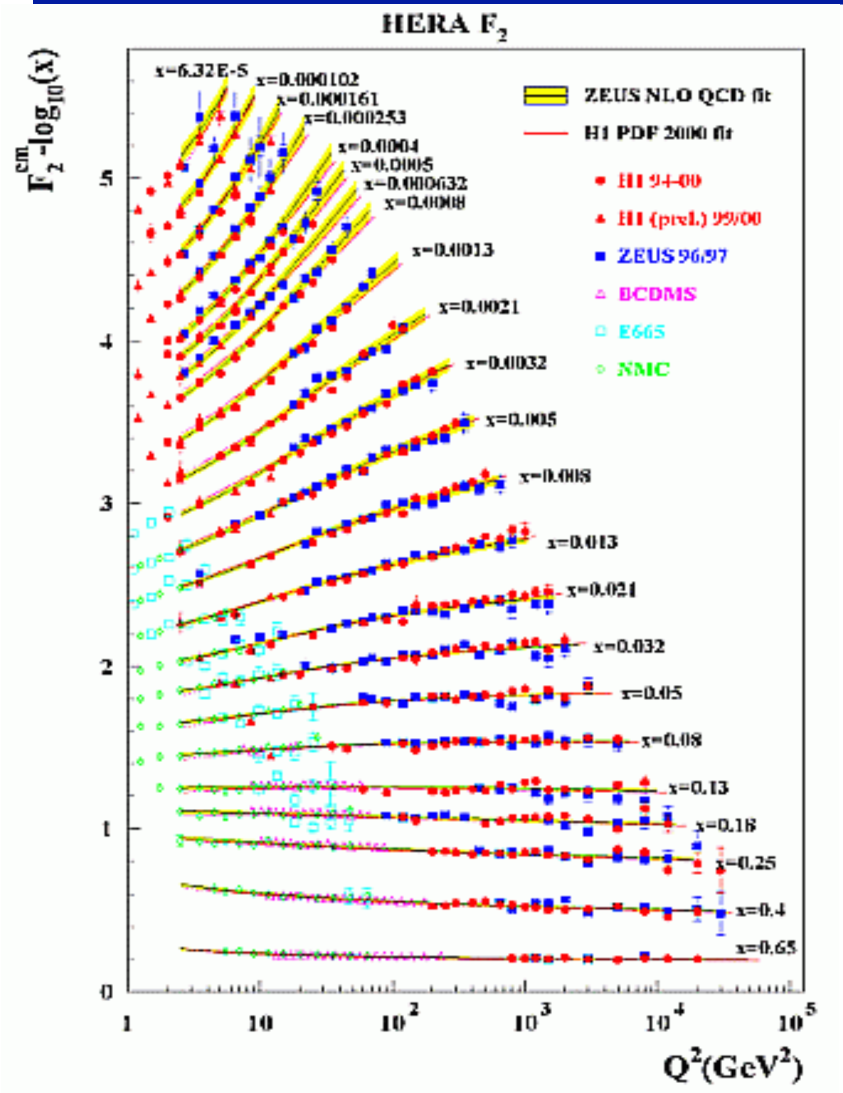


Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

1990 Nobel Prize

J. I. Friedman, H. W. Kendall and R. E. Taylor

Modern era: HERA



Unpolarized beam and target

Scaling violation due to QCD evolution