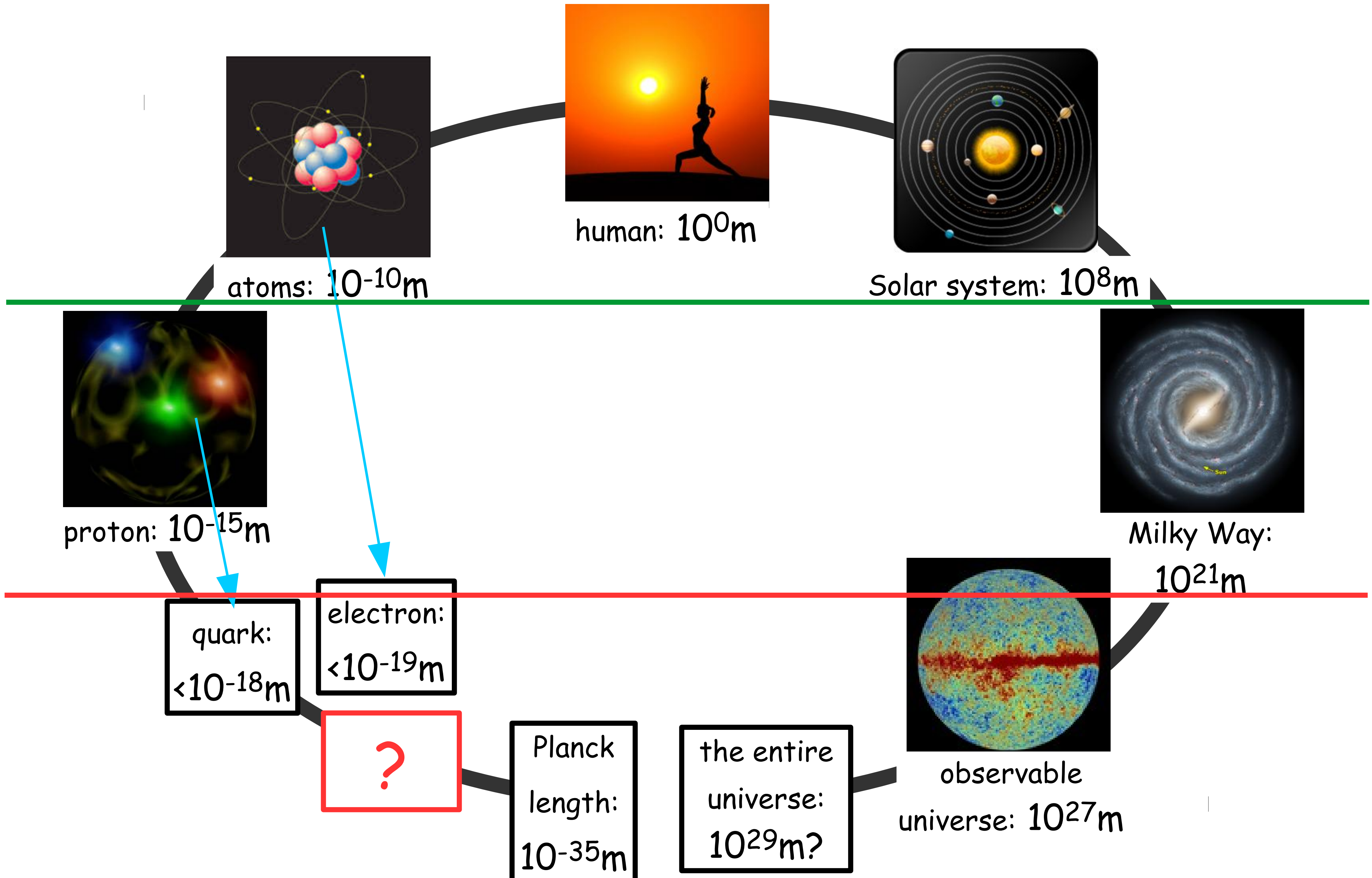
# Studies of the Nucleon Structure Using Electron Scattering

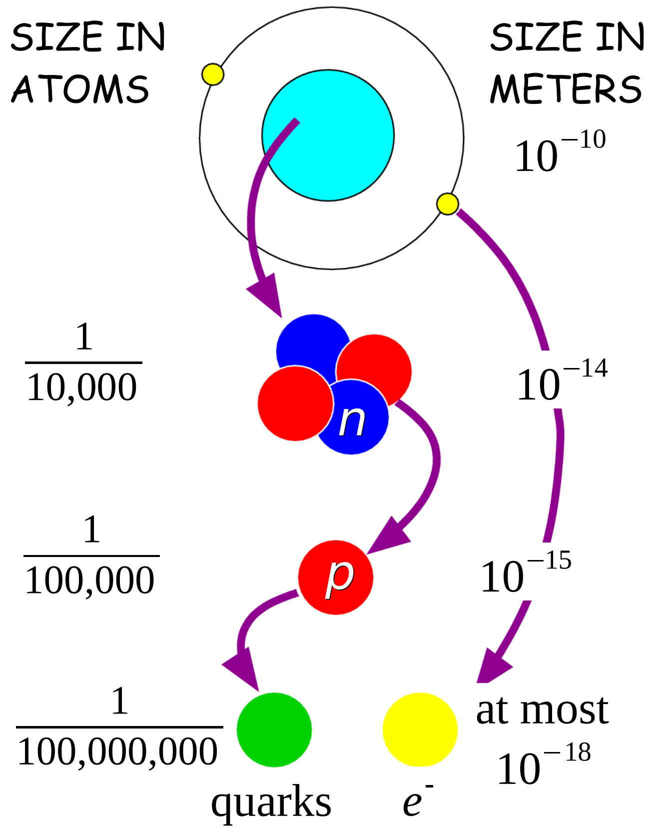
Xiaochao Zheng
University of Virginia,
Charlottesville, Virginia, USA

- From quarks to cosmos, and what we know today
- How do we study subatomic structure?
- Electron scattering at GeV level, from elastic to DIS
- Polarized DIS experiments and the nucleon spin structure
  - one example: large-x physics
- Summary

# The Beauty of Physics – From Leptons and Quarks to the Cosmos



# Scale of Nuclear (sub-atomic) Physics Research




proton:
$m=1.6726\times10^{-27}$ kg = 938.272 MeV/$c^2$

neutron:
$m=1.6749\times10^{-27}$ kg = 939.565 MeV/$c^2$

electron:
$m=9.1094\times10^{-31}$ kg = 0.511 MeV/$c^2$

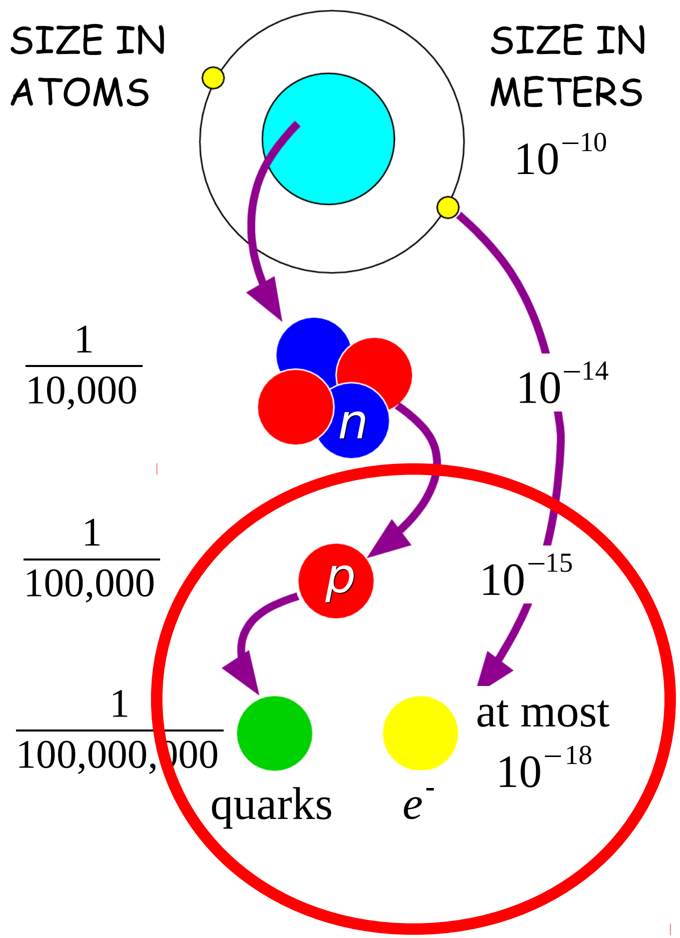
proton mass: $10^{-35}$ of Empire State Building

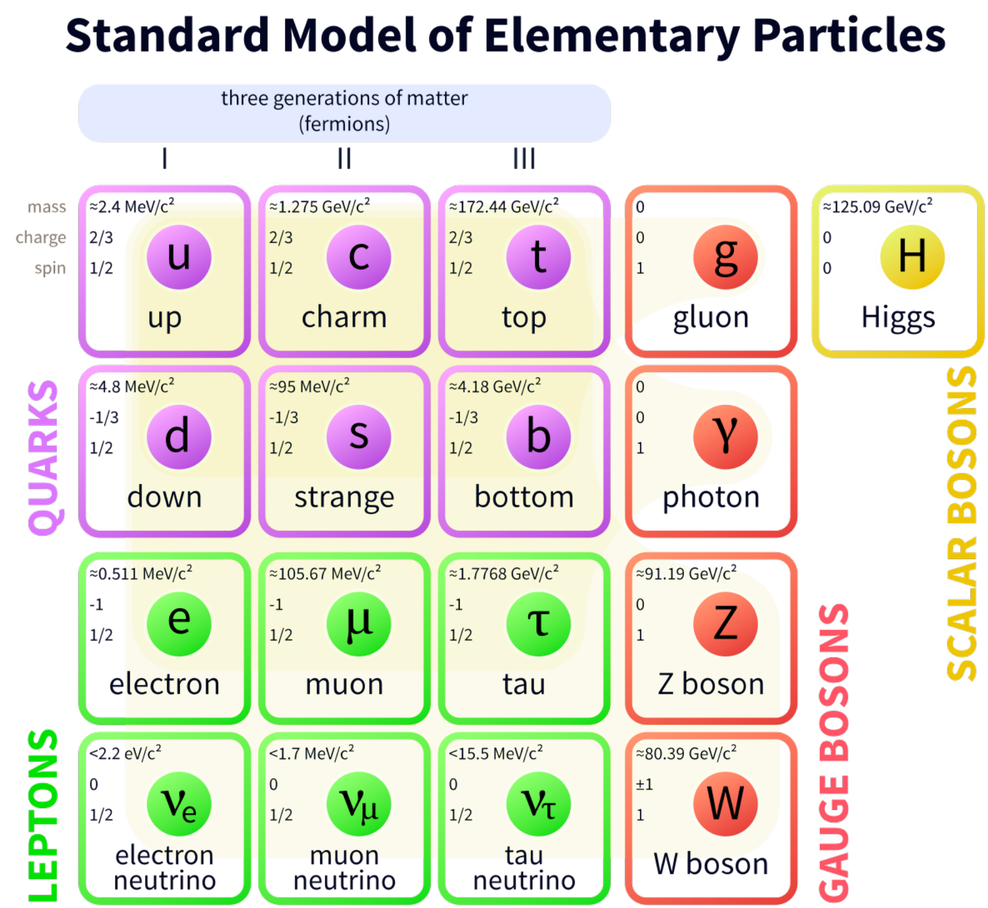
# The Standard Model

(1) the elementary fermions – quarks and leptons

(2) the symmetries (of charges → interactions)

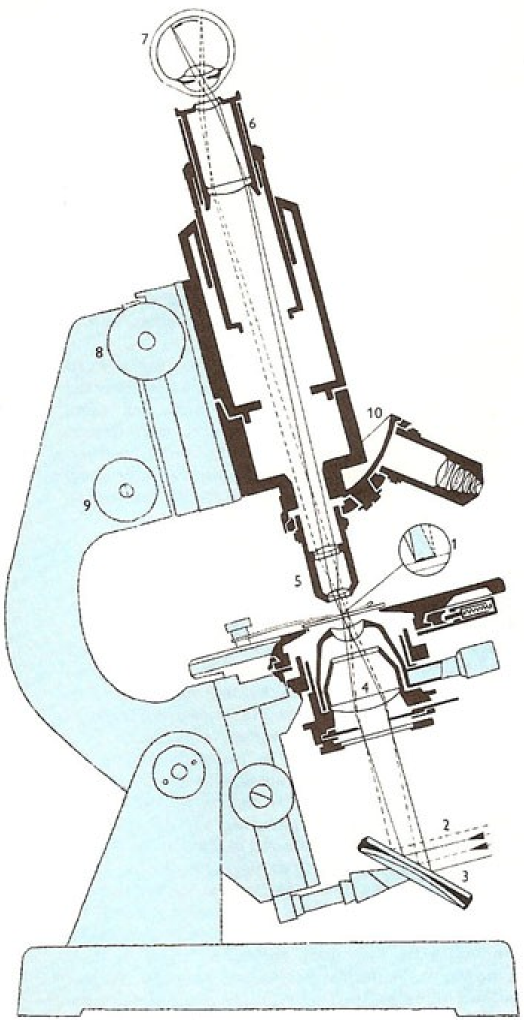
(3) the origin of masses

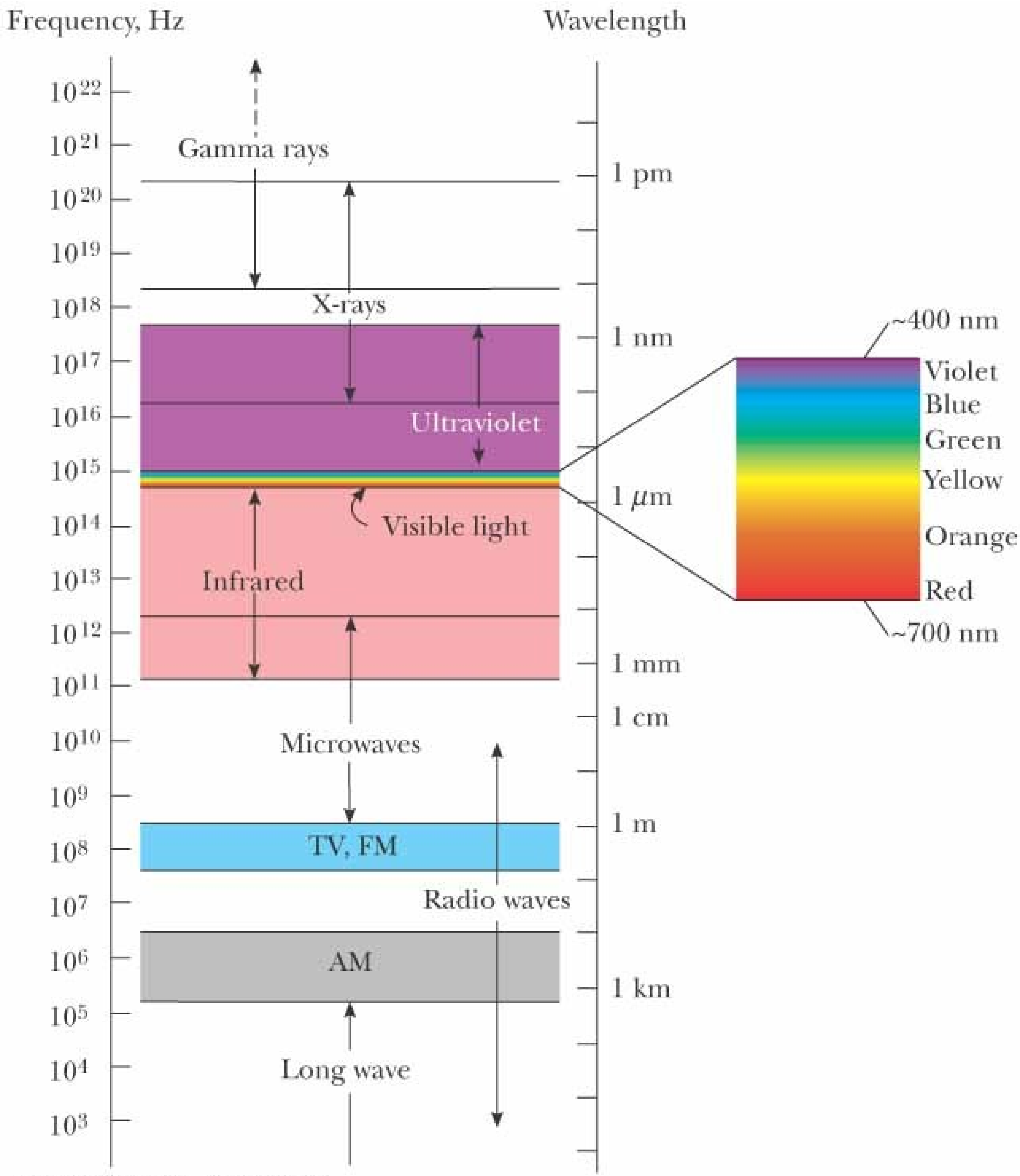



$$D^{\mu} = \partial^{\mu} - i g_1 \frac{Y}{2} B^{\mu} - i g_2 \frac{\tau_i}{2} W_i^{\mu} - i g_3 \frac{\lambda_\alpha}{2} G_\alpha^{\mu}$$

# How do we look into the nucleus?



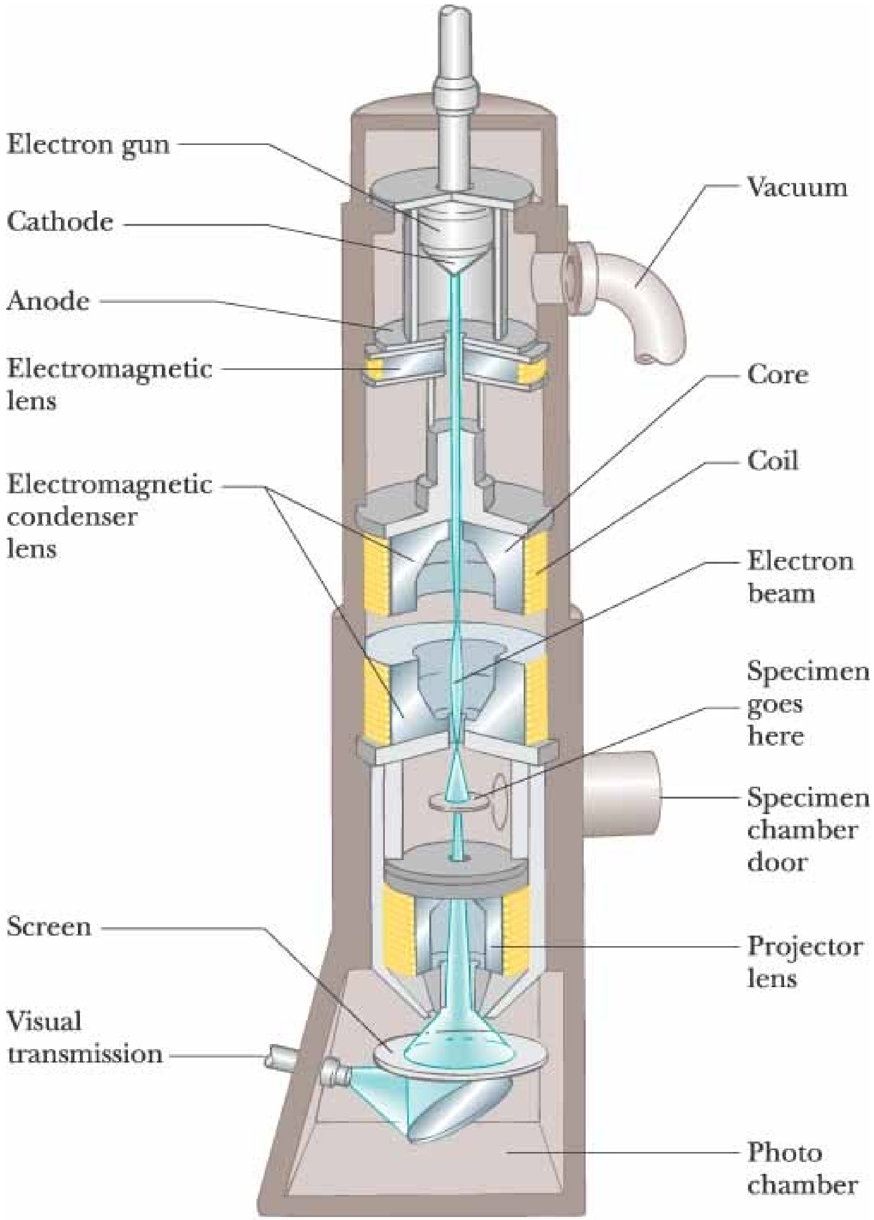
- Answer: waves are particles, but particles are also waves. By accelerating particles to high energy, they serve effectively as a microscope.

  - de Broglie wavelength: $$\boxed{\lambda = \frac{h}{|\vec{p}|}}$$

$$\hbar c = 197.33\ \mathrm{MeV} \cdot \mathrm{fm}$$

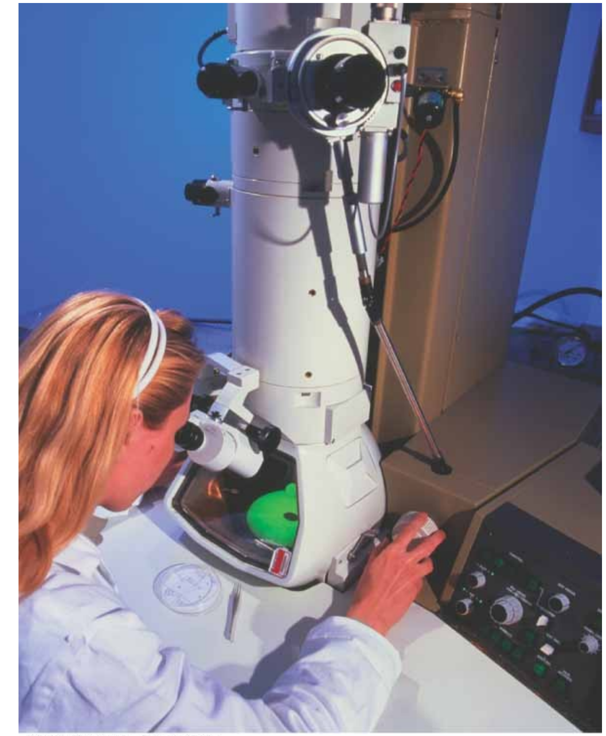
- Example 1: calculate the wavelength of 4-40keV electrons.

# Using keV-level Electron Microscopes to Study Molecular Structure




(a)







- Answer: waves are particles, but particles are also waves. By accelerating particles to high energy, they serve effectively as a microscope.

    - de Broglie wavelength: $\boxed{\lambda = \dfrac{h}{|\vec{p}|}}$

$$\hbar c = 197.33\ \mathrm{MeV}\cdot\mathrm{fm}$$

- Example 2: calculate the wavelength of 5 MeV $\alpha$ particles.
- At the beginning of nuclear physics study (early 1900's), there was no particle accelerator. All what was available was natural radiation, that's why Rutherford used ~5 MeV $\alpha$ particles in his famous experiment, that was good enough to look into the atoms and established the planetary structure of the atoms

# Early Electron Scattering and Unpolarized DIS

- 1933: Protons are not point-like ($k_p$=1.79); Estermann, Stern 1943

O. Stern — "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

- Answer: waves are particles, but particles are also waves. By accelerating particles to high energy, they serve effectively as a microscope.

  - de Broglie wavelength: $\boxed{\lambda = \frac{h}{|\vec{p}|}}$

$$\hbar c = 197.33\ \mathrm{MeV \cdot fm}$$

- Example 2: calculate the wavelength of 5 MeV $\alpha$ particles.
- At the beginning of nuclear physics study (early 1900's), there was no particle accelerator. All what was available was natural radiation, that's why Rutherford used ~5 MeV $\alpha$ particles in his famous experiment, that was good enough to look into the atoms and established the planetary structure of the atoms
- But MeV-level particles are not enough to look into the proton!

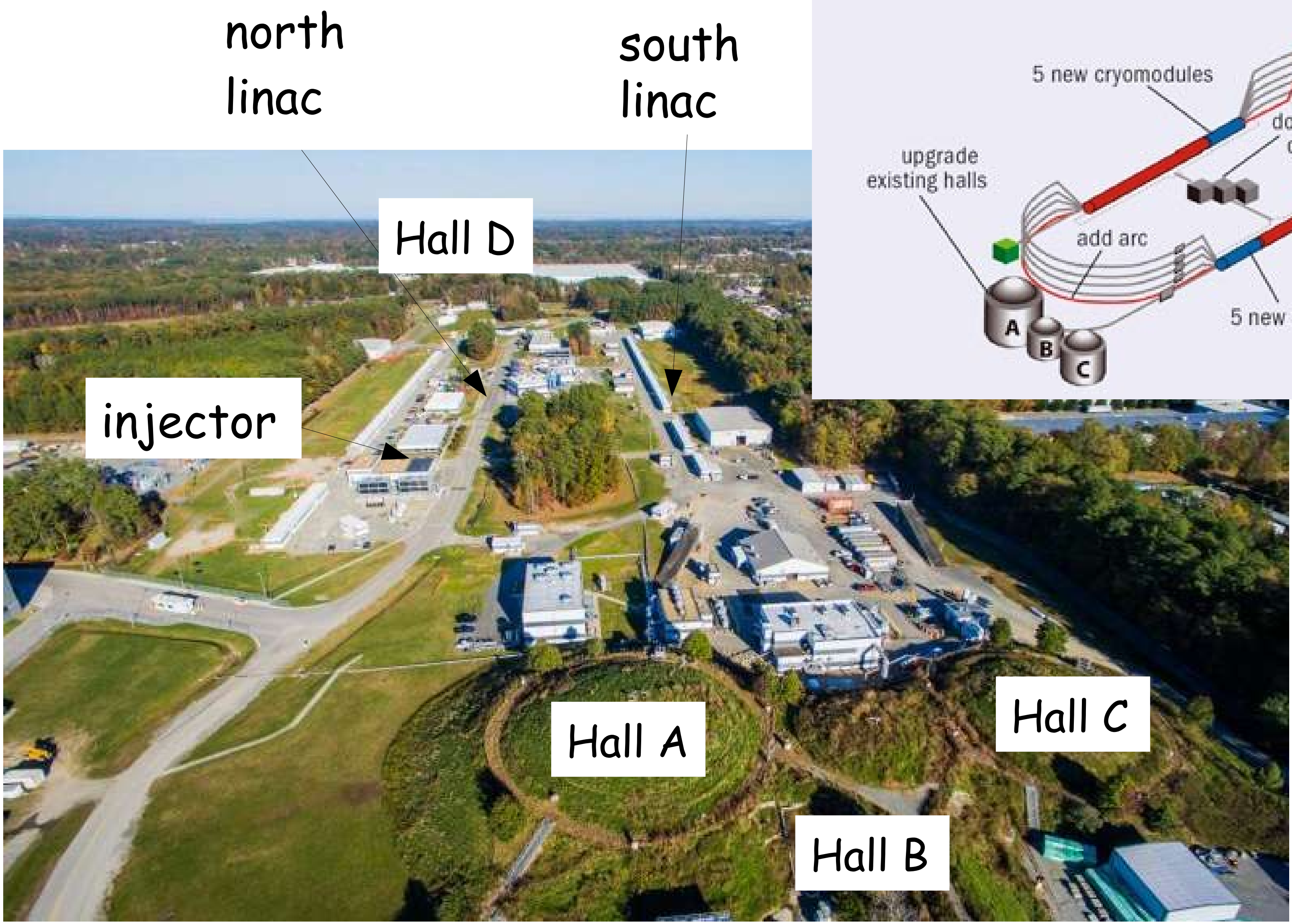
# From Rutherford to Modern Electron Scattering

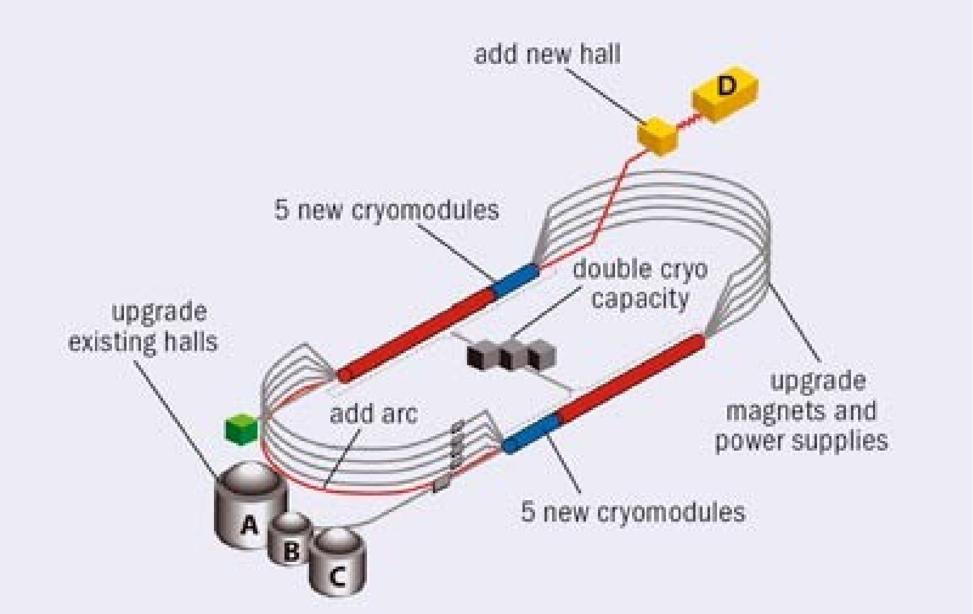
Modern study of the nucleon structure is not too different from Rutherford's method: We use more and more energetic particle beams to "look into" the target. At JLab, we focus on GeV-energy electron beams.

If data show differently from calculation assuming point-like target (simple Coulomb field) it means the target has a sub-structure!

Detection of the scattered electrons is fundamentally different from optical or electron microscopes

# Continuous Electron Beam Accelerator Facility (CEBAF) of Jefferson Lab



Going from KeV to MeV or GeV present a challenge:

Electron microscope – What's limiting the resolution?

1) Wavelength of the probe (property of the ray);
2) How well you can direct the ray (property of the detector);
3) How well you can magnify (and thus see/measure) the scattered ray.

While we can use electromagnetic lenses to amplify the image given by electrons in the electron microscope (when studying molecular structures such as DNAs), it is impossibly to do so for GeV-energy electrons!

What can we do?

Going from KeV to MeV or GeV present a challenge:

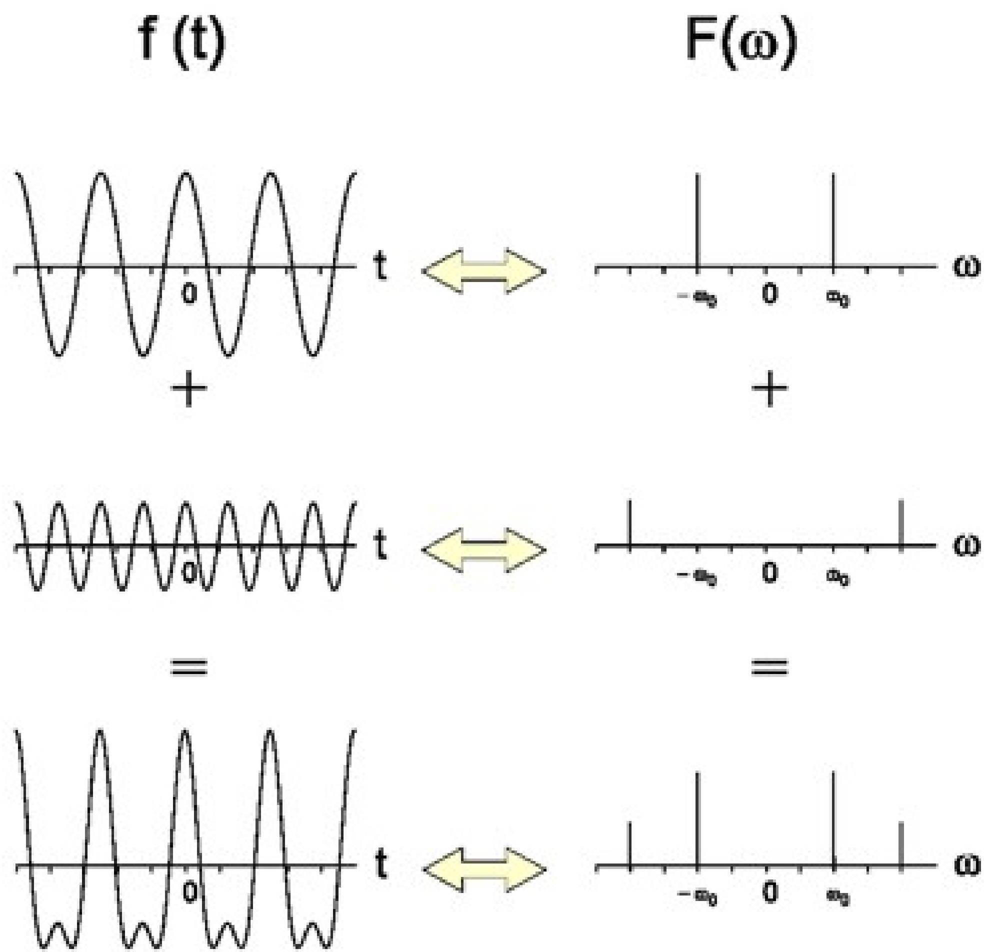
Electron microscope – What's limiting the resolution?

1) Wavelength of the probe (property of the ray);
2) How well you can direct the ray (property of the detector);
3) How well you can magnify (and thus see/measure) the scattered ray.

While we can use electromagnetic lenses to amplify the image given by electrons in the electron microscope (when studying molecular structures such as DNAs), it is impossibly to do so for GeV-energy electrons!

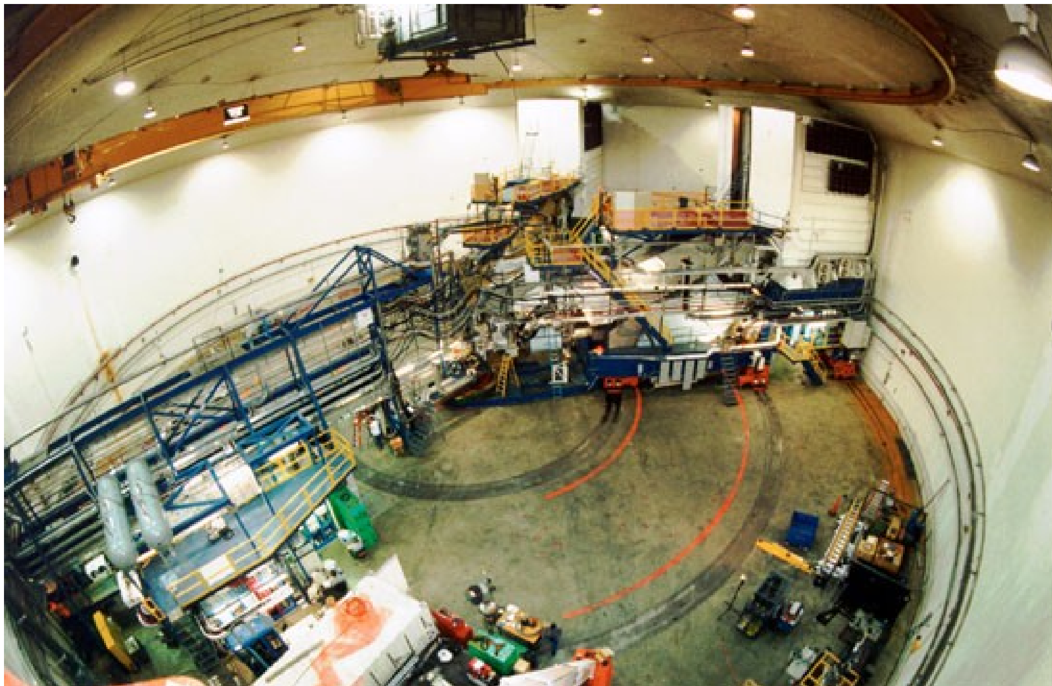
What can we do? Answer: go to momentum space!

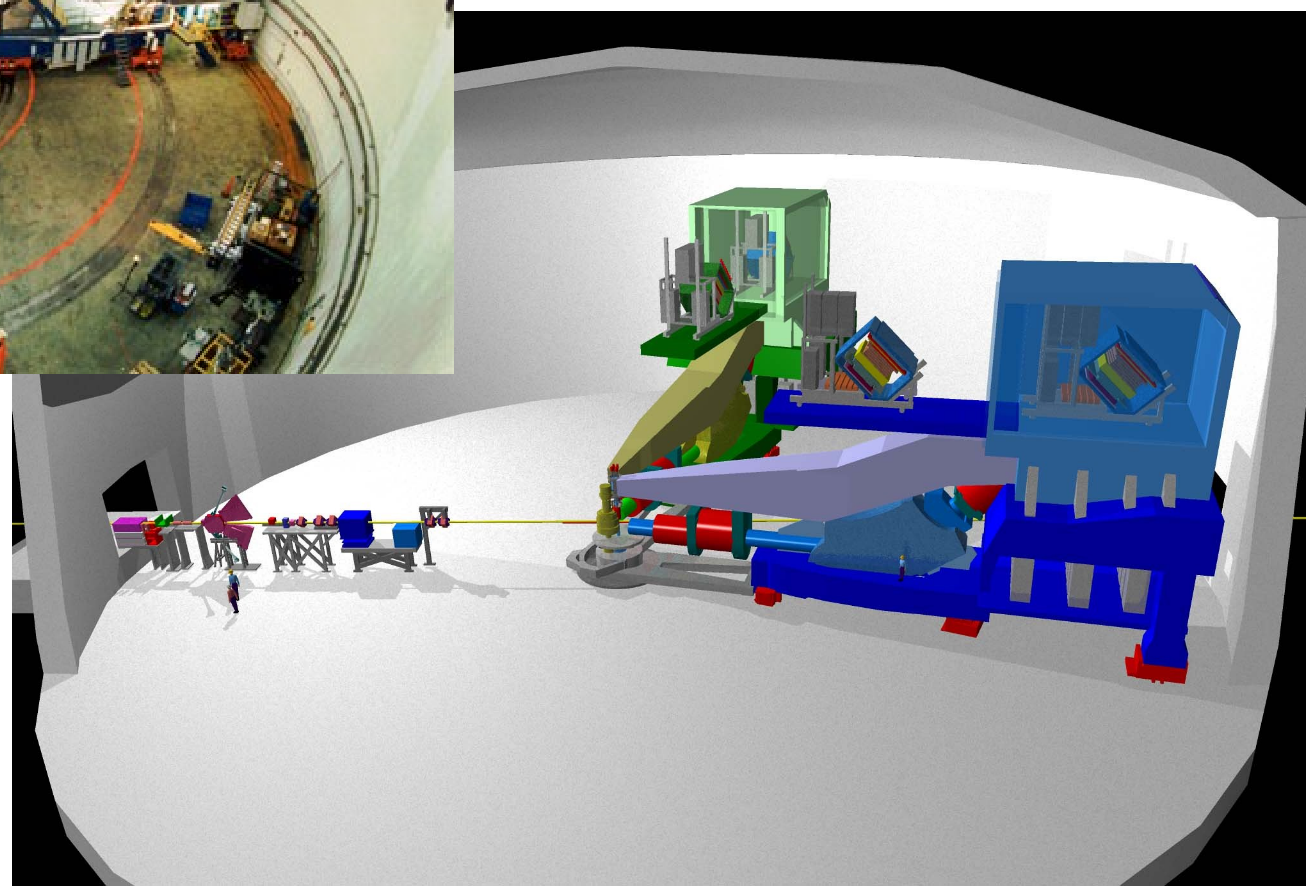
# The Solution – Go to Momentum Space!



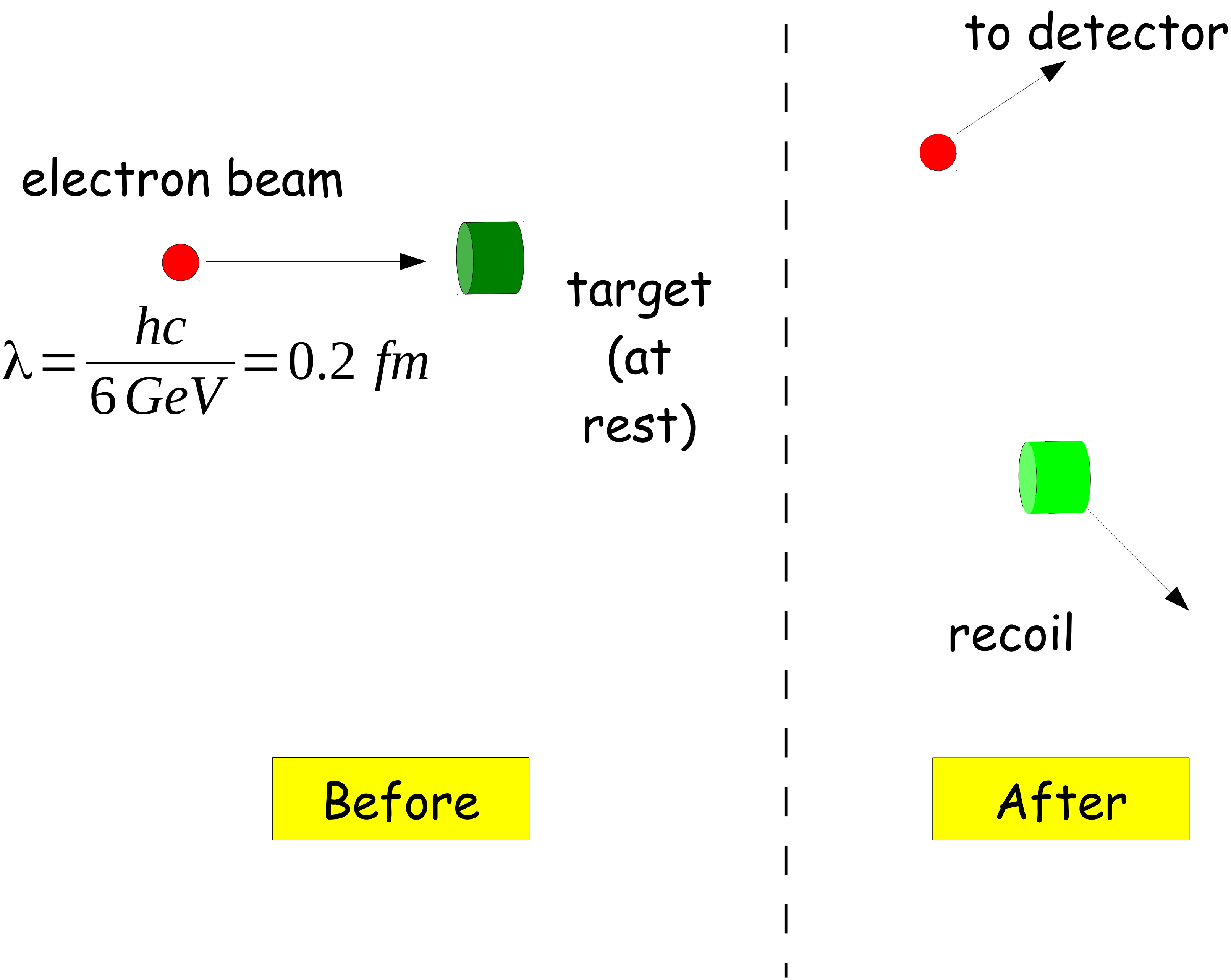

Fourier Transform

**Instead of studying the spatial distribution of scattered electrons (as in electron microscope), we measure their momentum distribution using gigantic spectrometers**





# Basics of Electron Scattering on Fixed Nuclear Targets




$$\lambda = \frac{hc}{6\,GeV} = 0.2\ fm$$

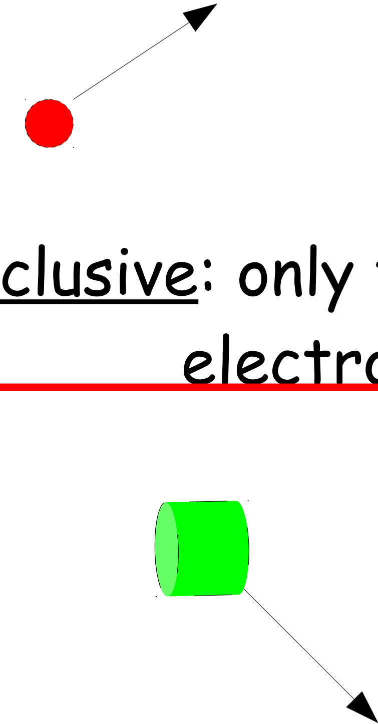
# Basics of Electron Scattering on a Fixed Nuclear Target

electron beam

$$\lambda = \frac{hc}{6\,GeV} = 0.2\ fm$$

target (at rest)

to detector



<u>Inclusive</u>: only the scattered electron is detected

recoil

**Before**

**After**

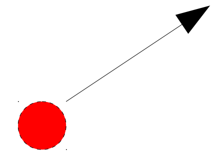
# Basics of Electron Scattering on a Fixed Nuclear Target

electron beam

target (at rest)

$$\lambda = \frac{hc}{6\,GeV} = 0.2\ fm$$

to detector



<u>Inclusive</u>: only the scattered electron is detected

$$\text{counting rate} = \text{beam intensity} \times \text{target thickness}$$

$$\times\,\text{detector solid angle and momentum acceptance}$$

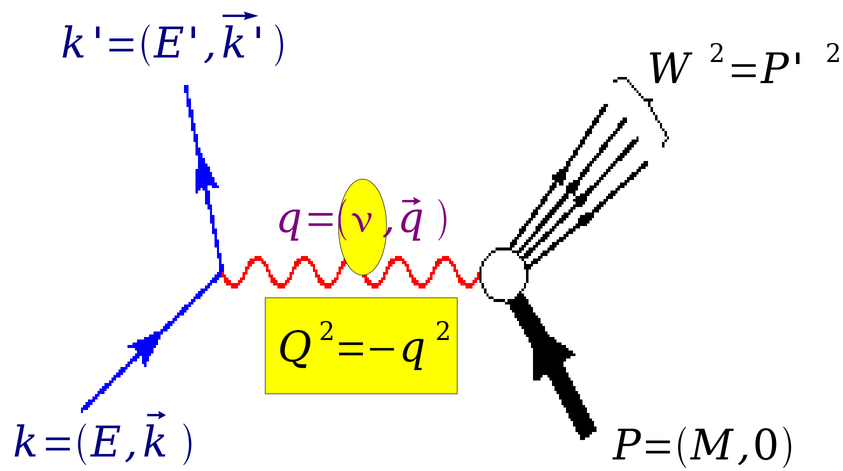
$$\times\,\text{physics cross section}$$

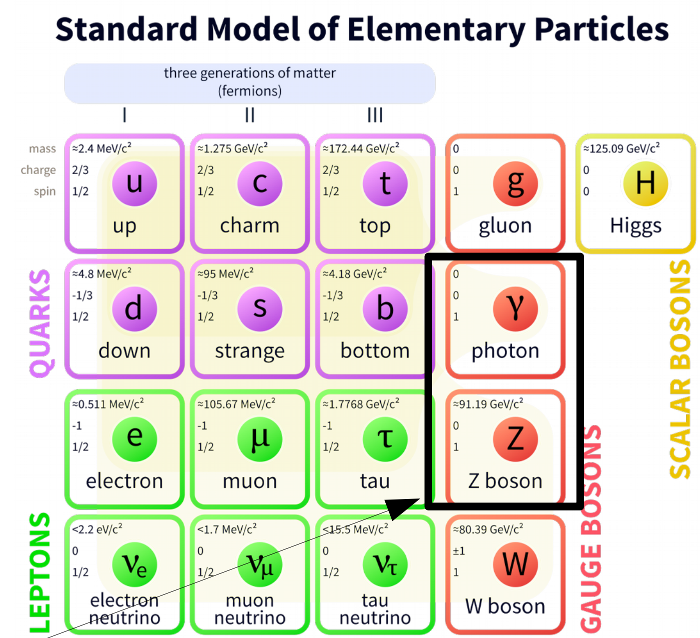
accelerator and facility capability

spectrometer capability

physics

# Electron Scattering - both EM and weak interactions



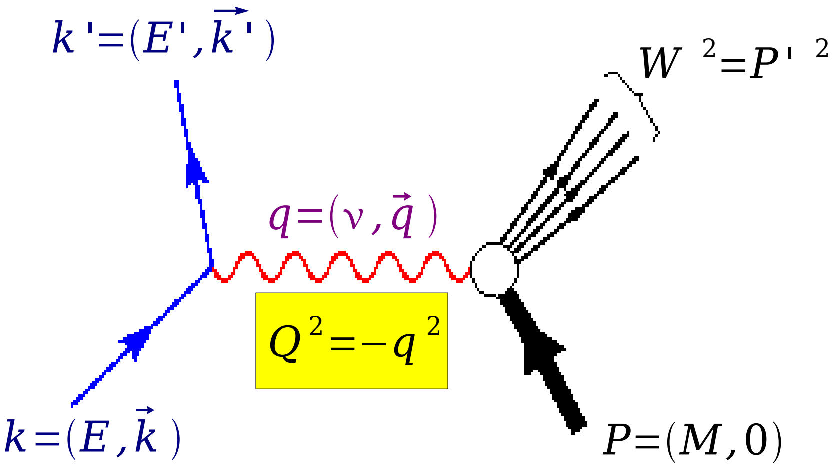

- Electrons (or μ's) interact with the target by exchanging a "virtual" photon or a $Z^0$;
- Two variables to describe how the target behave: $1/Q^2$ and ν;

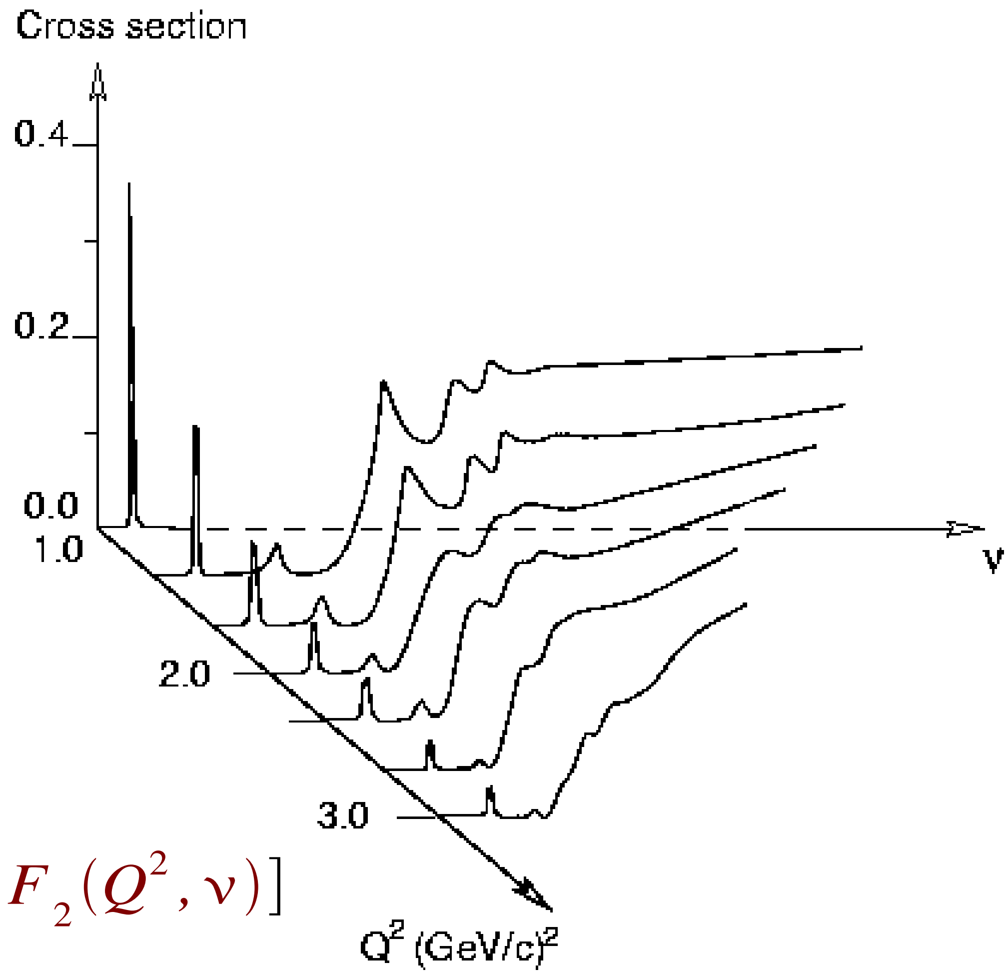
  $1/Q^2$ ~ resolution of the probe

  ν ~ how "hard" we kick the nucleus

  W: invariant mass of the target after it absorbs the photon

# Exploring Nucleon Structure Using EM Probe



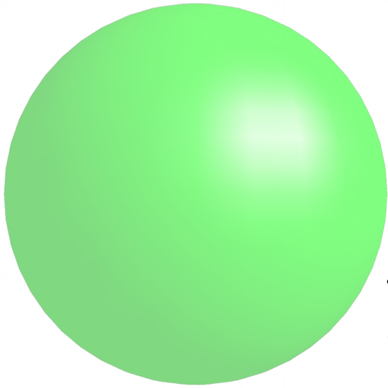




- The cross section:

$$\frac{d^2\sigma}{d\Omega\, dE'} = \sigma_{Mott}\left[\alpha F_1(Q^2,\nu) + \beta F_2(Q^2,\nu)\right]$$

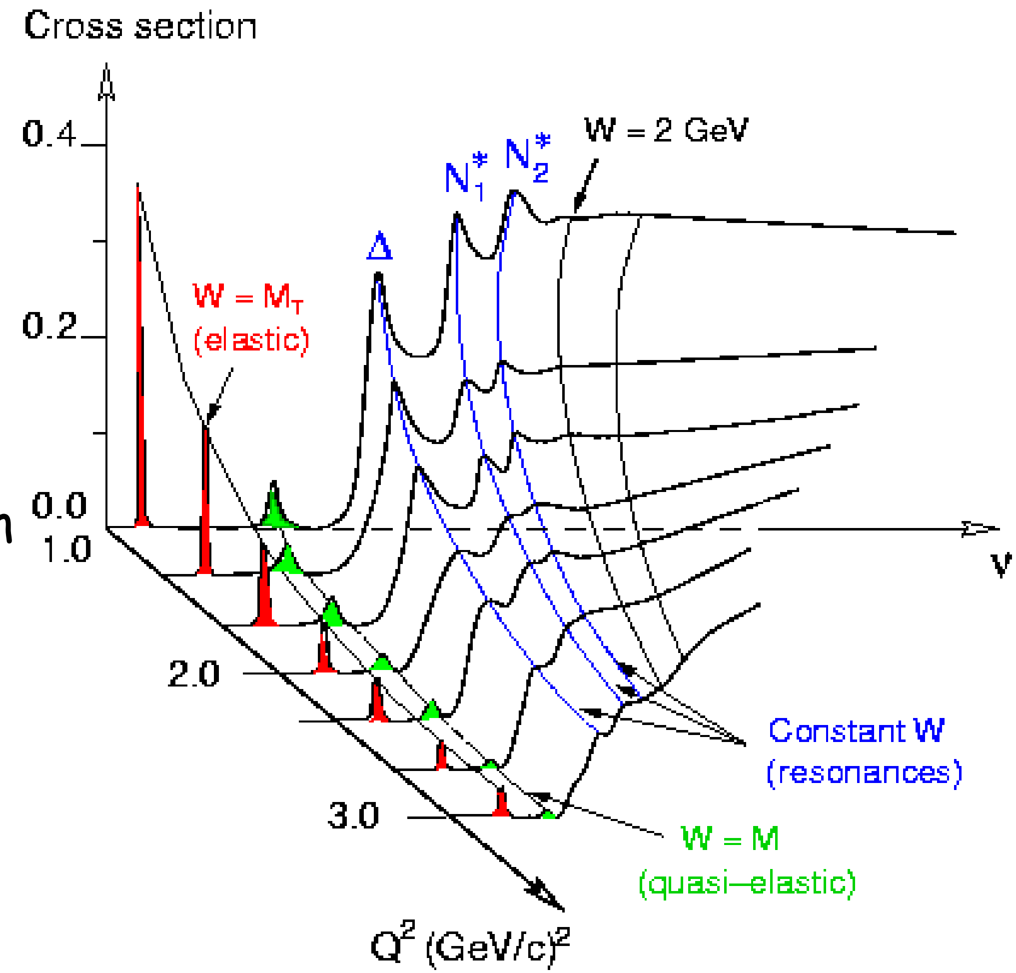
For point-like target

# Exploring Nucleon Structure Using EM Probe (cont.)

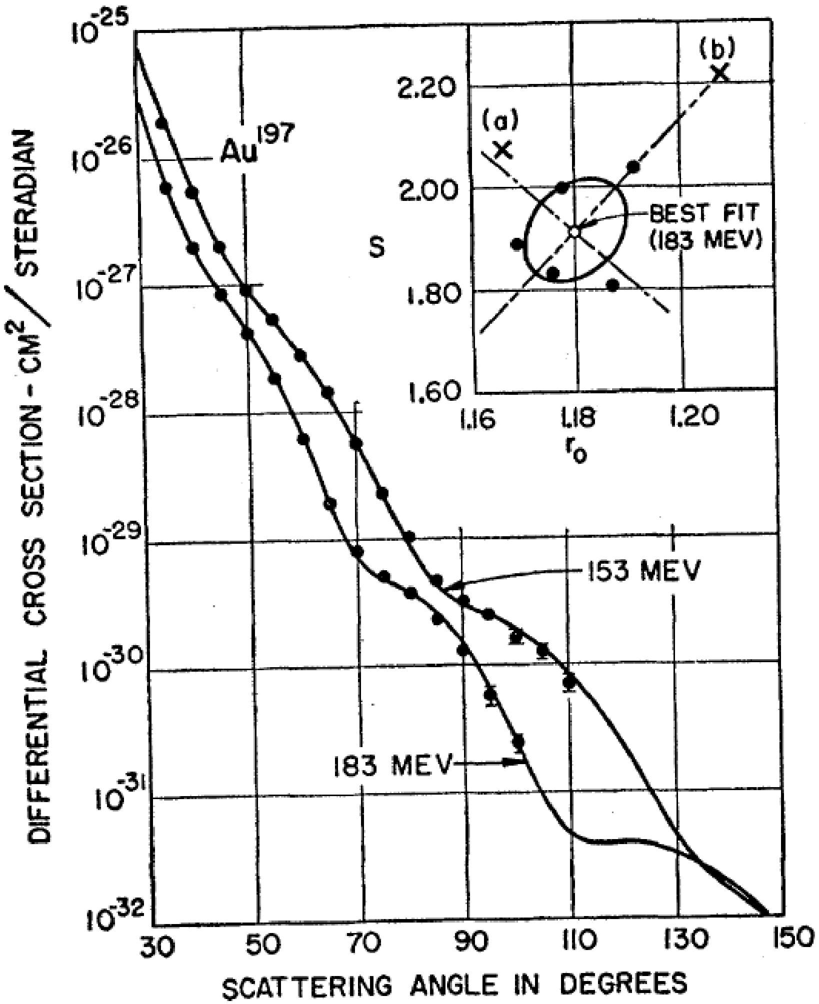


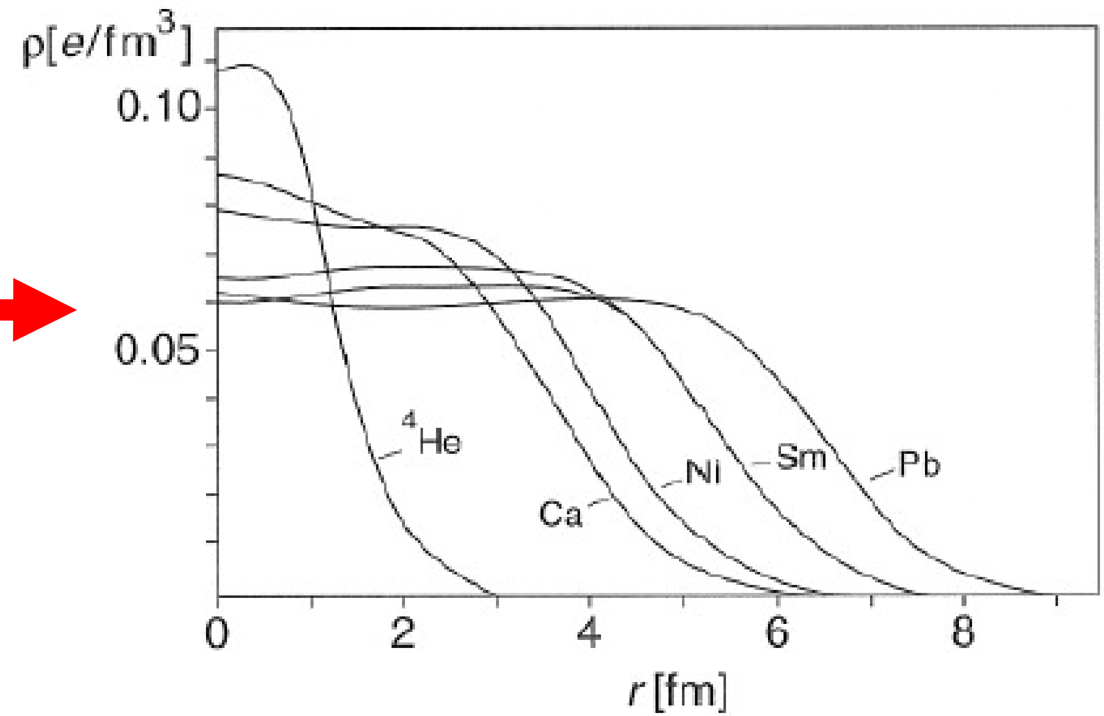
elastic — rigid body

structure functions for elastic are called “form factors” ↔ Fourier transformation of the electric charge distribution inside the nucleus



# Form Factors – Nuclear Structure in the Momentum Space




$$F_E(q) \propto \int \rho_E(\vec{x}) e^{i\vec{q}\cdot\vec{x}} d^3\vec{x}$$

Momentum distribution → Spatial Distribution

Fourier Transform

Form factor: F(q) → ρ(r)

# Early Electron Scattering and Unpolarized DIS

- 1933: Protons are not point-like ($k_p$=1.79); Estermann, Stern 1943

O. Stern — "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

# Early Electron Scattering and Unpolarized DIS

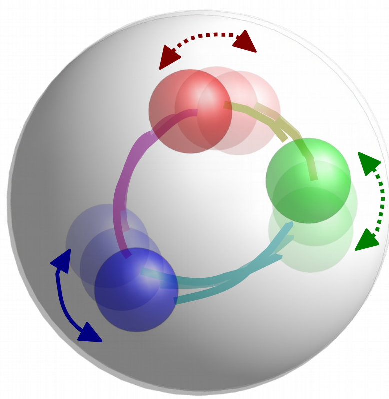
- 1933: Protons are not point-like ($k_p$=1.79); Estermann, Stern [1943]
- 1950's: Nucleons have a structure; Hofstadter *et al.* [1961]

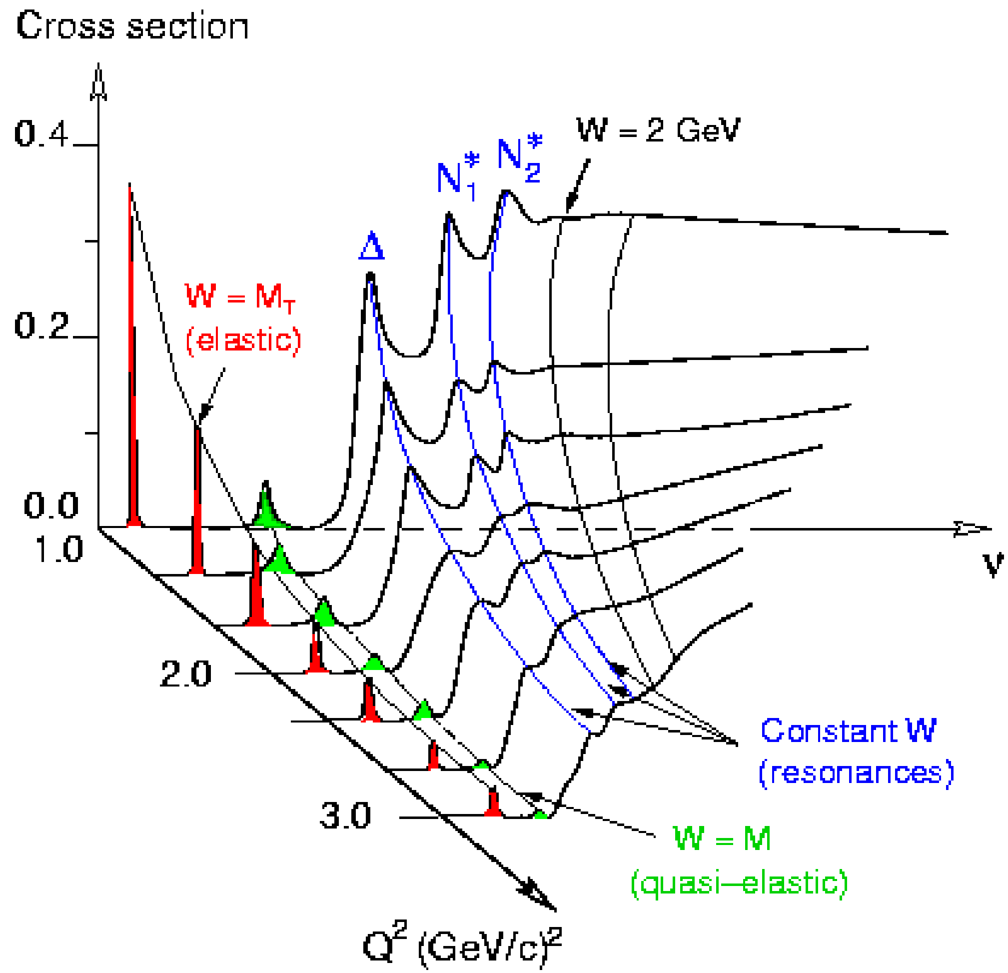
O. Stern — "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

R. Hofstadter — "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons" (shared with R. L. Mössbauer)

# Exploring Nucleon Structure Using EM Probe (cont.)

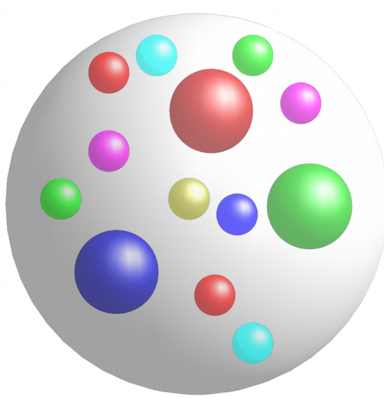
➔ Resonance region – quarks inside the nucleon react coherently

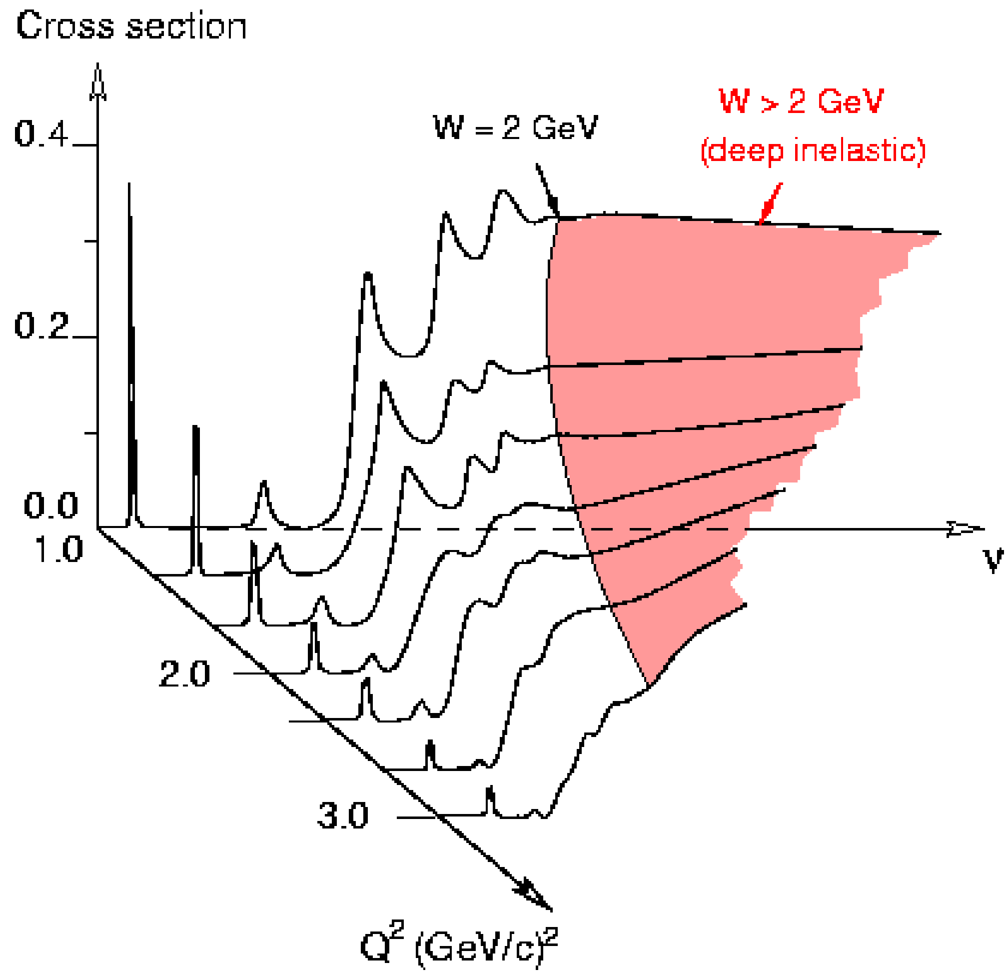




# Exploring Nucleon Structure Using EM Probe (cont.)

- **Deep Inelastic Scattering (DIS):**
  - Quarks start to react incoherently
  - Start to **see** constituents of the nucleon

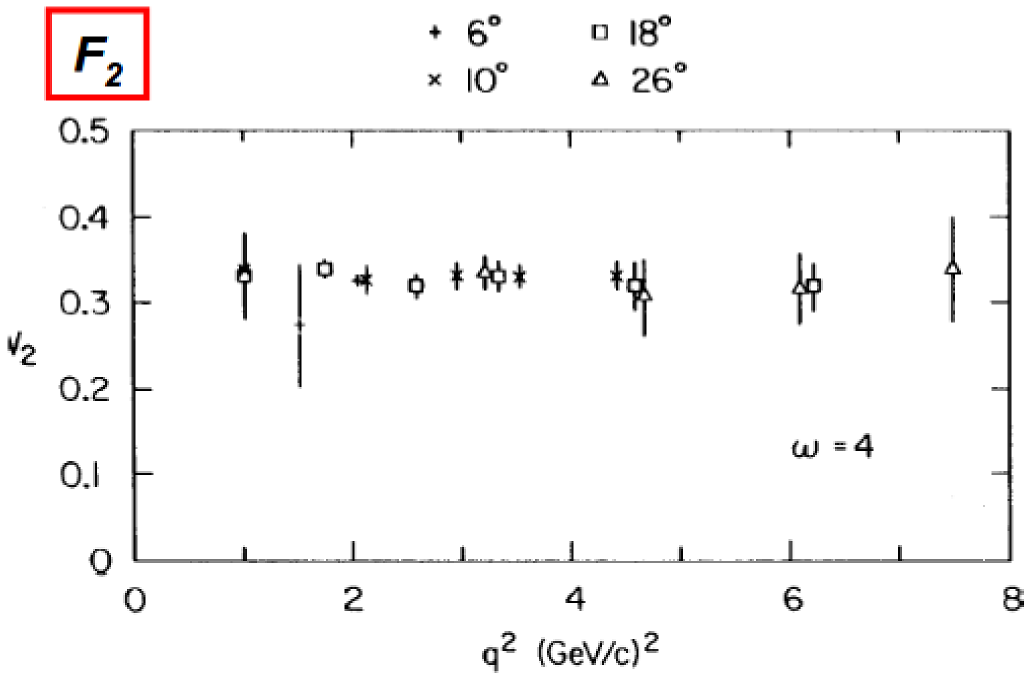





For DIS, perturbation theory starts to work !

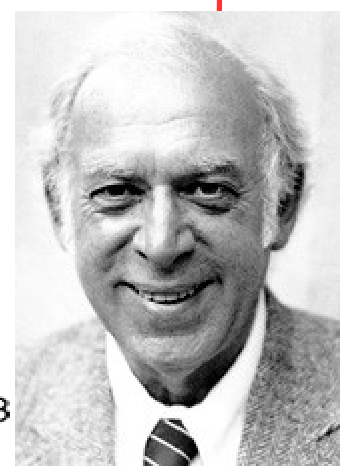
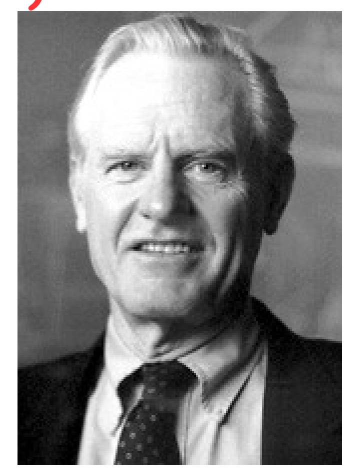
# Early Electron Scattering and Unpolarized DIS

- 1968: First DIS data from SLAC, Friedman, Kendall, Taylor *et al.*



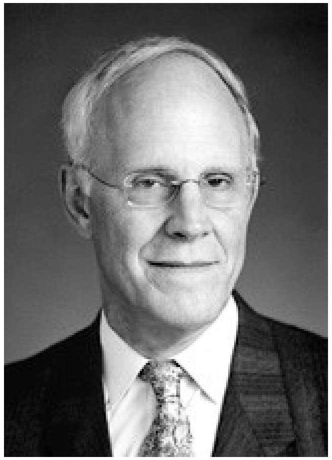
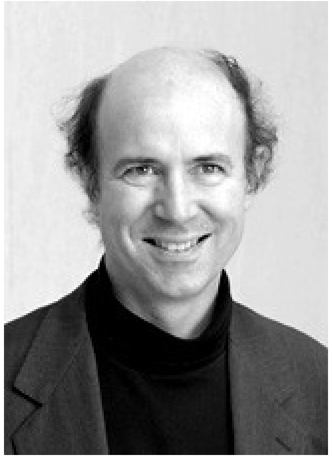

"scaling" (what you see no longer depend on the resolution of the probe)

1990


- 1969: nucleons are made of spin-1/2 point-like particles (quarks); DIS = incoherent sum of electron scattering off **asymptotically free** quarks
  - $x_{bj} = Q^2/(2M\nu)$ = fraction of the nucleon momentum carried by the struck quark;

"for the discovery of asymptotic freedom in the theory of the strong interaction"

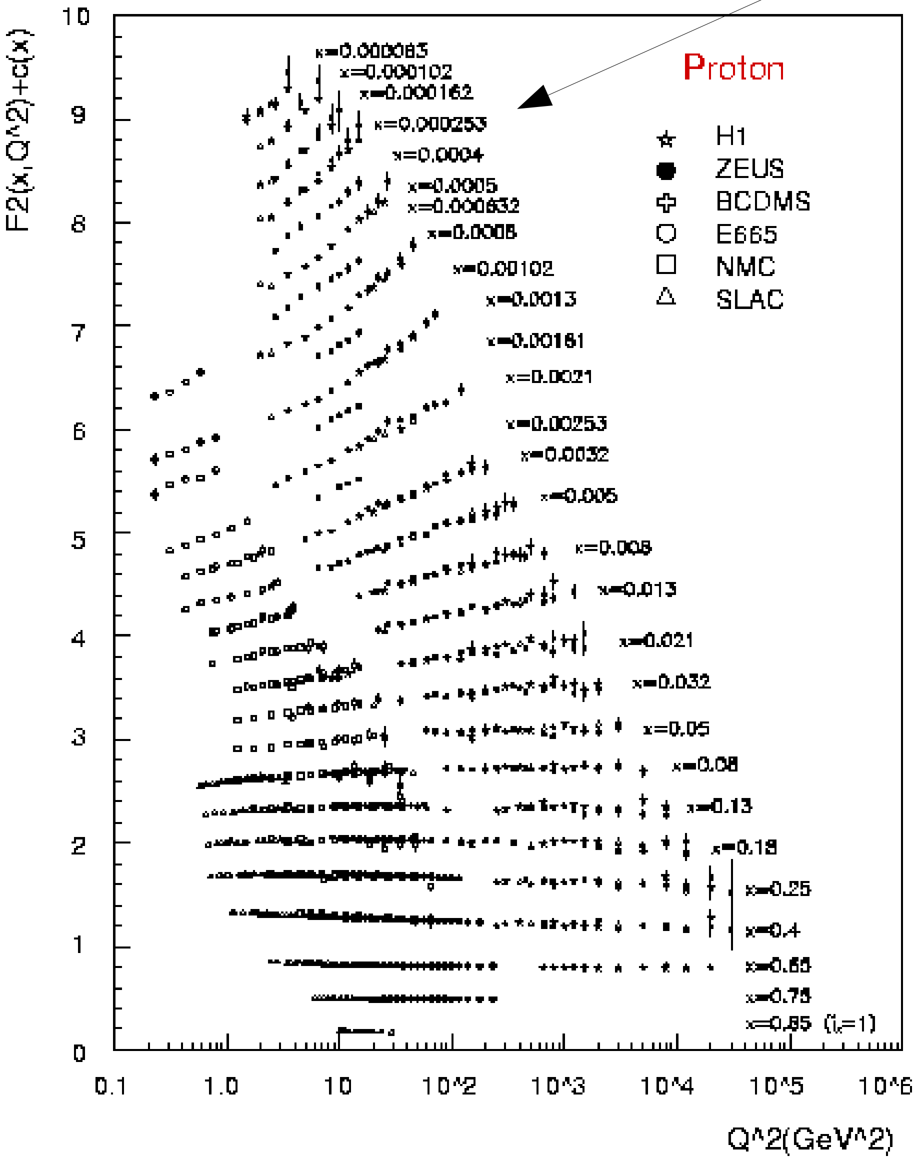
  

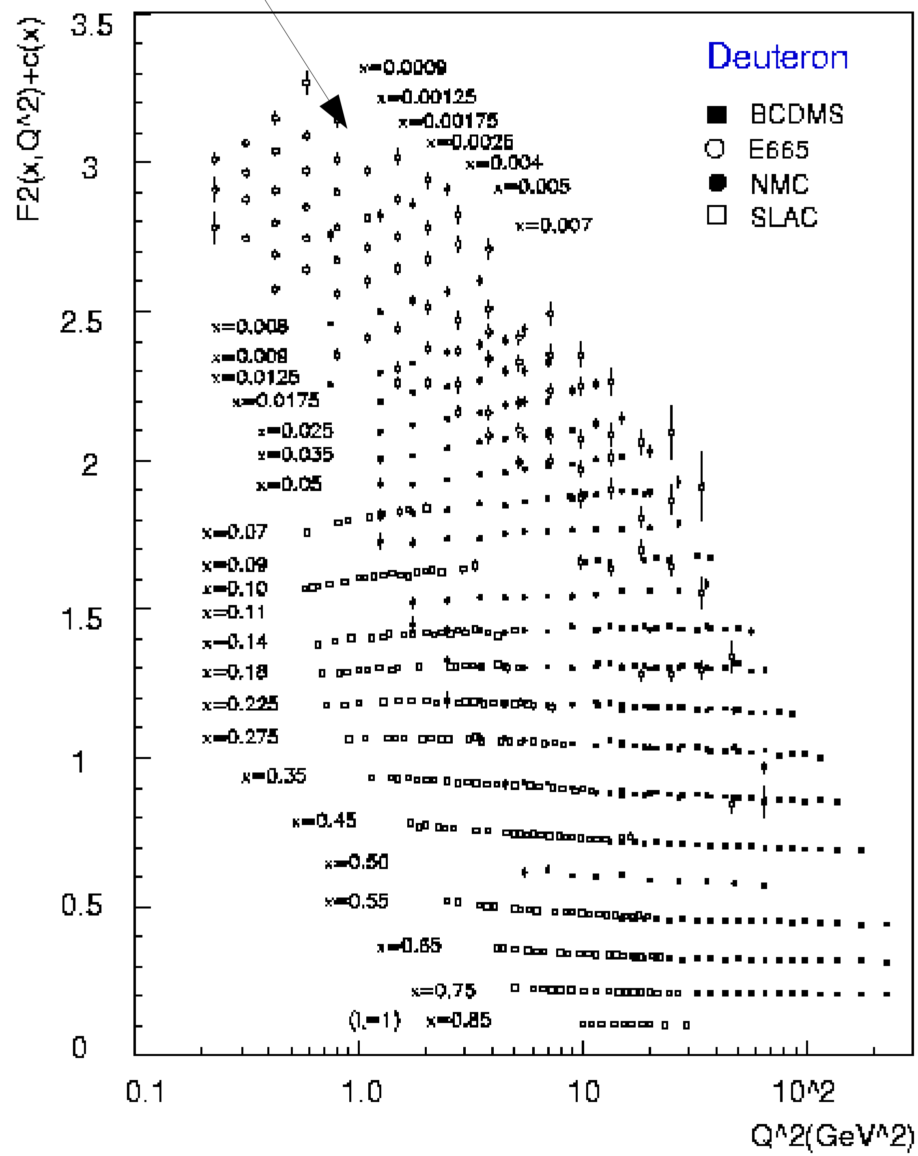
- 1972-1973: $$\alpha_s(Q^2) = \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$ 't Hooft, 1999
  - *Asymptotic freedom* Gross, Wilczek & Politzer
  - *QCD became a possible (and the leading) theory for the strong interaction.* 2004

# Current Knowledge of Nucleon Unpolarized Structure

$$\frac{d^2\sigma}{d\Omega\, dE'} = \sigma_{Mott}\left[\alpha F_1(Q^2,\nu) + \beta F_2(Q^2,\nu)\right]$$

"scaling violation" agree with pQCD (DGLAP equations)



# From 1933 to 1973

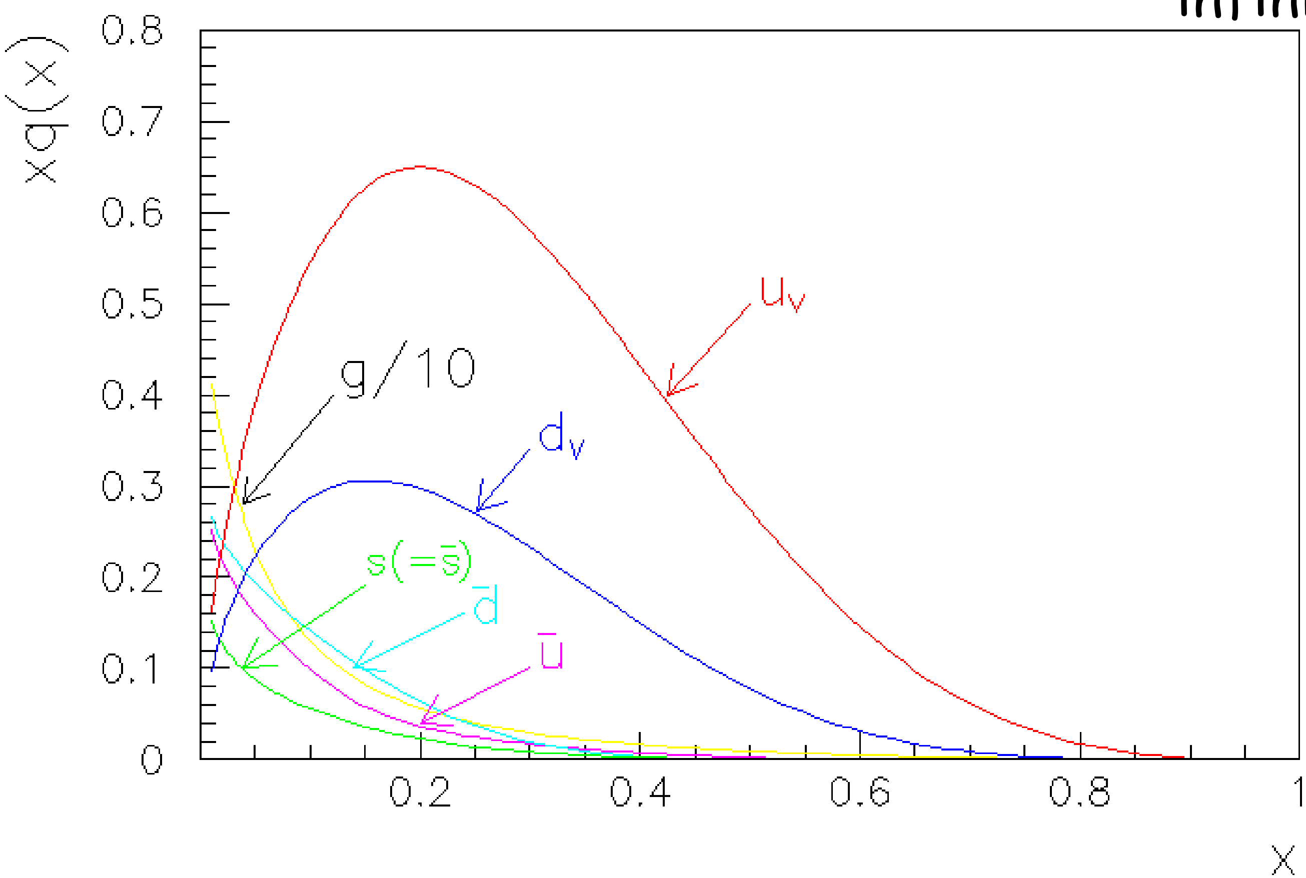
- 1933: Protons are not point-like ($k_p$=1.79); Estermann, Stern 1943
- 1950's: Nucleons have a structure; Hofstadter *et al.* 1961
- 1968: First DIS data from SLAC, Friedman, Kendall, Taylor *et al.* 1990
- 1969: nucleons are made of spin-1/2 point-like particles (quarks); DIS = incoherent sum of electron scattering off **asymptotically free** quarks
  - $x_{bj} = Q^2/(2M\nu)$ = fraction of the nucleon momentum carried by the struck quark;
- 1972-1973: $$\alpha_s(Q^2) = \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$ 't Hooft, 1999
  - Asymptotic freedom — Gross, Wilczek & Politzer 2004
  - QCD became a possible (and the leading) theory for the strong interaction.

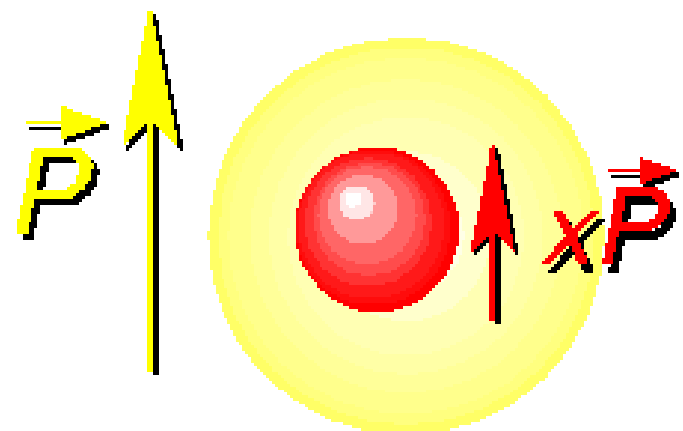
# Current Knowledge of Nucleon Unpolarized Structure

(after 40 years of study)

$$F_1(x) = \frac{1}{2}\Sigma e_i^2[q_i(x)]$$

in the Quark-Parton Model and the infinite momentum frame (IMF)



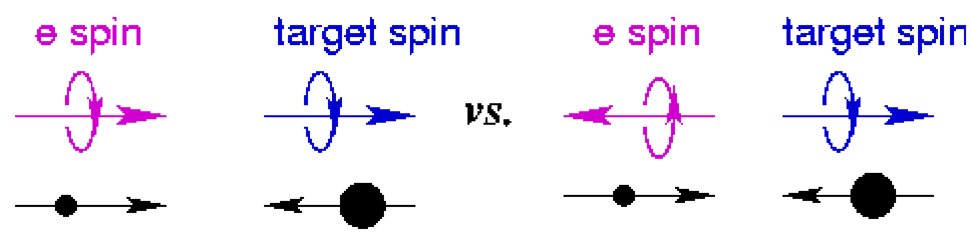

$(P \to \infty)$

- the unpolarized structure of the nucleon is reasonably well understood (for most of $x_{Bj}$ region).

# Polarized DIS (1980~present)

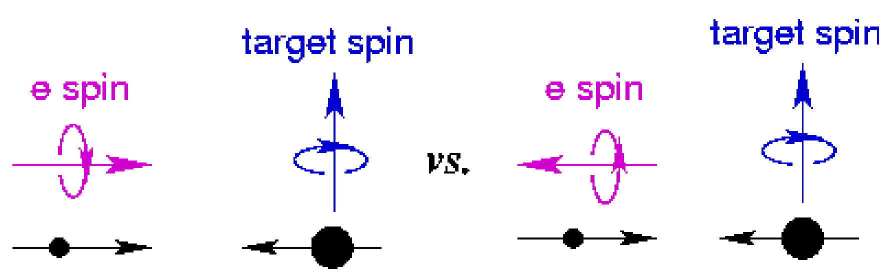
- Scattering cross section is spin-dependent (imagine throwing two small magnets together) S N N S *vs.* N S N S

- Longitudinal




$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega\, dE'} \propto \sigma_{point-like}[\alpha' g_1(x,Q^2) + \beta' g_2(x,Q^2)]$$

- Transverse

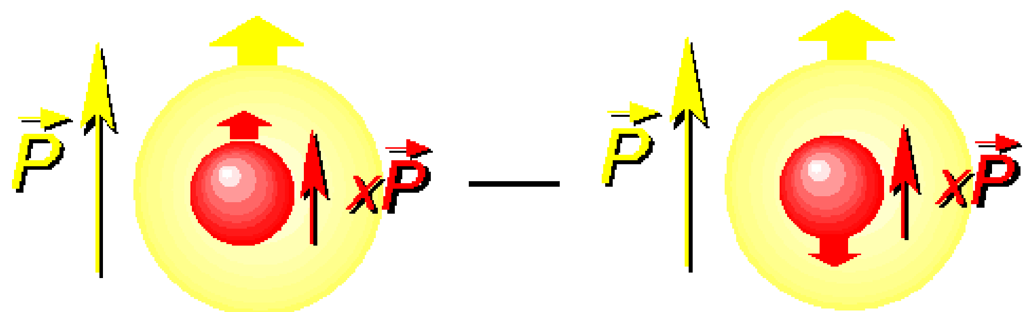


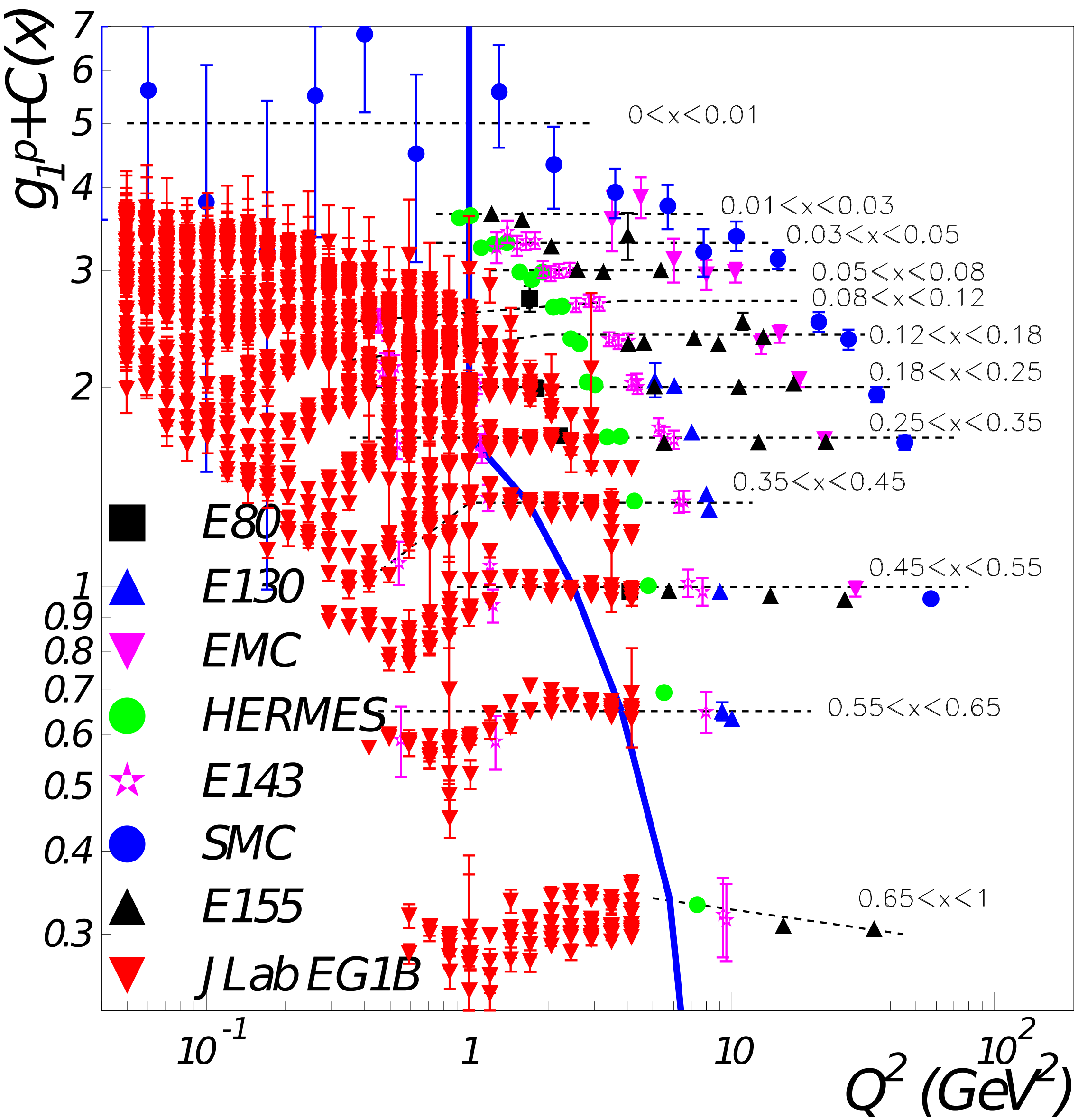

$$\frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega\, dE'} \propto \sigma_{point-like}[\alpha'' g_1(x,Q^2) + \beta'' g_2(x,Q^2)]$$

# Polarized Structure Function and the Nucleon Spin Structure

- in QPM and the infinite momentum frame:

$$g_1(x) = \frac{1}{2}\sum e_i^2[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)] = \frac{1}{2}\sum e_i^2[\Delta q_i(x)]$$



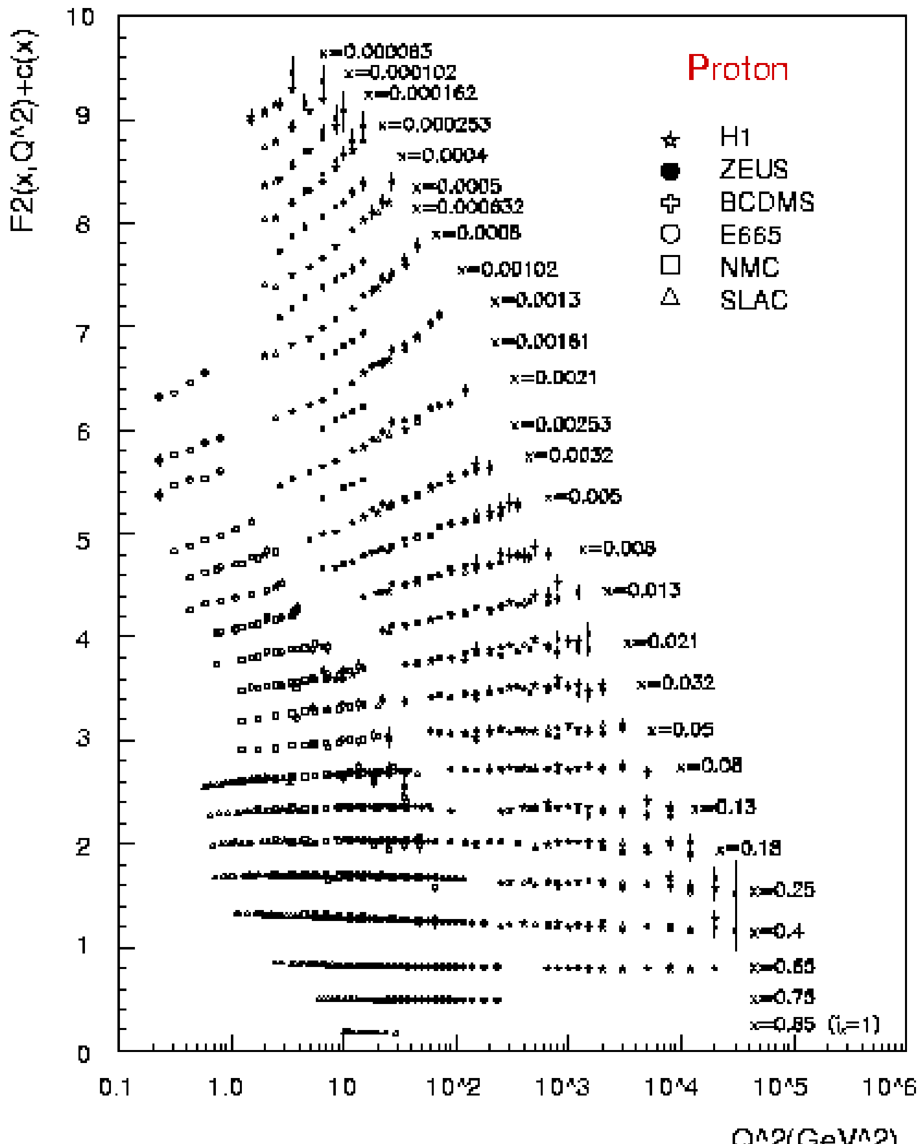


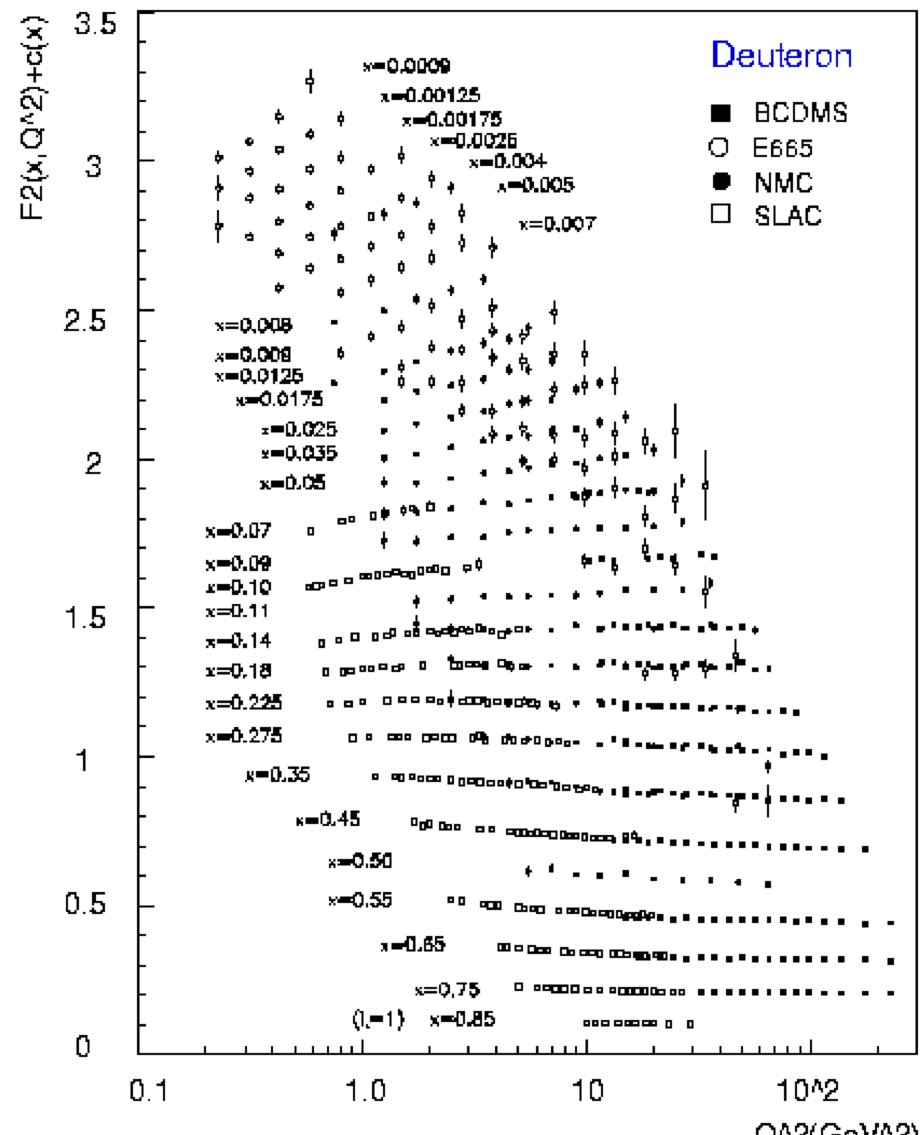

Similar to the unpolarized case, "scaling violation" agree with pQCD (DGLAP equations)

# Success of QCD – but only in the perturbative regime

Most of theoretical progress was made between 1933 and 1973, ending with

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$



# Compare to Other Interactions:

- QED has been tested to 9 orders of magnitude
- Electroweak unification has been tested rigorously and so far data do not indicate any new physics
- Strong interaction: asymptotic freedom vs. confinement

We do not yet understand confinement!

# Success and Challenges – Hadronic Structure Study and QCD

- DIS established the existence of quarks
- QCD can successfully explain asymptotic freedom, and perturbative calculations explain well the $Q^2$-evolution of structure functions
- But we do not know or understand:
  - how confinement arises from QCD Lagrangian, quantitatively – this is a serious problem, are quarks even real? ("Are you still so religious?")
  - the mechanism of chiral symmetry breaking and the nature of the QCD vacuum
  - the nature of the QCD vacuum and to explain it theoretically
  - how to calculate/predict the value of form factors or structure functions

# How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? - Theoretical Aspect

- To understand the compositeness – how do partons form the nucleon spin? – the proton spin crisis/puzzle
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations
- non-perturbative/low-energy/long-distance regime: to test effective field theories that using the hadronic degrees of freedom
- to provide predictions for structure functions
- how hadrons arise from quark and gluon degrees of freedom? – lattice QCD

# How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? - Observables

- To understand the compositeness – how do partons form the nucleon spin? – moments (of polarized structure functions)
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations – $Q^2$ evolution of g1, etc
- non-perturbative/low-energy/long-distance regime: to test effective field theories that using the hadronic degrees of freedom – moments at very low $Q^2$/long distances
- to provide predictions for structure functions
  – structure function ratios at large x
- how hadrons arise from quark and gluon degrees of freedom?
  – $Q^2$ dependence of moments

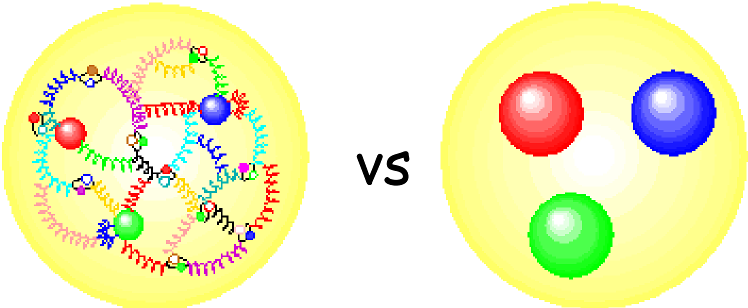
# How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? – Observables

- To understand the compositeness – how do partons form the nucleon spin? – moments (of polarized structure functions)
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations – $Q^2$ evolution of g1, etc
- non-perturbative/low-energy/long-distance regime: to test effective field theories that using the hadronic degrees of freedom – moments at very low $Q^2$/long distances
- to provide predictions for structure functions
  – structure function ratios at large x
- how hadrons arise from quark and gluon degrees of freedom?
  – $Q^2$ dependence of moments

see Thursday's talk

# Nucleon (spin) Structure at High $x_{Bj}$

- We need structure function measurements for which QCD can make absolute predictions!

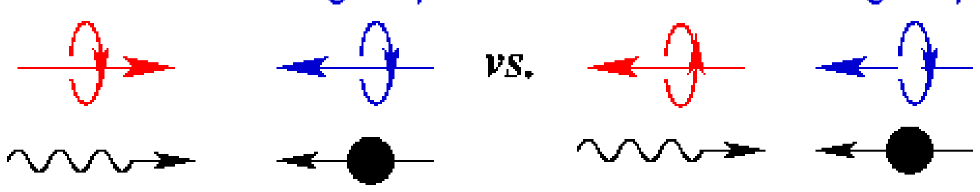


The far valence domain (x>0.5)

- is definitive of the hadrons
- is the only domain where QCD (and many other models) can make absolute predictions for (the ratio of) structure functions
- the ratio of structure functions at $x \to 1$ provide unambiguous, scale invariant, non-perturbative features of QCD

☆ $F_2^p/F_2^n$ and d/u

☆ $A_1^p$, $A_1^n$ , or $\Delta u/u$ and $\Delta d/d$




$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$ at large $Q^2$

$$\gamma^2 = \frac{Q^2}{\nu^2} = \frac{4M^2x^2}{Q^2}$$

# Predictions for $A_1$ and $\Delta q/q$ at large x

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)_{10}\right\rangle - \frac{1}{3}\left|u^{\downarrow}(ud)_{11}\right\rangle - \frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

| Model | $F_2^n/F_2^p$ | d/u | Δ u/u | Δ d/d | $A_1^n$ | $A_1^p$ |
|---|---|---|---|---|---|---|
| SU(6) = SU3 flavor + SU2 spin | 2/3 | 1/2 | 2/3 | -1/3 | 0 | 5/9 |
| Valence Quark + Hyperfine | 1/4 | 0 | 1 | -1/3 | 1 | 1 |
| pQCD + HHC | 3/7 | 1/5 | 1 | 1 | 1 | 1 |
| DSE-1 (realistic) | 0.49 | 0.28 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 (contact) | 0.41 | 0.18 | 0.88 | -0.33 | 0.34 | 0.88 |

- The only place where models and/or QCD can make absolute predictions for structure functions.

# Predictions for $A_1$ and $\Delta q/q$ at large x

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)\right.$$

$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(\right.$$

hyperfine interaction: the two quarks in the spectator di-quark prefer to form a S=0 to a S=1 state.
– based on nucleon-Delta mass plitting, etc.
– but the breaking of SU(6) may not be that big.

| Model | $F_2^n/F_2^p$ | d/u | $\Delta$ u/u | $\Delta$ d/d | $A_1^n$ | $A_1^p$ |
|---|---|---|---|---|---|---|
| SU(6) = SU3 flavor + SU2 spin | 2/3 | 1/2 | 2/3 | -1/3 | 0 | 5/9 |
| Valence Quark + Hyperfine | 1/4 | 0 | 1 | -1/3 | 1 | 1 |
| pQCD + HHC | 3/7 | 1/5 | 1 | 1 | 1 | 1 |
| DSE-1 (realistic) | 0.49 | 0.28 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 (contact) | 0.41 | 0.18 | 0.88 | -0.33 | 0.34 | 0.88 |

- The only place where models and/or QCD can make absolute predictions for structure functions.

# Predictions for $A_1$ and $\Delta q/q$ at large x

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)_{10}\right\rangle - \frac{1}{3}$$

$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at x→1

| Model | $F_2^n/F_2^p$ | d/u | $\Delta$ u/u | $\Delta$ d/d | $A_1^n$ | $A_1^p$ |
|---|---|---|---|---|---|---|
| SU(6) = SU3 flavor + SU2 spin | 2/3 | 1/2 | 2/3 | -1/3 | 0 | 5/9 |
| Valence Quark + Hyperfine | 1/4 | 0 | 1 | -1/3 | 1 | 1 |
| pQCD + HHC | 3/7 | 1/5 | 1 | 1 | 1 | 1 |
| DSE-1 (realistic) | 0.49 | 0.28 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 (contact) | 0.41 | 0.18 | 0.88 | -0.33 | 0.34 | 0.88 |

- The only place where models and/or QCD can make absolute predictions for structure functions.

# Predictions for $A_1$ and $\Delta q/q$ at

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)_{10}\right\rangle - \frac{1}{3}$$

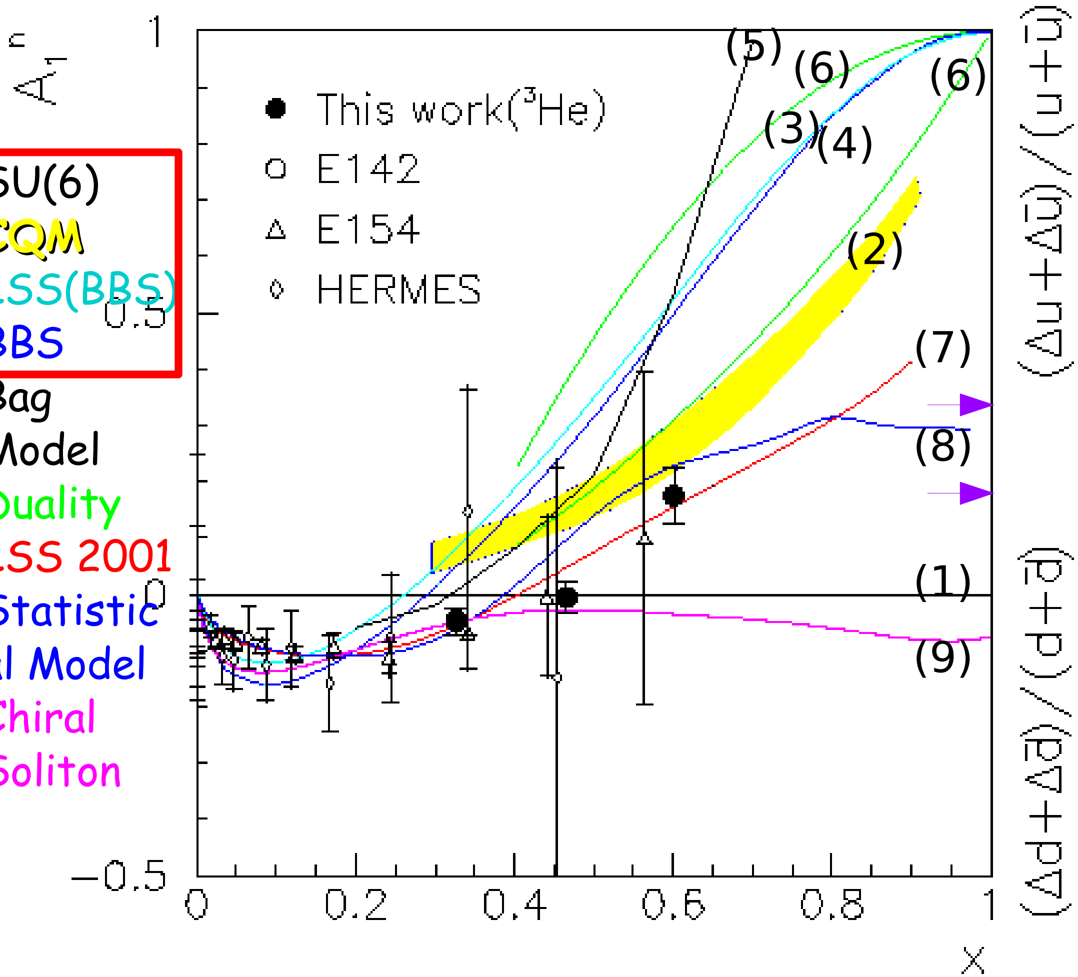
$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

| Model | $F_2^n/F_2^p$ | d/u | $\Delta$ u/u | $\Delta$ d/d | $A_1^n$ | $A_1^p$ |
|---|---|---|---|---|---|---|
| SU(6) = SU3 flavor + SU2 spin | 2/3 | 1/2 | 2/3 | -1/3 | 0 | 5/9 |
| Valence Quark + Hyperfine | 1/4 | 0 | 1 | -1/3 | 1 | 1 |
| pQCD + HHC | 3/7 | 1/5 | 1 | 1 | 1 | 1 |
| DSE-1 (realistic) | 0.49 | 0.28 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 (contact) | 0.41 | 0.18 | 0.88 | -0.33 | 0.34 | 0.88 |

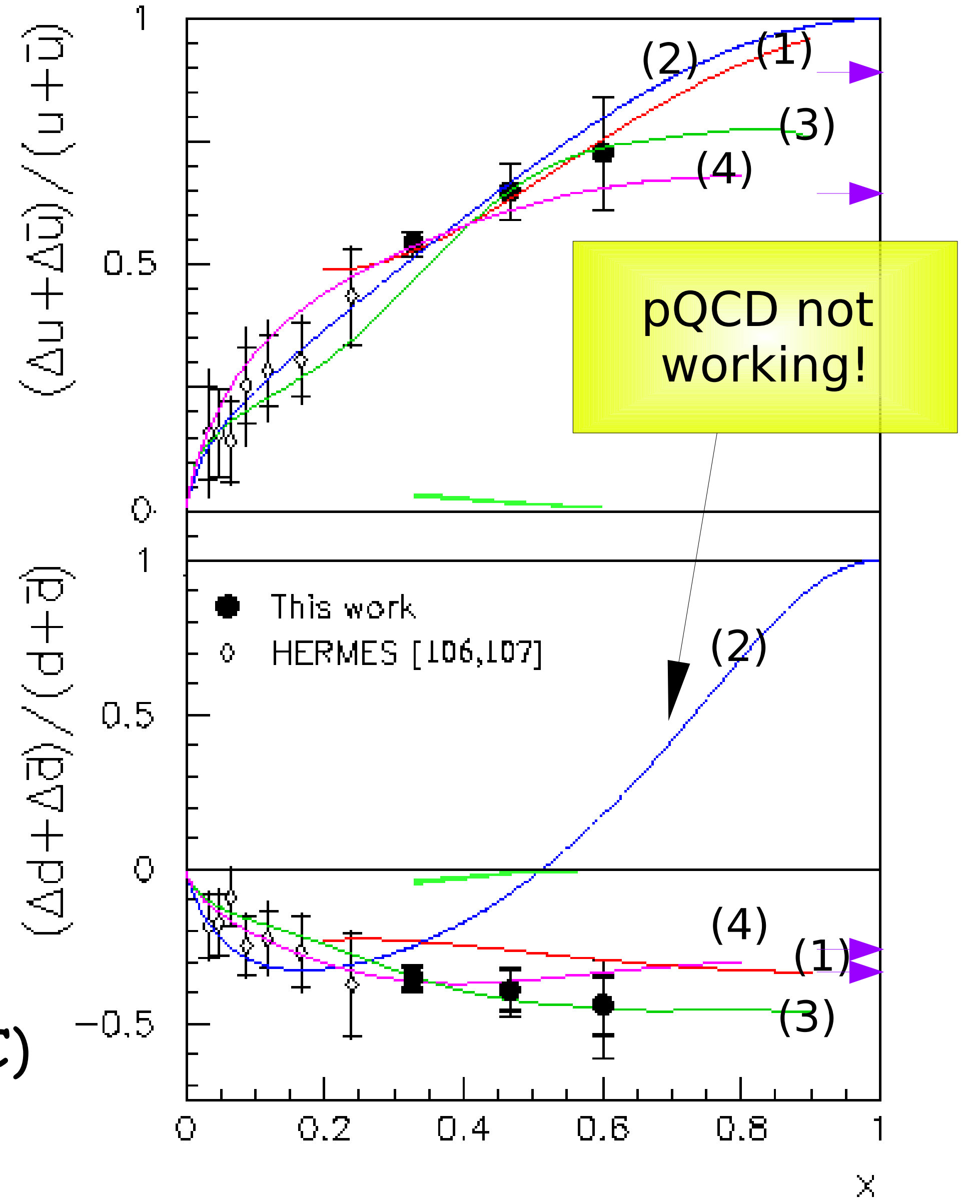
- The only place where models and/or QCD can make absolute predictions for structure functions.

# The 6 GeV Hall A Measurement (21 PAC days, 2001)



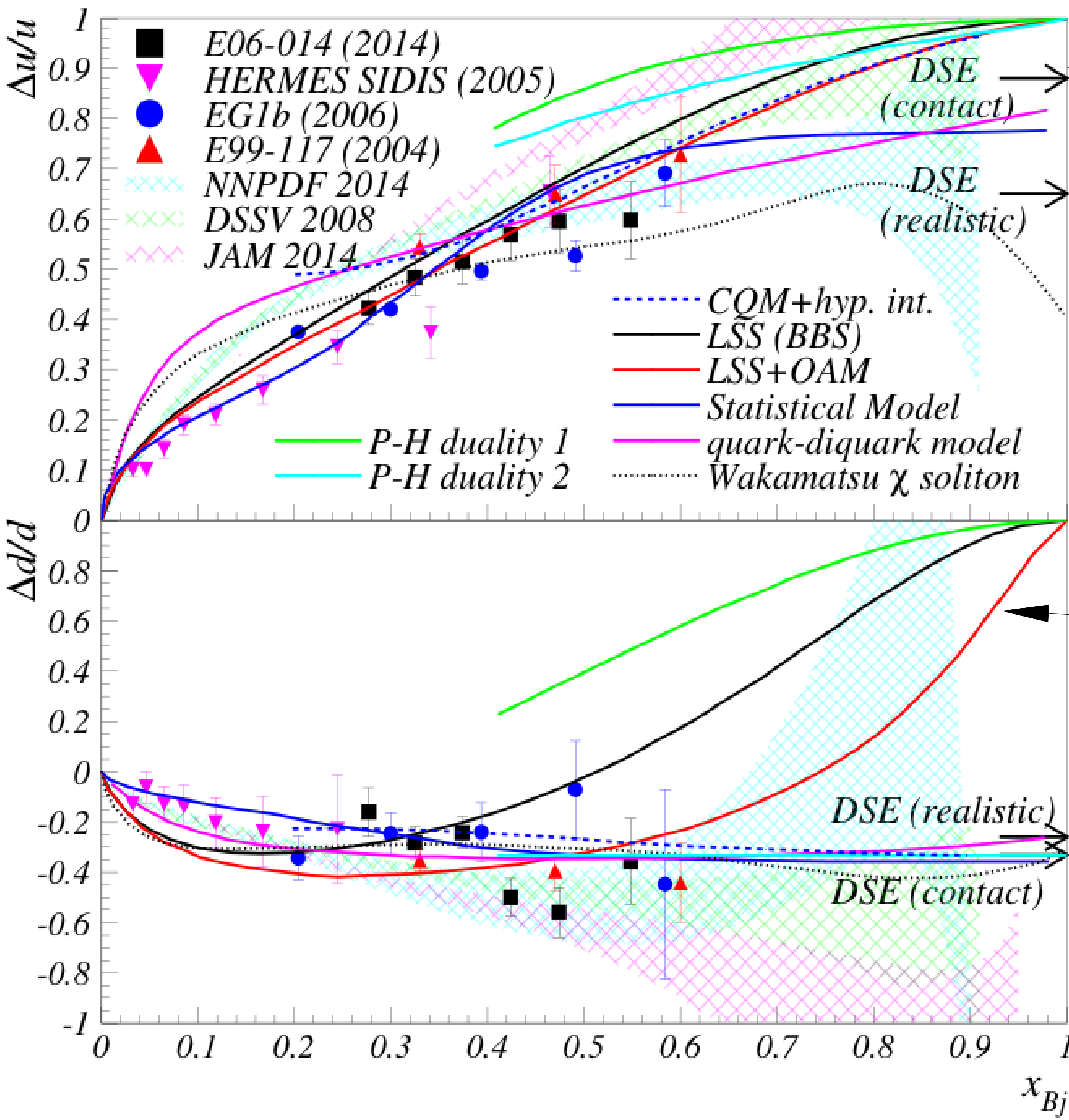

(1) SU(6)
**(2) CQM**
(3) LSS(BBS)
(4) BBS
(5) Bag Model
(6) Duality
(7) LSS 2001
(8) Statistical Model
(9) Chiral Soliton

(Deutron data not shown: E143, E155, SMC)




X. Zheng *et al.*, Phys. Rev. Lett. 92, 012004 (2004); Phys. Rev. C 70, 065207 (2004)

(1)CQM (2)LSS(BBS):pQCD+HHC
(3)Statistical Model (4)LSS 2001




A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at x→1

now added quark OAM, but Δd/d still must be 1 at x=1

# Summary

- One main goal of present "nuclear physics" research is to understand the structure of the proton and the neutron, and to be able to explain them using theories of strong interaction
- Hadron physics and the nature of confinement are the last unresolved question within the Standard Model.
- Nucleon spin structure study provide crucial information to the such study, from low energy (non-perturbative, confinement) to high energy (perturbative, asymptotic freedom) regime, and the transition in between.
- As one example of such study: Spin asymmetries at large x provide test of many models such as constituent quark model, pQCD, and Dyson-Schwinger Eq calculations. The polarization of the down quark, $\Delta d/d$, will tell us the perturbative (or non-perturbative) nature of the nucleon's behavior at high x.
- See more talks at the workshop on recent experiments at Jefferson Lab
- For testing the Standard Model in the electroweak sector using electron scattering, come back this afternoon!