- I came from China
- B. Eng. and M.S. (physics) at Tsinghua University
- Came to the US in 1999, Ph.D. at MIT, doing JLab physics
- First postdoc at Argonne National Lab (3 years), again JLab physics
- Second postdoc at MIT (7 months), JLab physics + job hunting
- Came to UVa in 2006, still doing JLab physics, although have expanded somewhat.

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- I like to use quizzes in teaching

Nucleon Structure Study Using Inclusive Electron Scattering

Xiaochao Zheng
University of Virginia,
Charlottesville, Virginia, USA

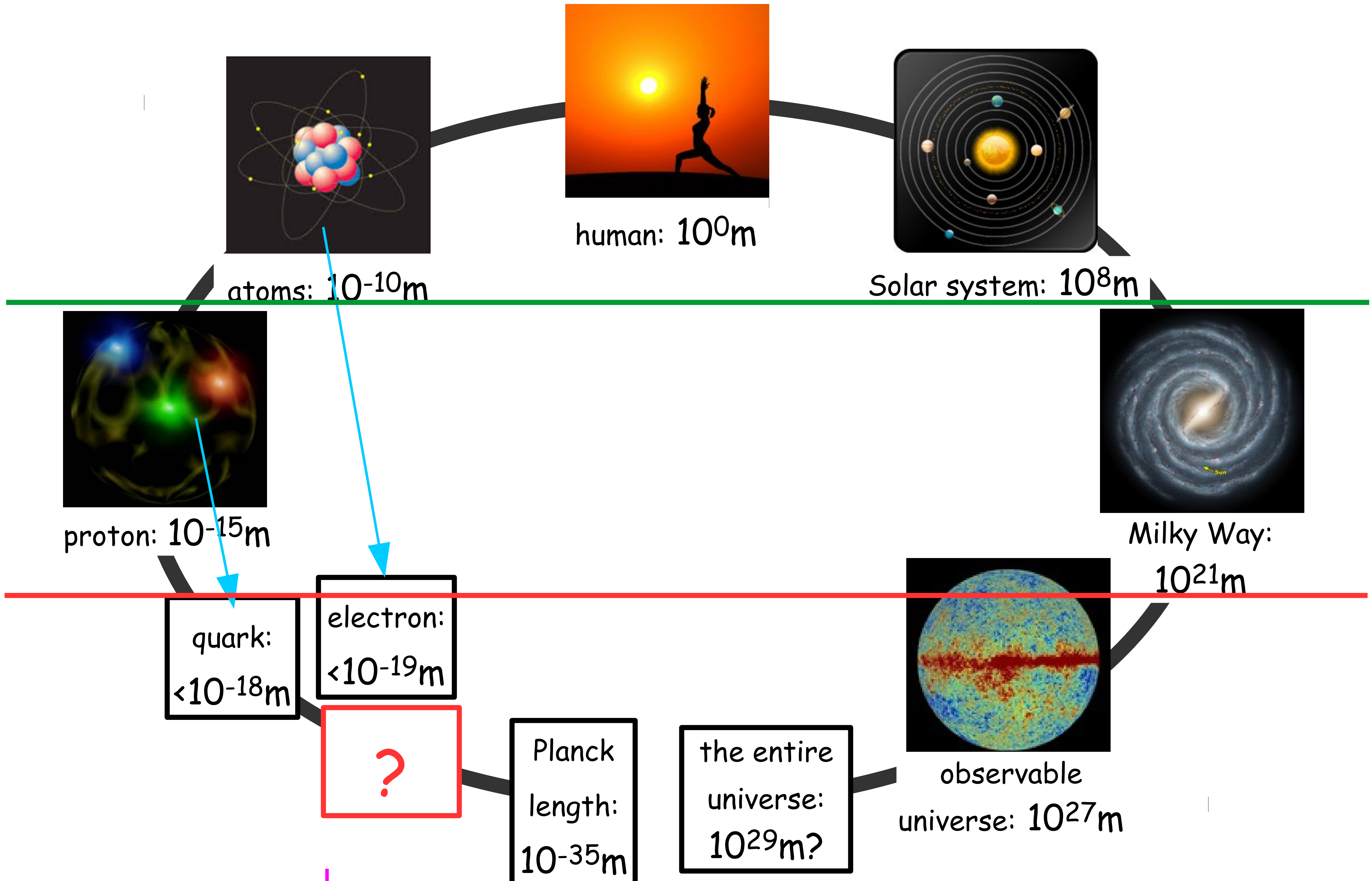
- From quarks to cosmos, and what we know today
- How do we study subatomic structure – from Rutherford scattering to today's electron scattering
- Nucleon structure from elastic to DIS
- Polarized DIS experiments and the nucleon spin structure
  - large-x physics
  - spin sum rules
- Summary

Lecture #1

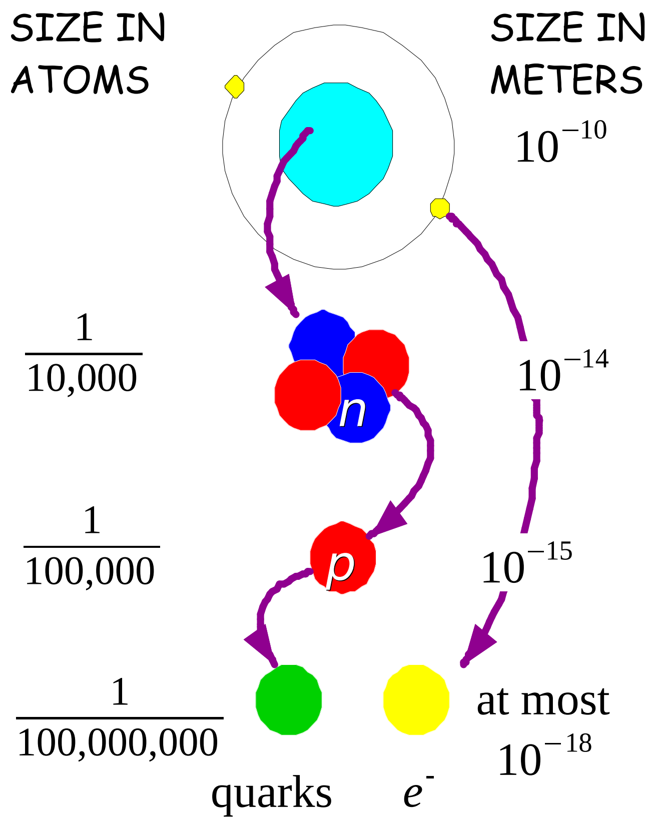
Introduction – Our quest to probe deeper and deeper into matter

Electron Scattering – 3 Kinematic Regions

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

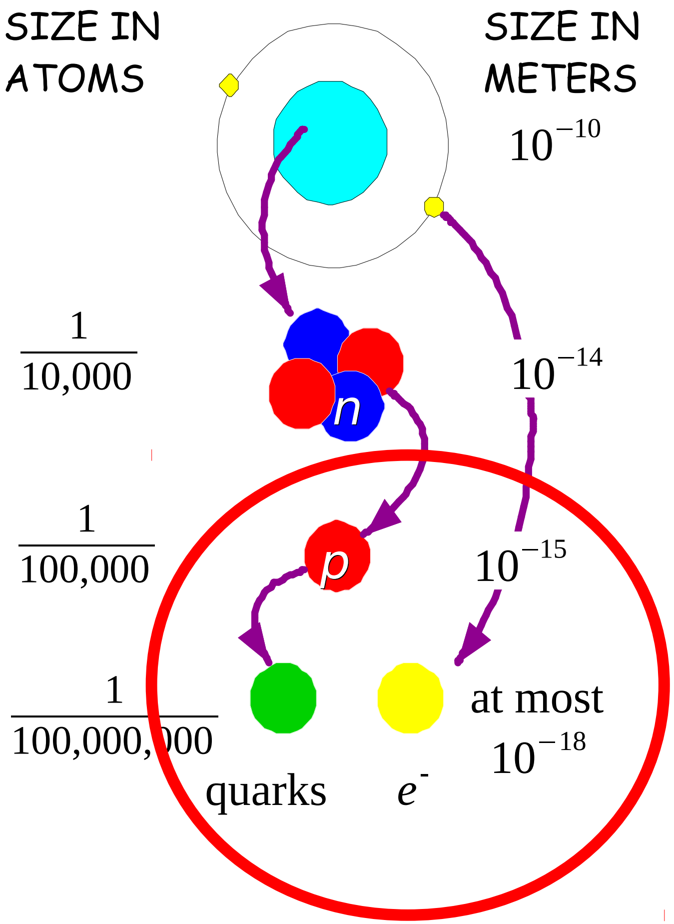
proton mass: 10^{-35} of Empire State Building

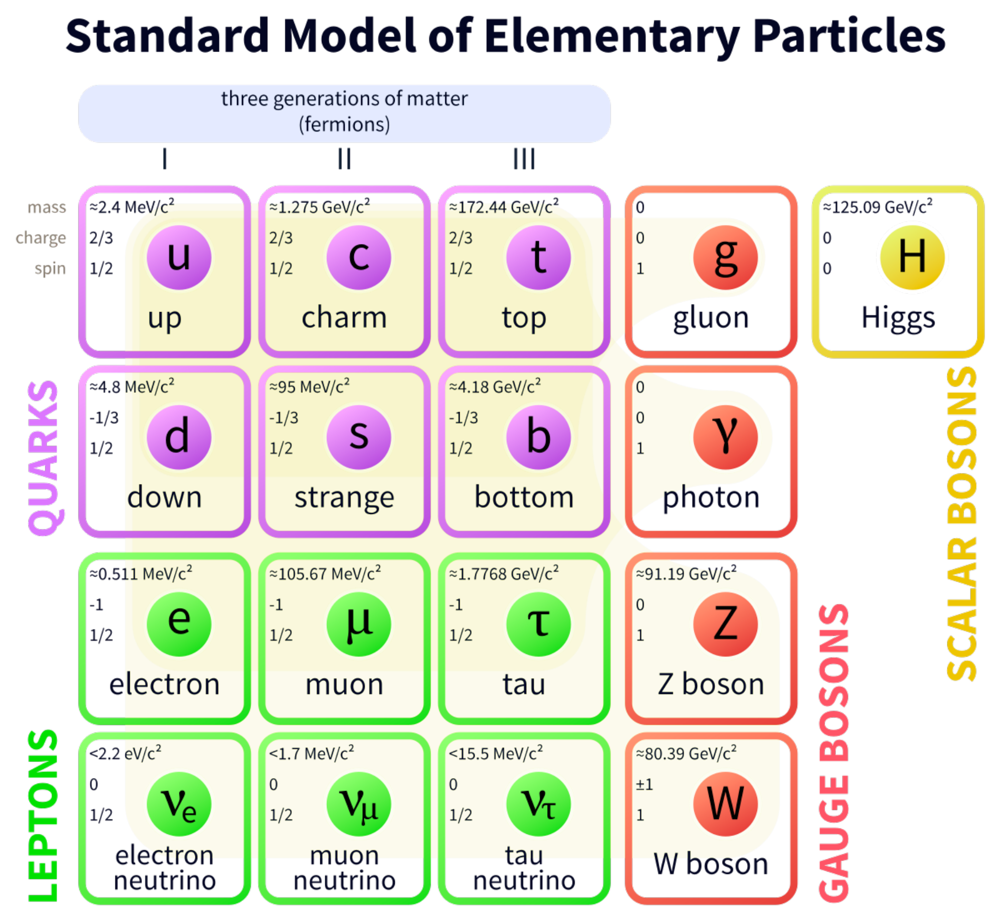
The Standard Model

(1) the elementary fermions – quarks and leptons

(2) the symmetries (of charges → interactions)

(3) the origin of masses

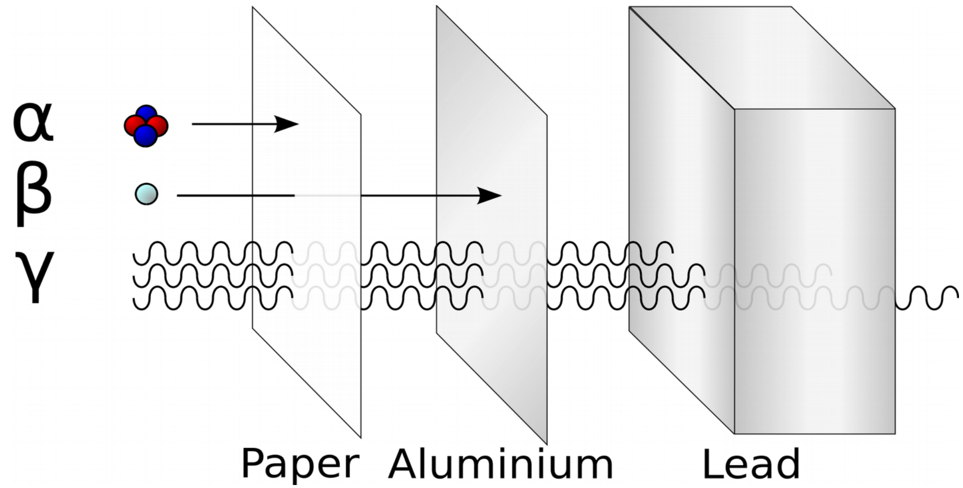




$$D^{\mu} = \partial^{\mu} - i g_1 \frac{Y}{2} B^{\mu} - i g_2 \frac{\tau_i}{2} W_i^{\mu} - i g_3 \frac{\lambda_{\alpha}}{2} G_{\alpha}^{\mu}$$

The Founding of Modern Nuclear Physics

1896 Henri Becquerel discovers radioactivity:



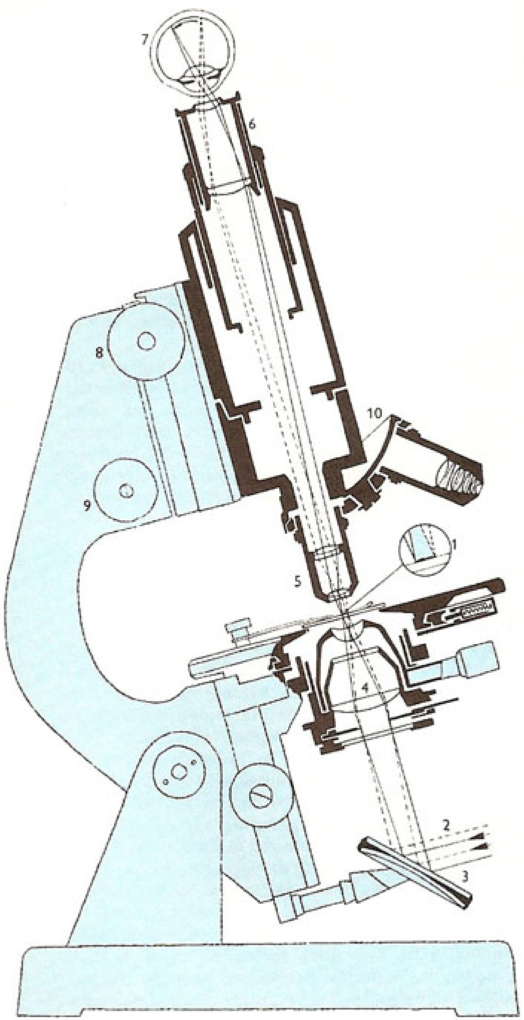
later identified as

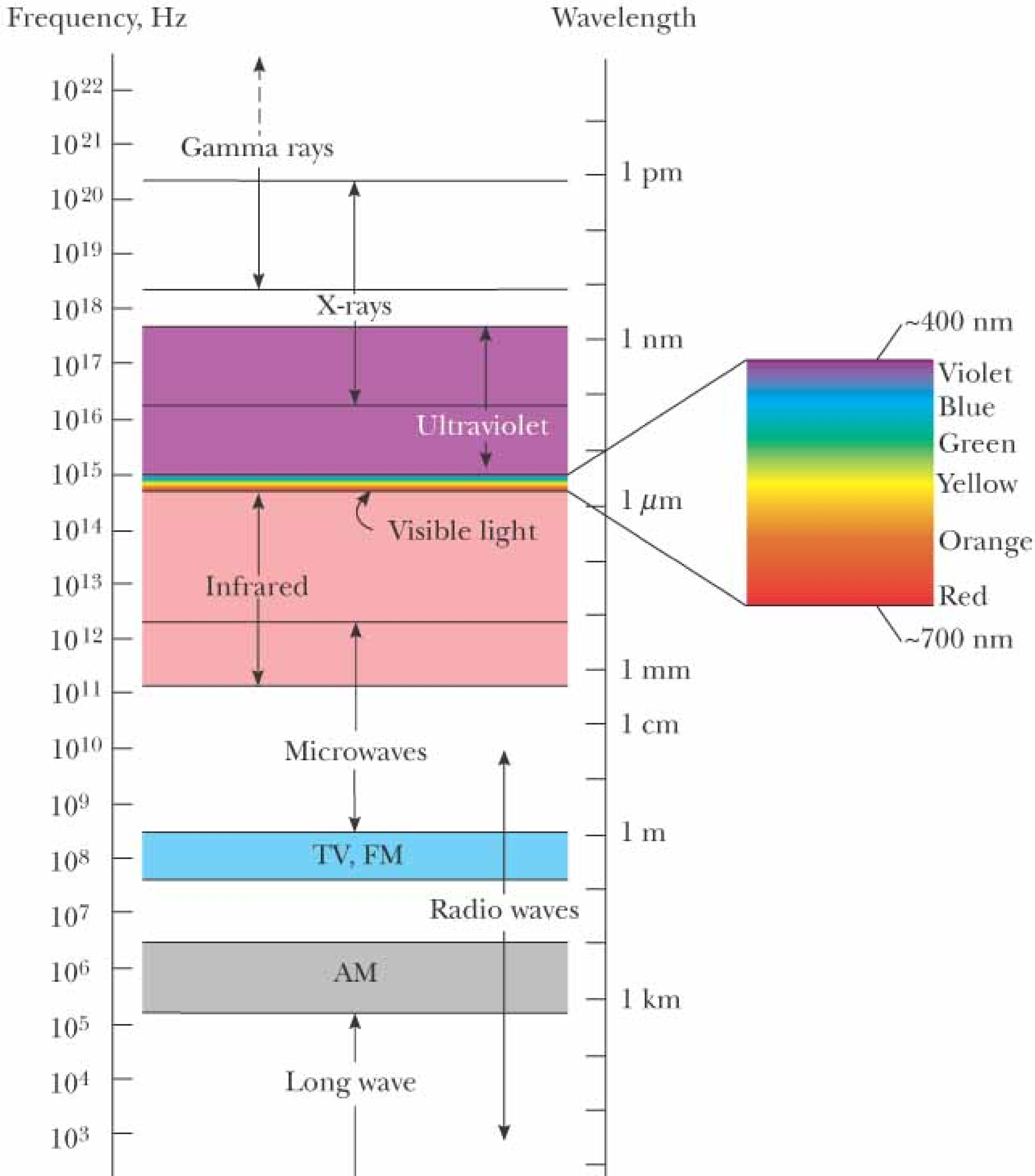
- α: ^{4}He nucleus
- β: electron/positron
- γ: photon

all are at MeV level !

- It was already known that material/atoms contains electrons. But what exactly is the structure of the atom?
- What can we use to "look inside" the atom??

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.

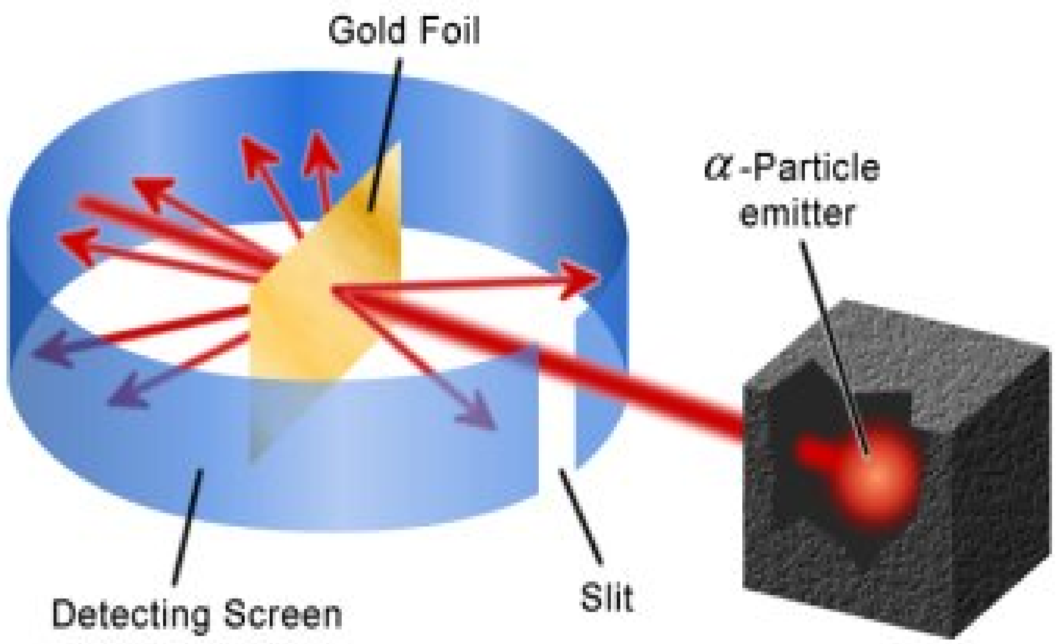
  - de Broglie wavelength: $$\boxed{\lambda = \frac{h}{|\vec{p}|}}$$

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

- Quiz 1: calculate the wavelength of 5 MeV alpha particles.

Rutherford Scattering

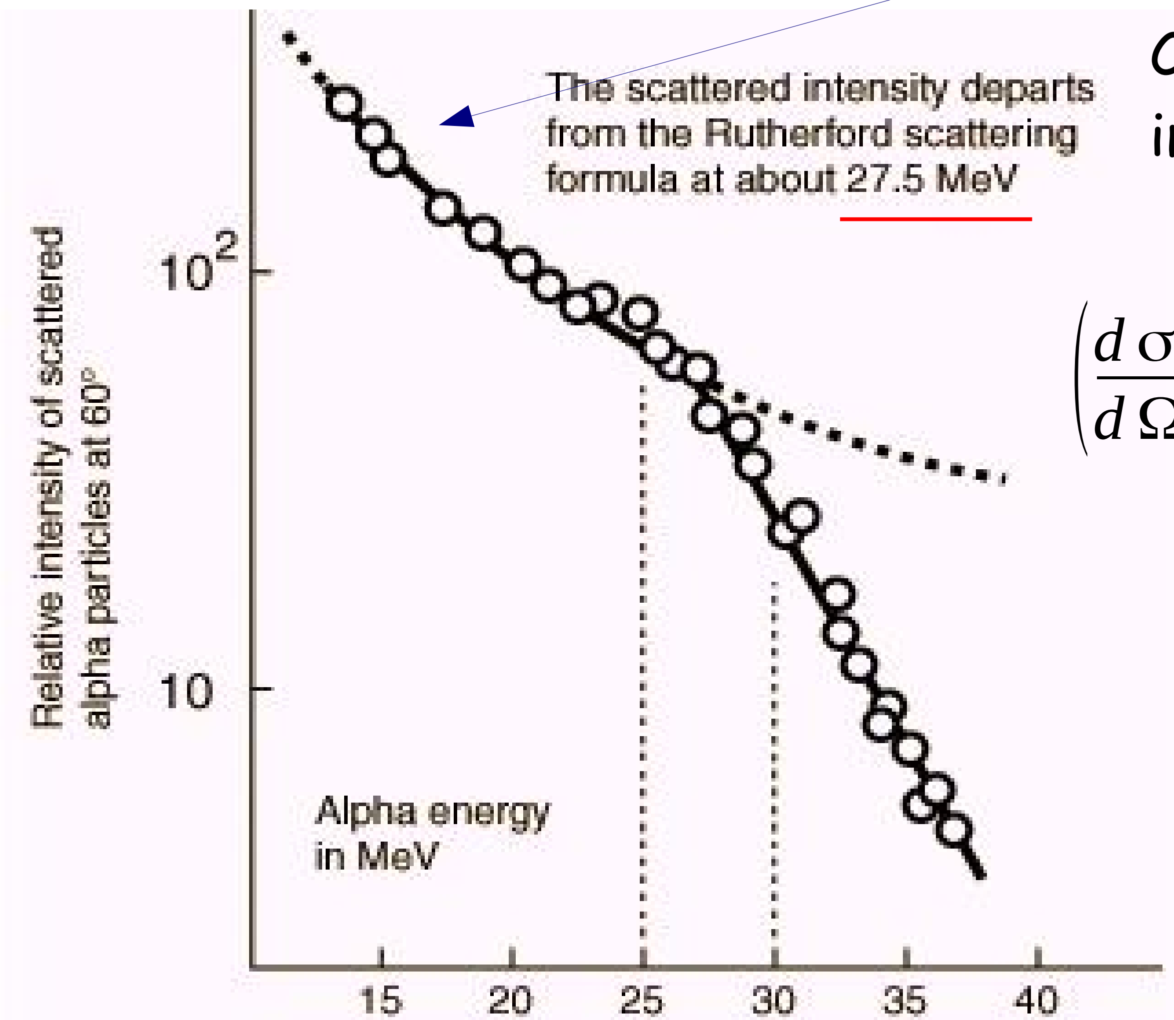
In 1909-1911, Rutherford and his coworkers examined how alpha particles (4He nuclei) scattered from a gold foil leaf that is only a few atoms thick. They found many more large-angle scatters than expected – 1 out of 8000 would scatter at 90 degrees – something that could only happen if the positive charge were concentrated in a tiny volume, rather than spread throughout the atom.



Quiz #2:

Use your knowledge about classical electric force and potential, calculate the "closest approach" of alpha to the gold nucleus (Z=97). (This gives the upper bound for the size of the "highly-mass-and-charge-concentrated nucleus".)

More recent data

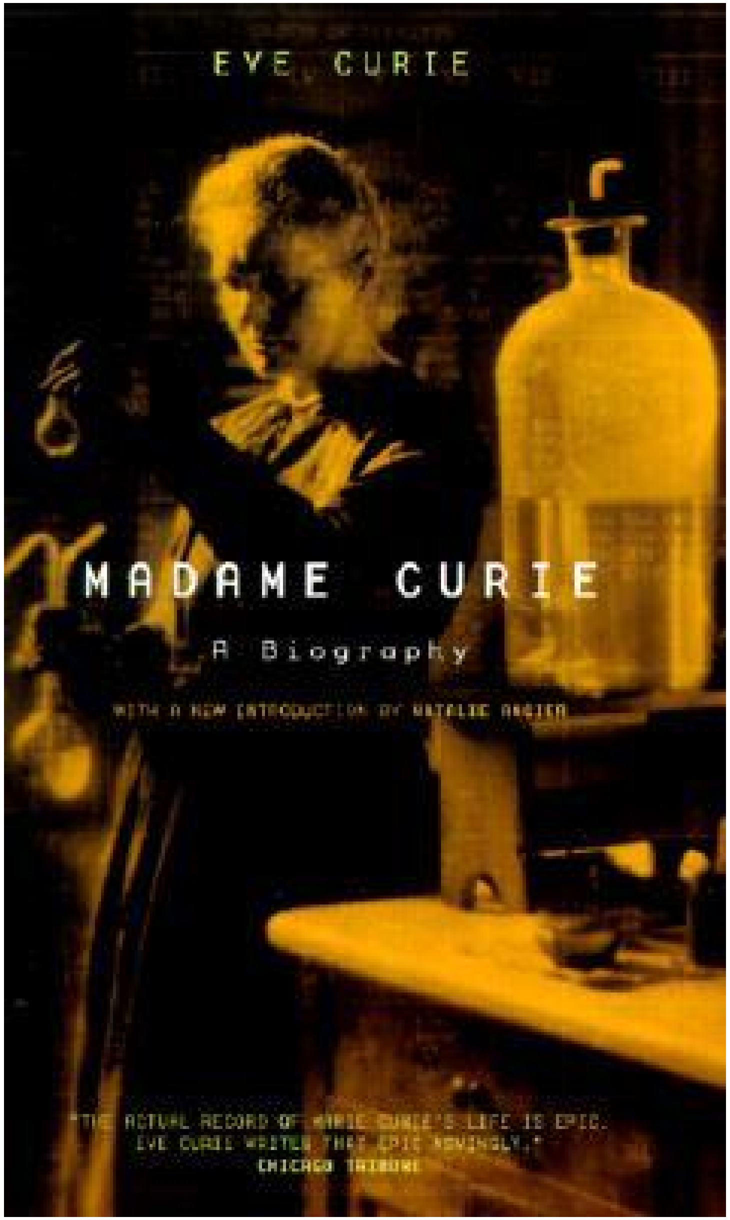


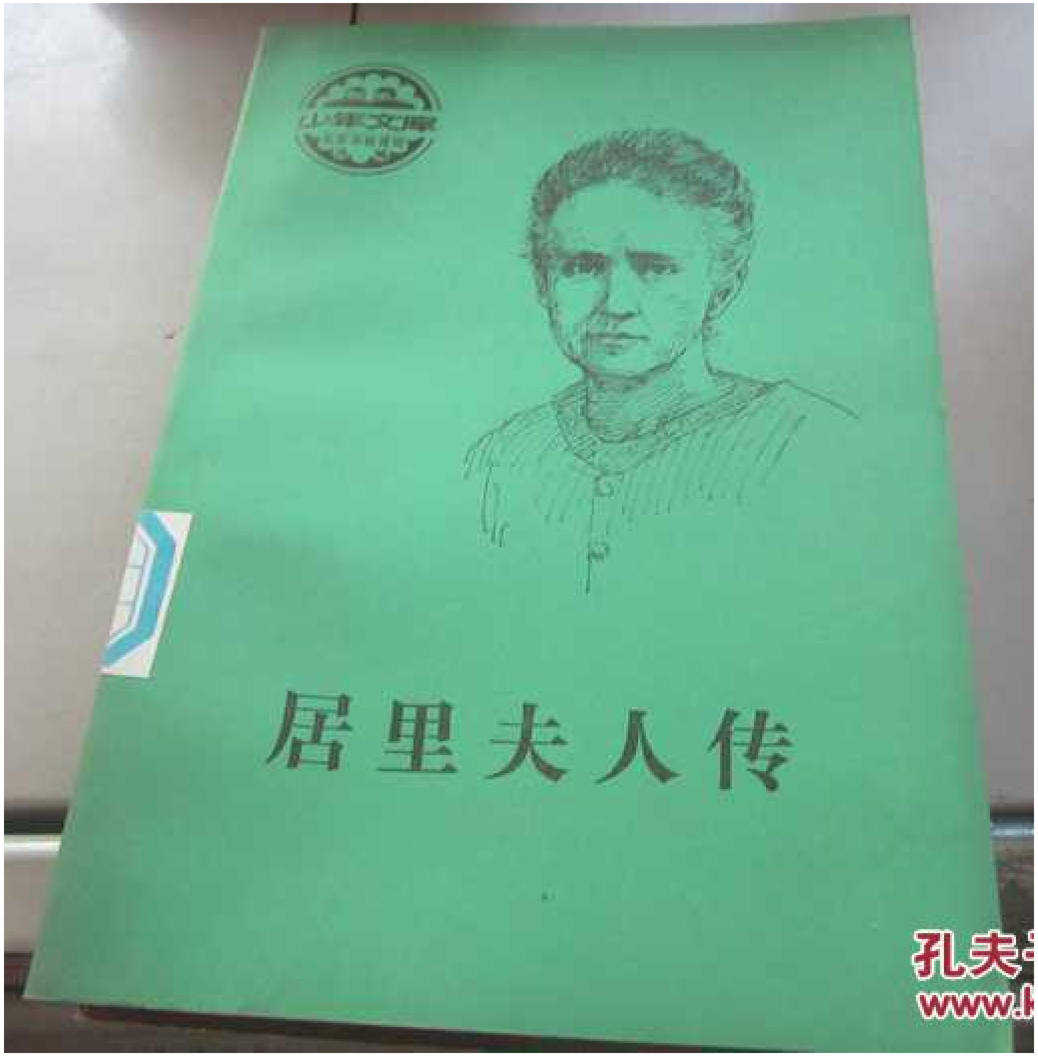
Rutherford formula (point charged particle from Coulomb field of an infinitely-heavy target

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \left(\frac{Z_1 Z_2 e^2}{16\pi\epsilon_0 E}\right)^2 \cos^4\left(\frac{\theta}{2}\right)$$

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.


EVE CURIE
MADAME CURIE
A Biography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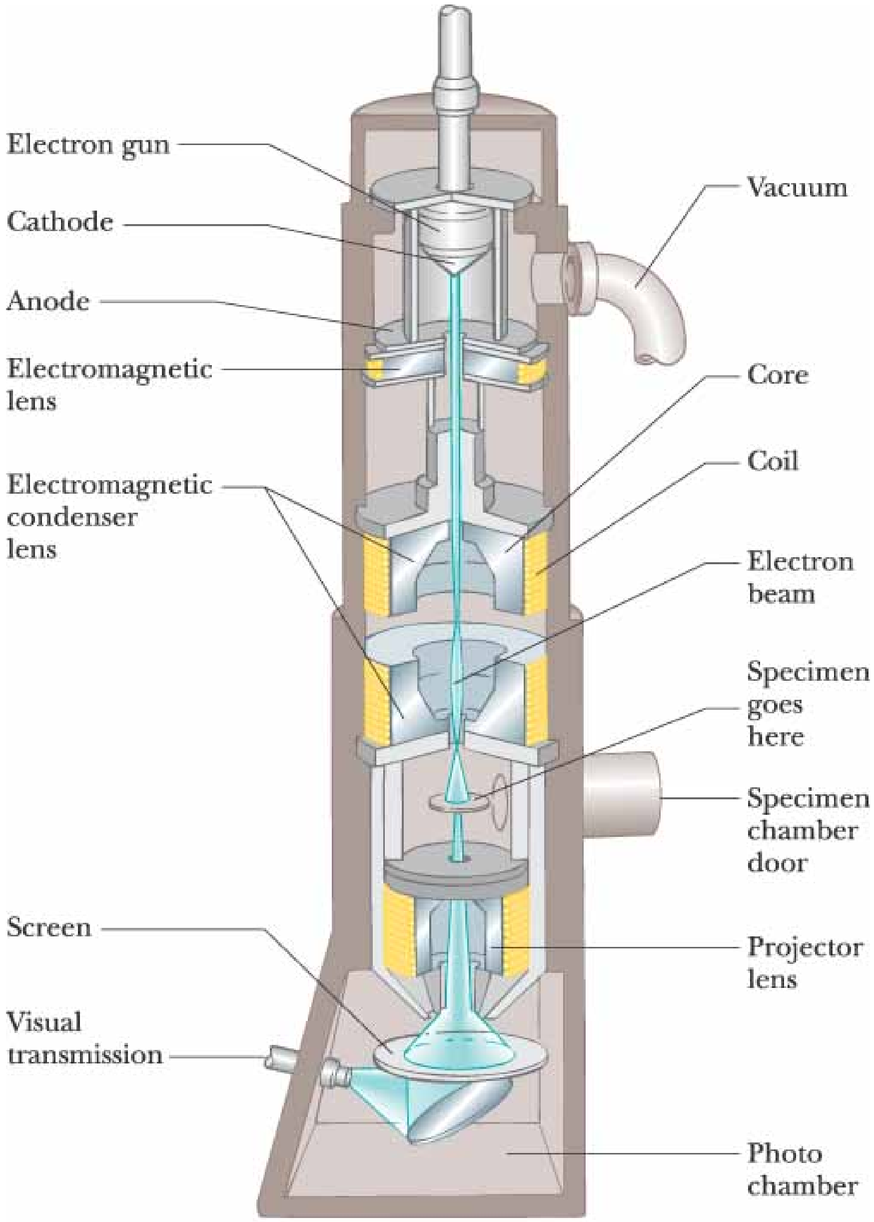
From Rutherford to Modern Electron Scattering

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.

However, detection of the scattered electrons is fundamentally different from optical or electron microscopes

Using keV-level Electron Microscopes to Study Molecular Structure



(a)

Going from KeV to MeV or GeV present several challenges:

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 systems 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 several challenges:

Electron microscope – What's limiting the resolution?

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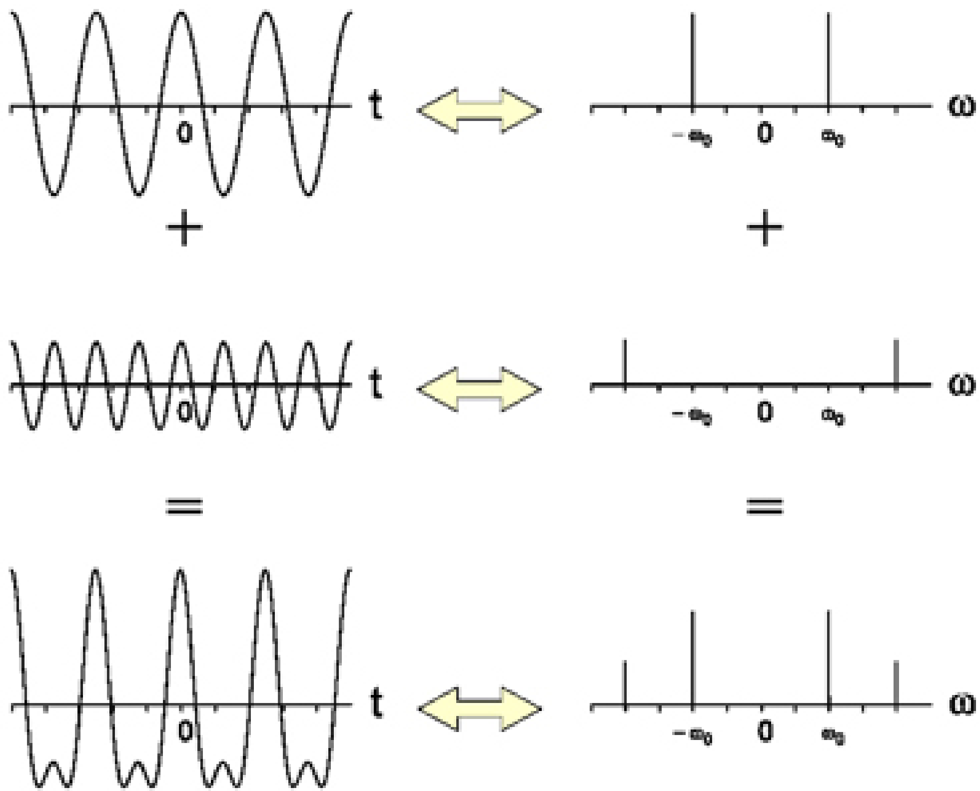
What can we do? *Answer: go to momentum space!*

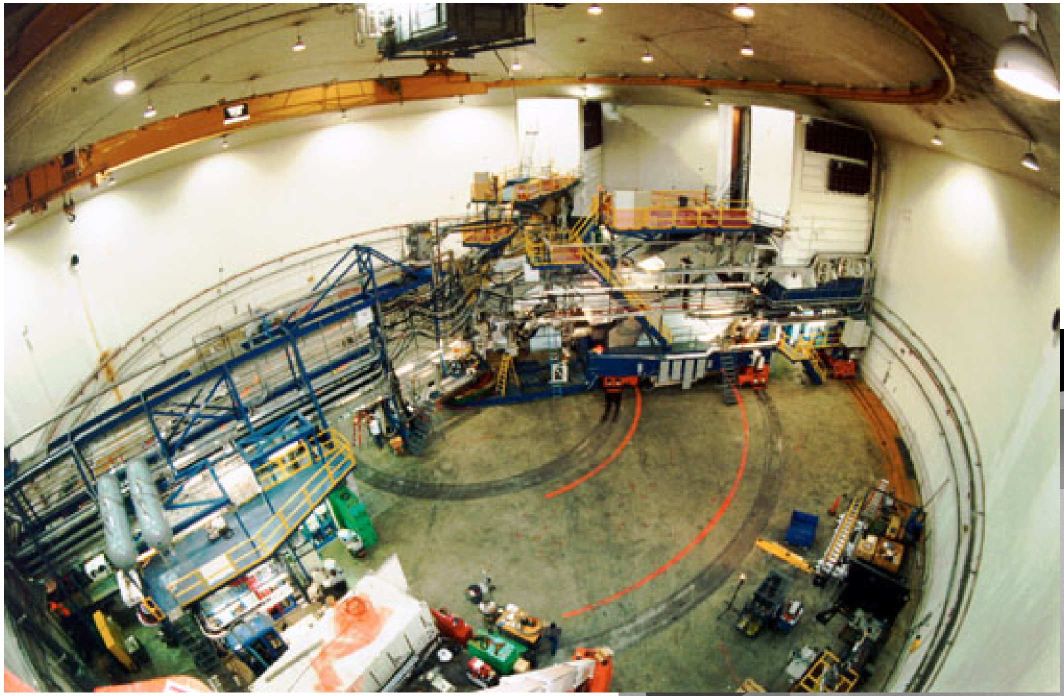
The Solution – Go to Momentum Space!

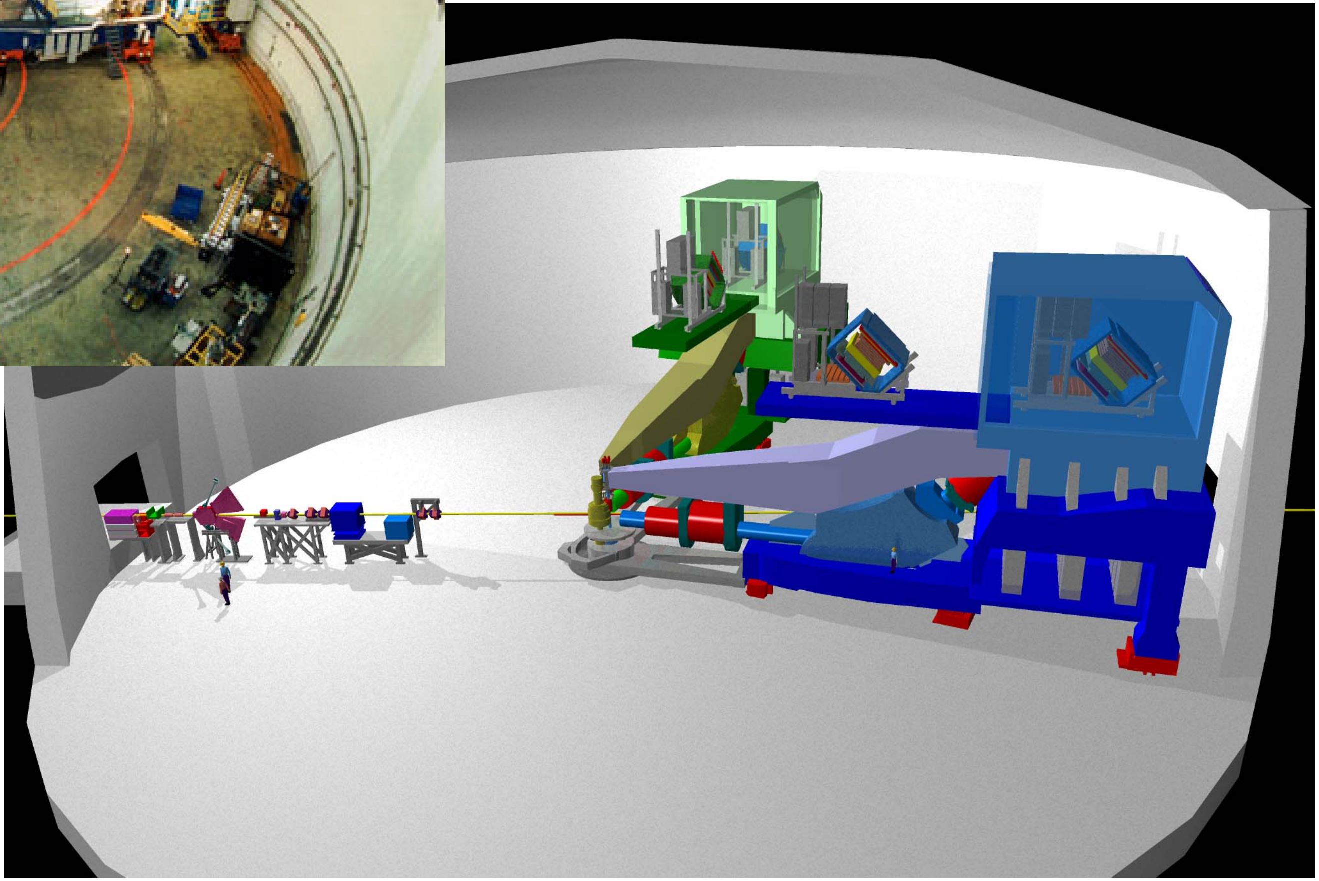
$f(x)$ f (t) F(ω) $F(p)$



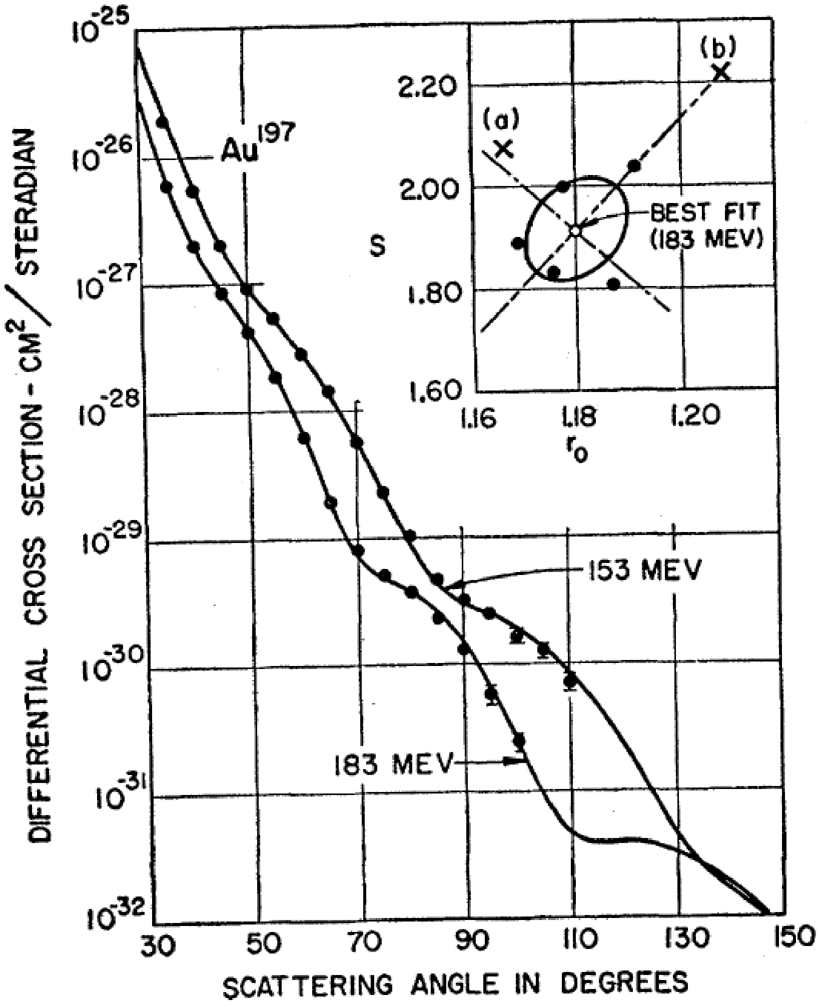
Fourier Transform

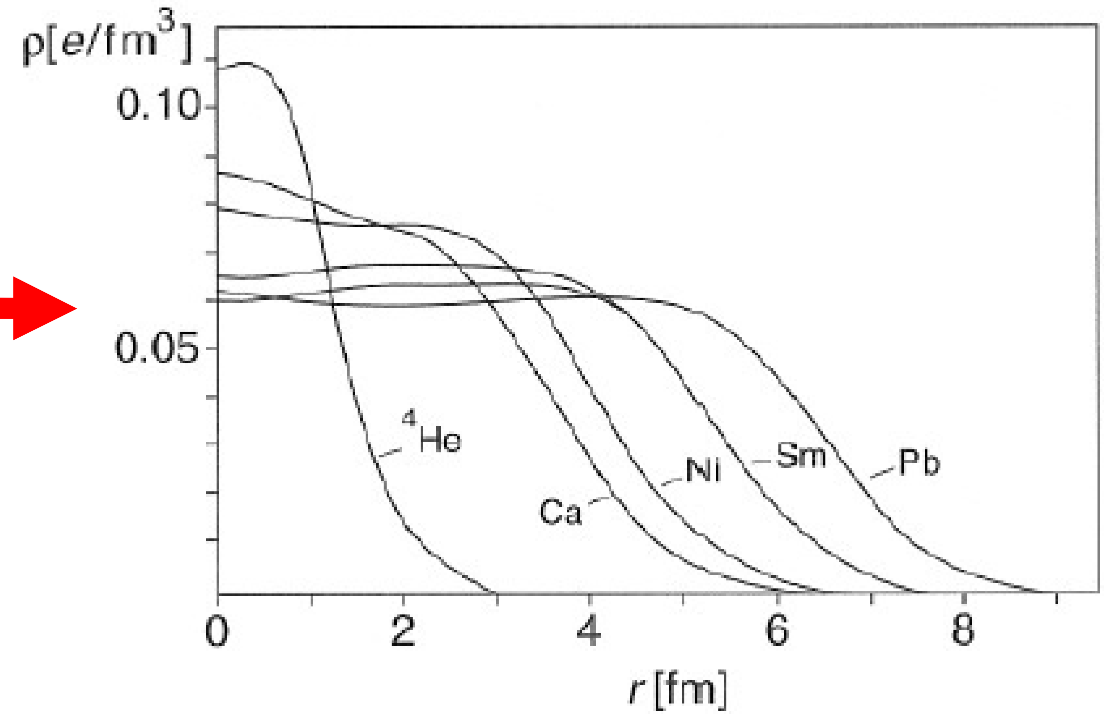
Instead of studying the spatial distribution of scattered electrons (as in electron microscope), we measure their momentum distribution using gigantic spectrometers





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

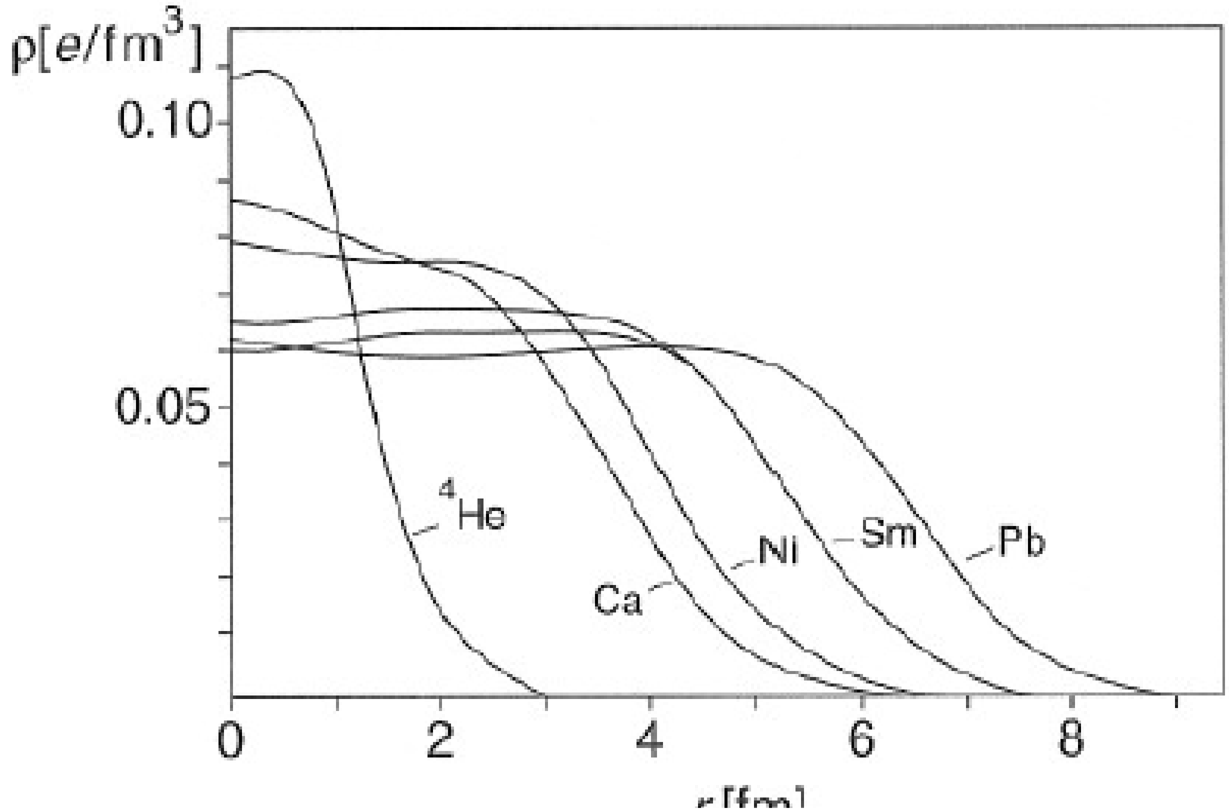
Fourier Transform

Form factor: F(q) → ρ(r)

Size of the Nucleus (extracted from Nuclear Form Factors)

$$r \approx r_0 A^{1/3}$$

$$r_0 = 1.2\ fm$$



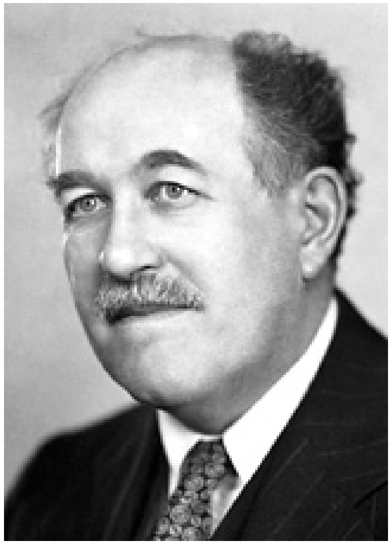
•<u>Studying the subatomic structure is not as simple as "put the object under a GeV beam and look at the reflection of the beam", but NP and HEP experimentalists develop a (clever) way to learn the exact shape of the nucleus</u>

Quiz: sketch the charge distribution of a heavy nucleus, and label the scale

Early Electron Scattering and Unpolarized DIS

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

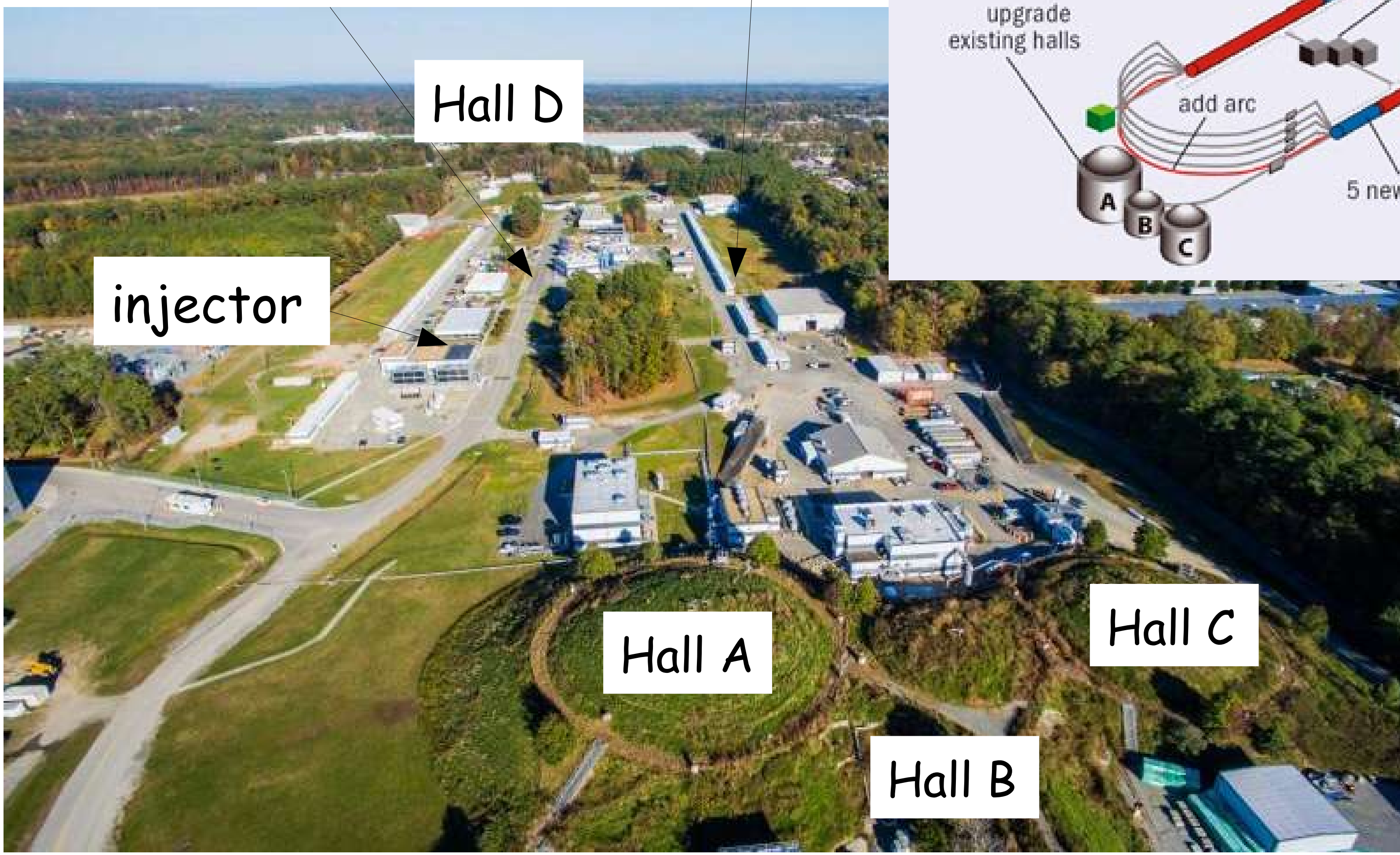
O. Stern — "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

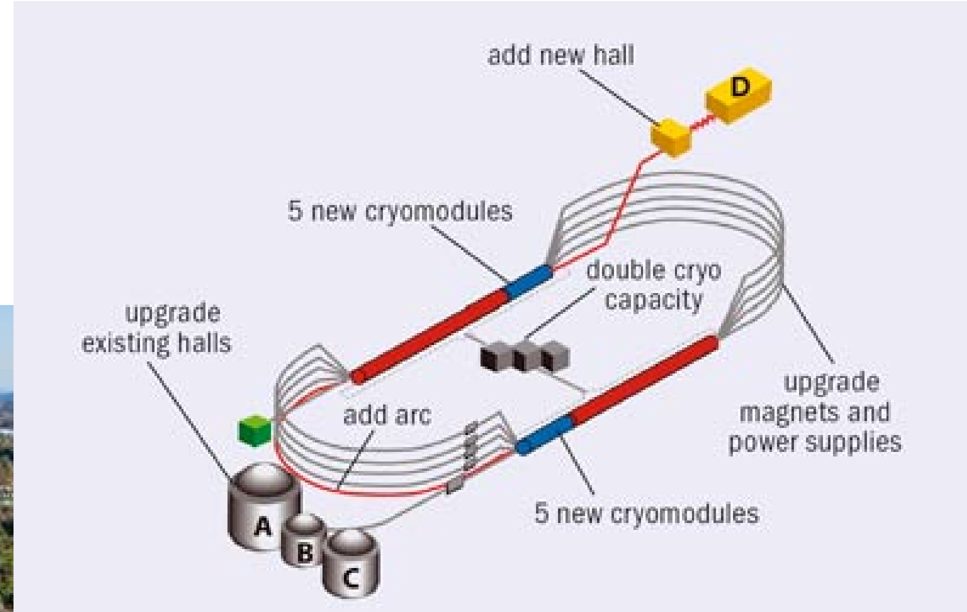


Continuous Electron Beam Accelerator Facility (CEBAF) of Jefferson Lab

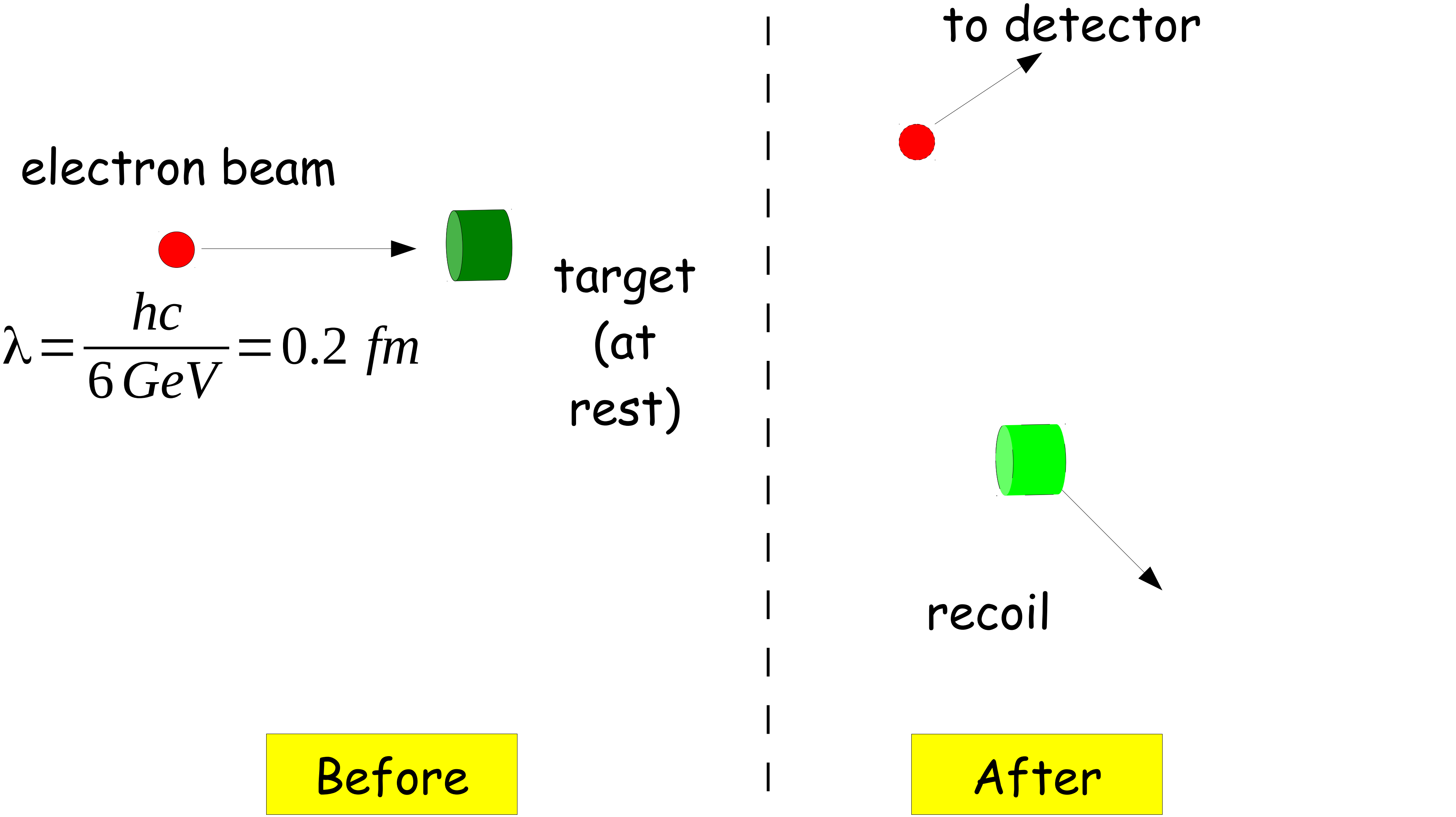
north linac

south linac





Basics of Electron Scattering on a Fixed Nuclear Target



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

Basics of Electron Scattering on a Fixed Nuclear Target

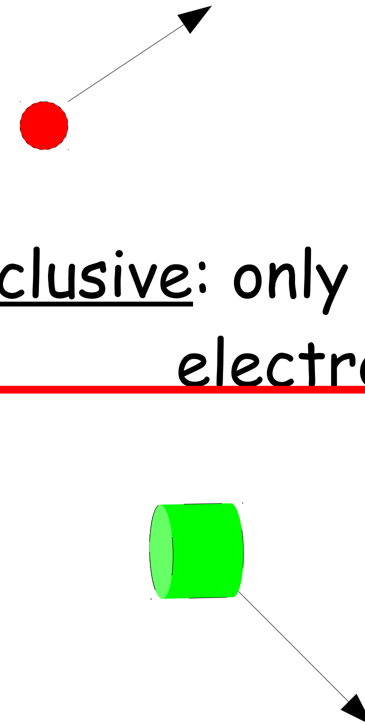
electron beam

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

target (at rest)

Before

to detector



Inclusive: only the scattered electron is detected

recoil

After

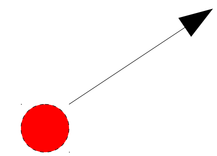
Basics of Electron Scattering on a Fixed Nuclear Target

electron beam

target (at rest)

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

to detector



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

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

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

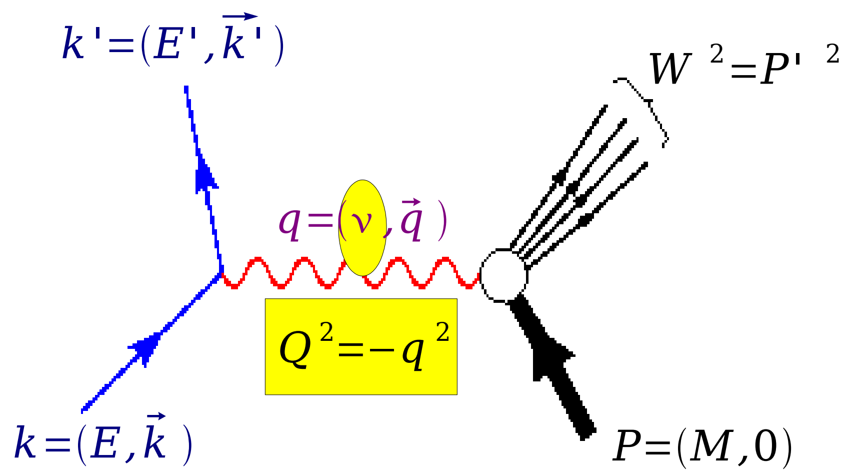
$$\times\, \text{physics cross section}$$

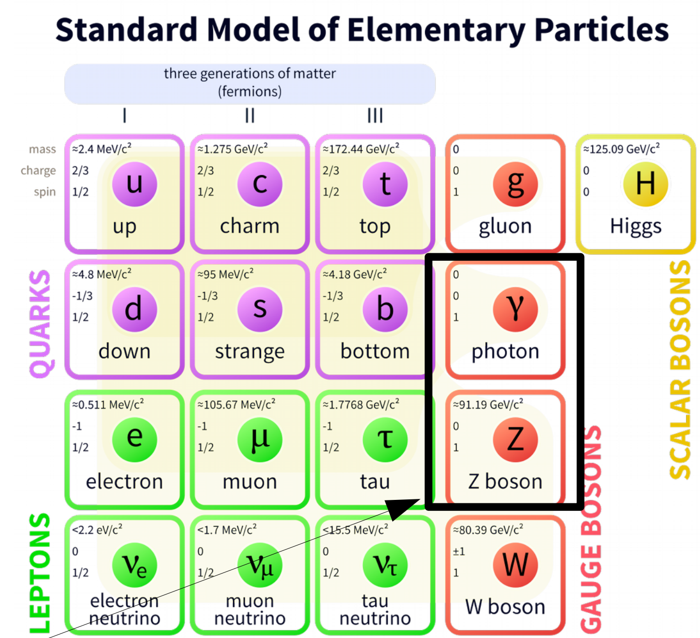
accelerator and facility capability

spectrometer capability

physics

Electron Scattering - both EM and weak interactions





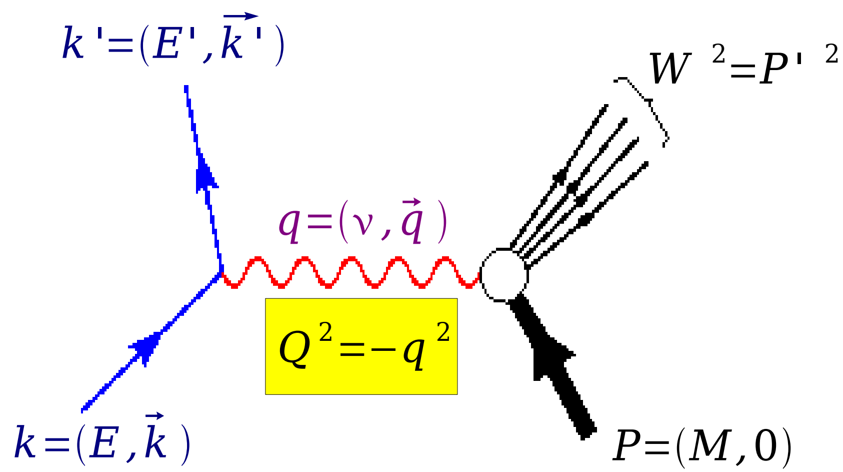
- Electrons (or μ's) interact with the target by exchanging a "virtual" photon or a Z^0;
- Two variables to describe how the target behave: $1/Q^2$ and ν;

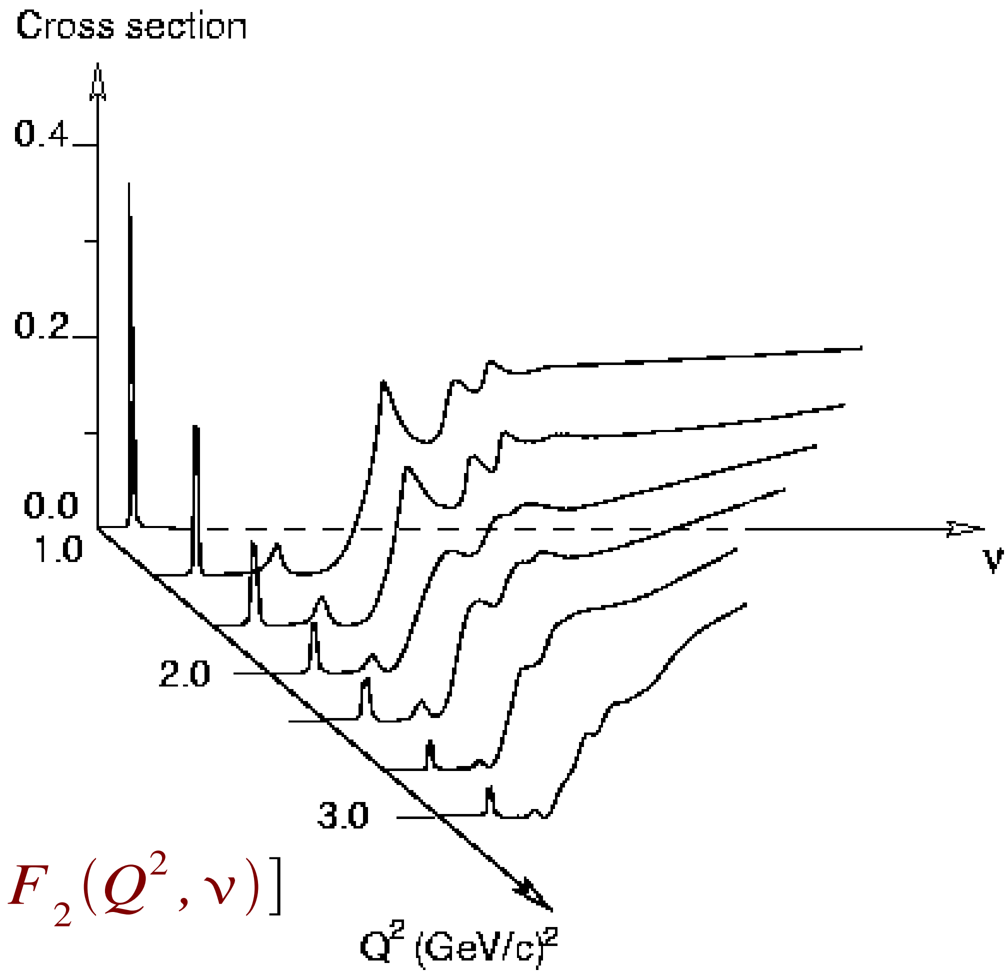
$1/Q^2$ ~ resolution of the probe

ν ~ how "hard" we kick the nucleus

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

Exploring Nucleon Structure Using EM Probe



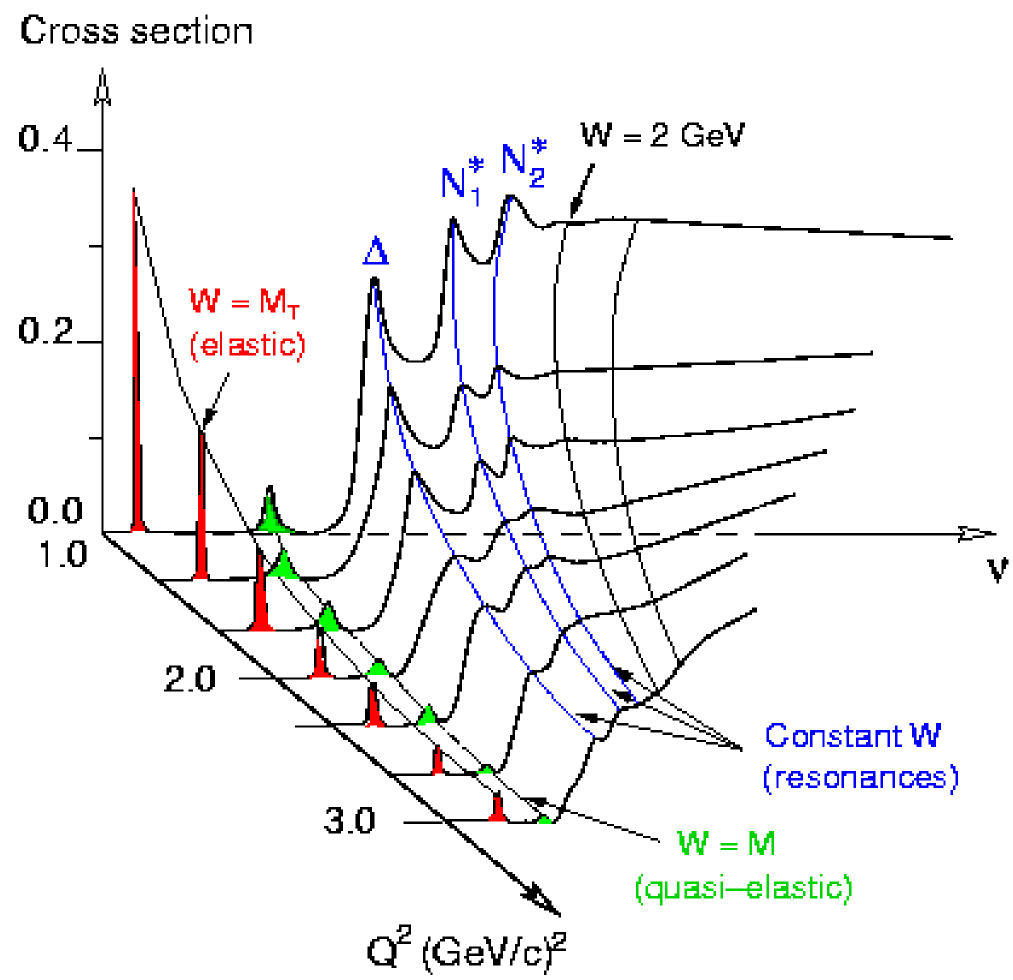


- The cross section:

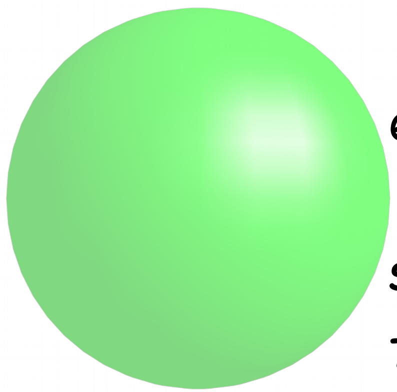
$$\frac{d^2\sigma}{d\Omega\, dE'} = \sigma_{Mott}\left[\alpha F_1(Q^2,\nu) + \beta F_2(Q^2,\nu)\right]$$

For point-like target

Exploring Nucleon Structure Using EM Probe (cont.)

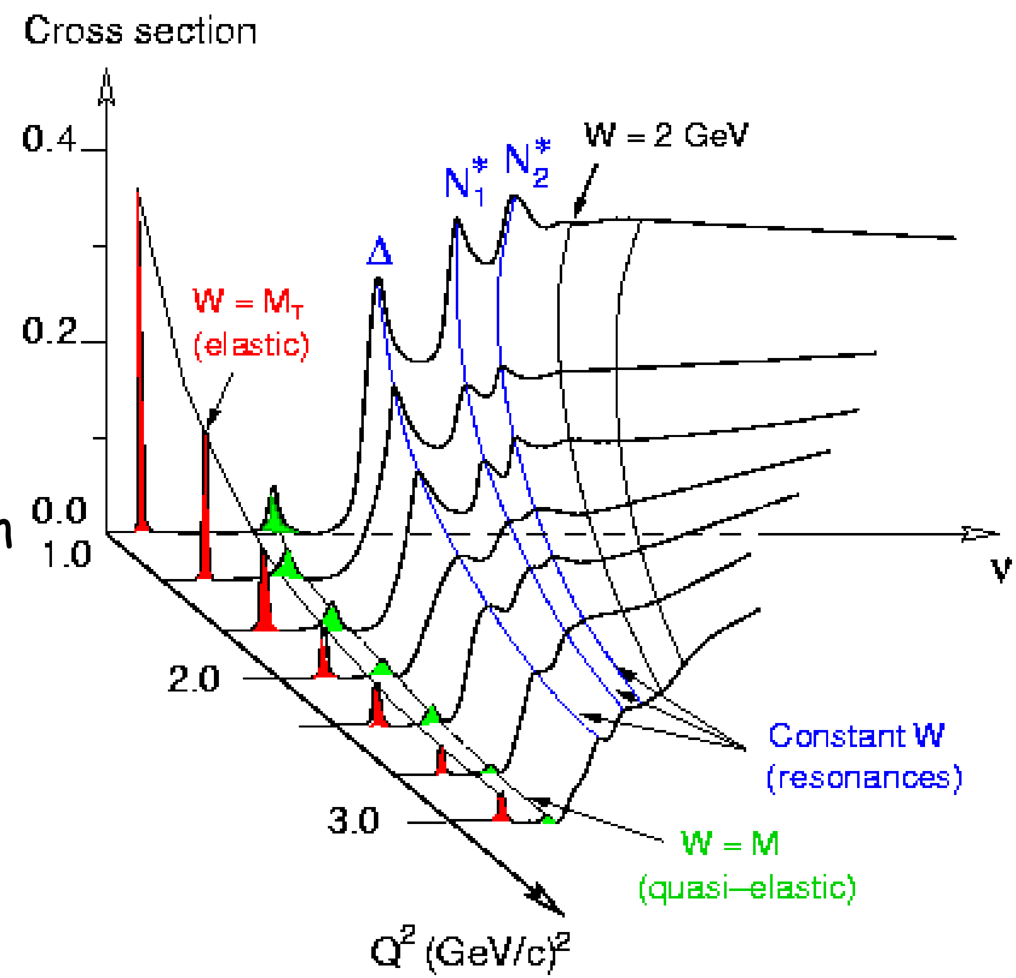


Exploring Nucleon Structure Using EM Probe (cont.)

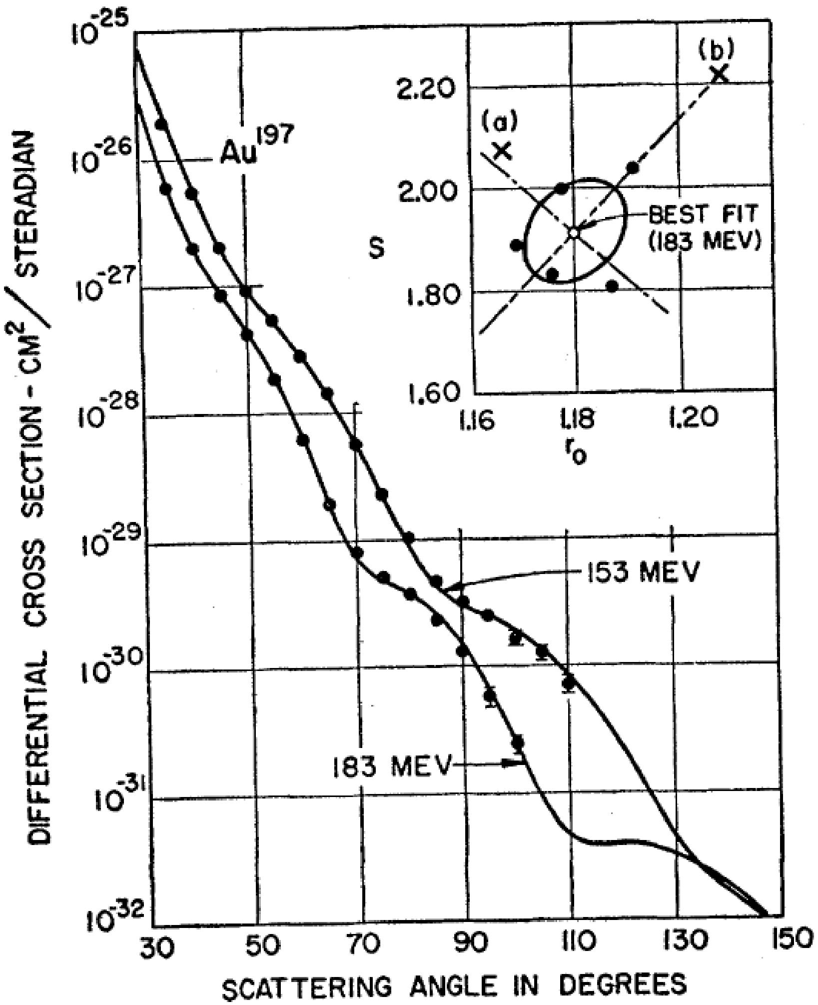


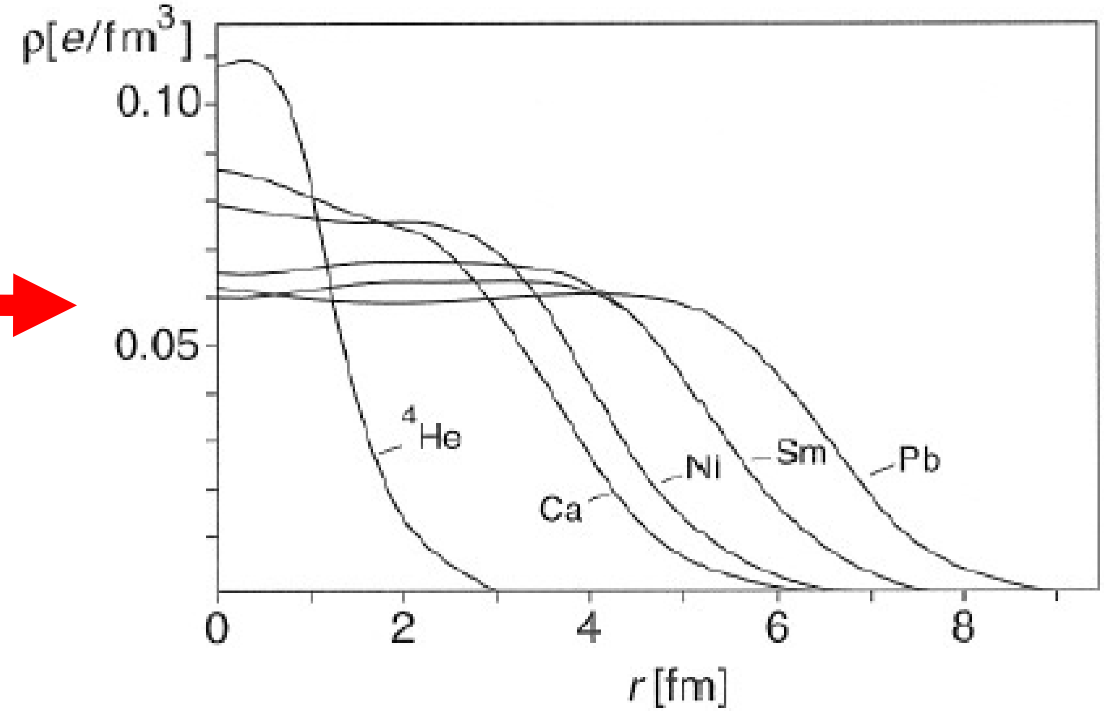
elastic — rigid body

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 → Fourier Transform → Spatial Distribution

Form factor: F(q) → ρ(r)

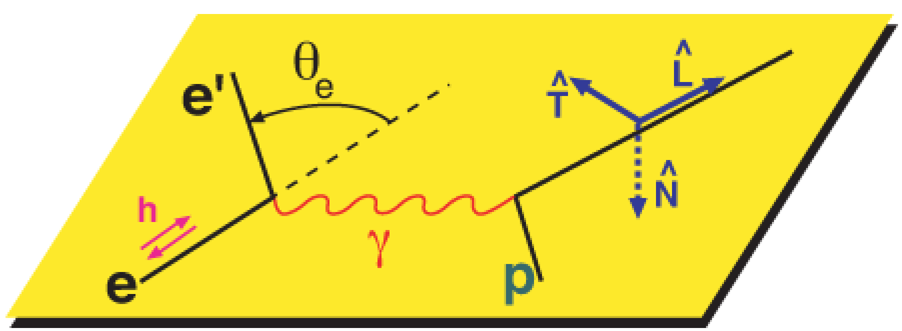
Structure of the Nucleon

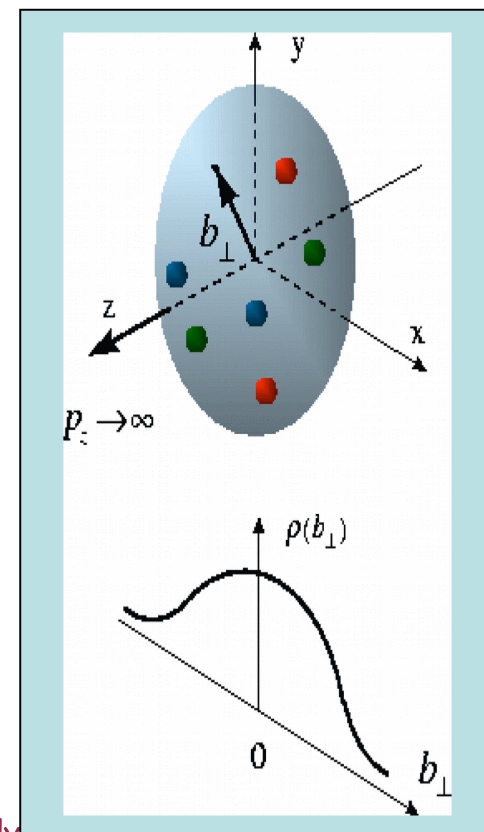
Nucleon Electromagnetic Form Factors

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M \left[\frac{G_E^2(Q^2)+G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2) \right]$$

$$\sigma_M = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)} \propto \frac{1}{Q^4}$$

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan(\theta/2)$$

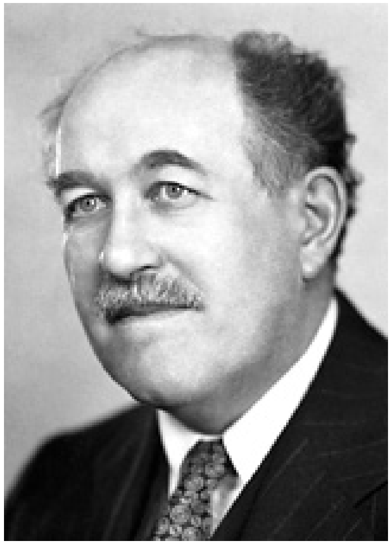




Early Electron Scattering and Unpolarized DIS

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

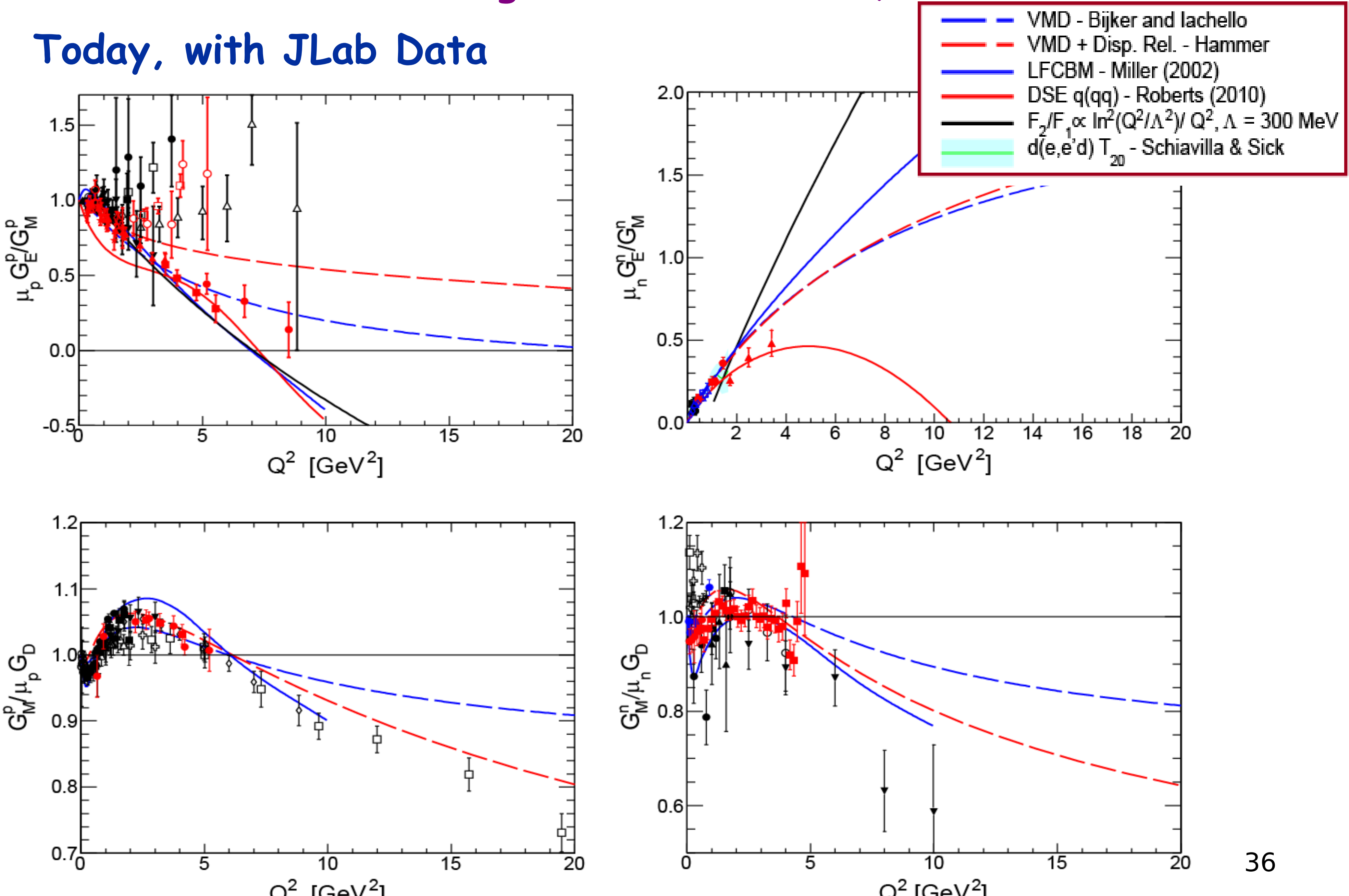
O. Stern — "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"



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)

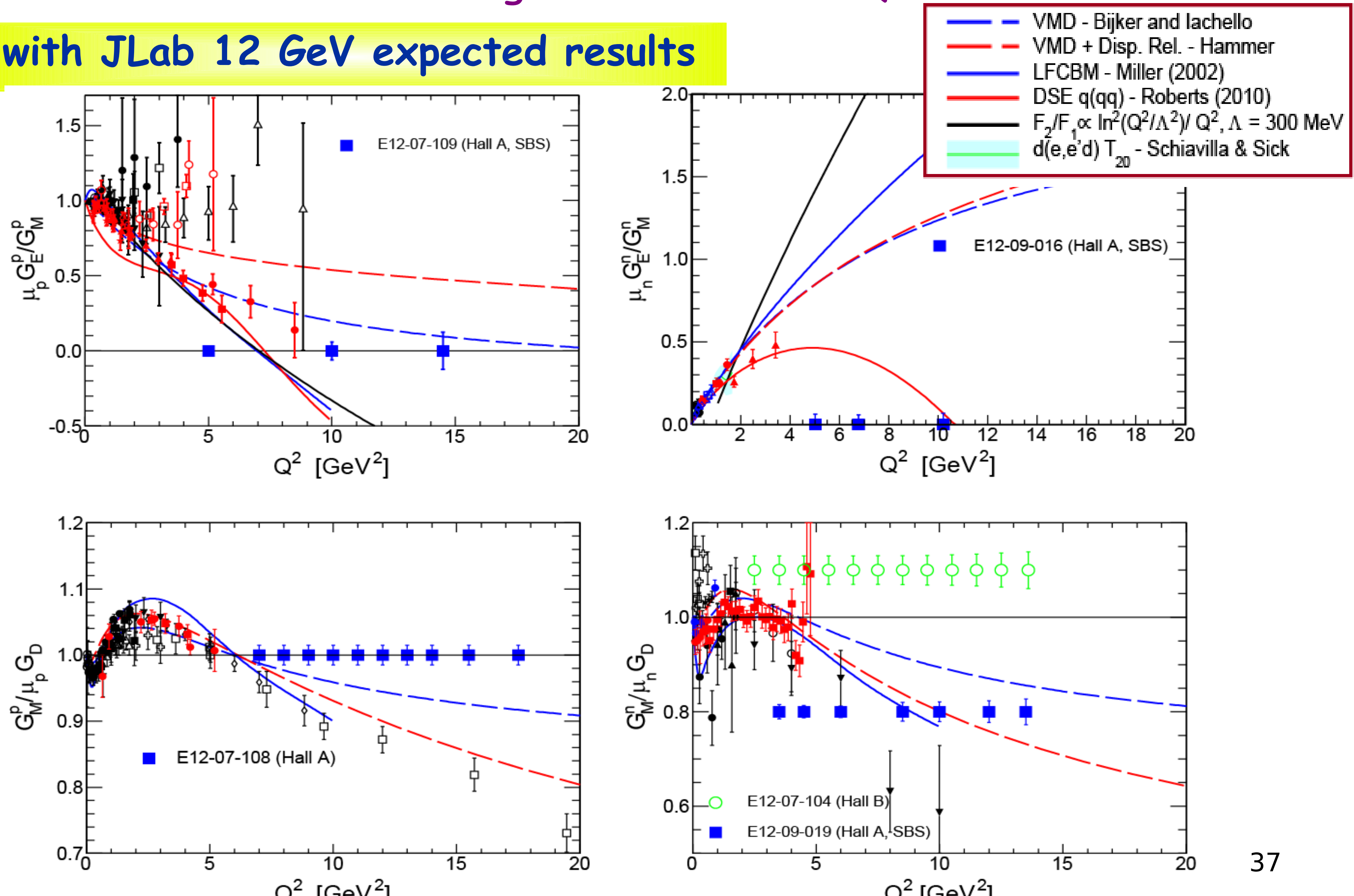
JLab Data on the EM Form Factors Provide a Testing Ground for Theories Constructing Nucleons from Quarks and Glue

Today, with JLab Data



JLab Data on the EM Form Factors Provide a Testing Ground for Theories Constructing Nucleons from Quarks and Glue

with JLab 12 GeV expected results



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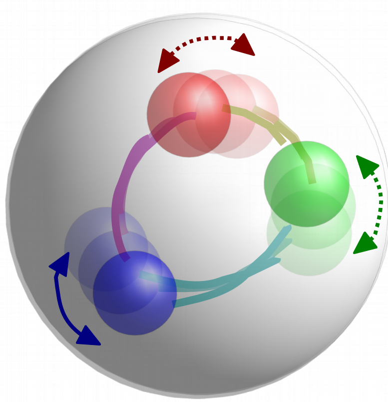
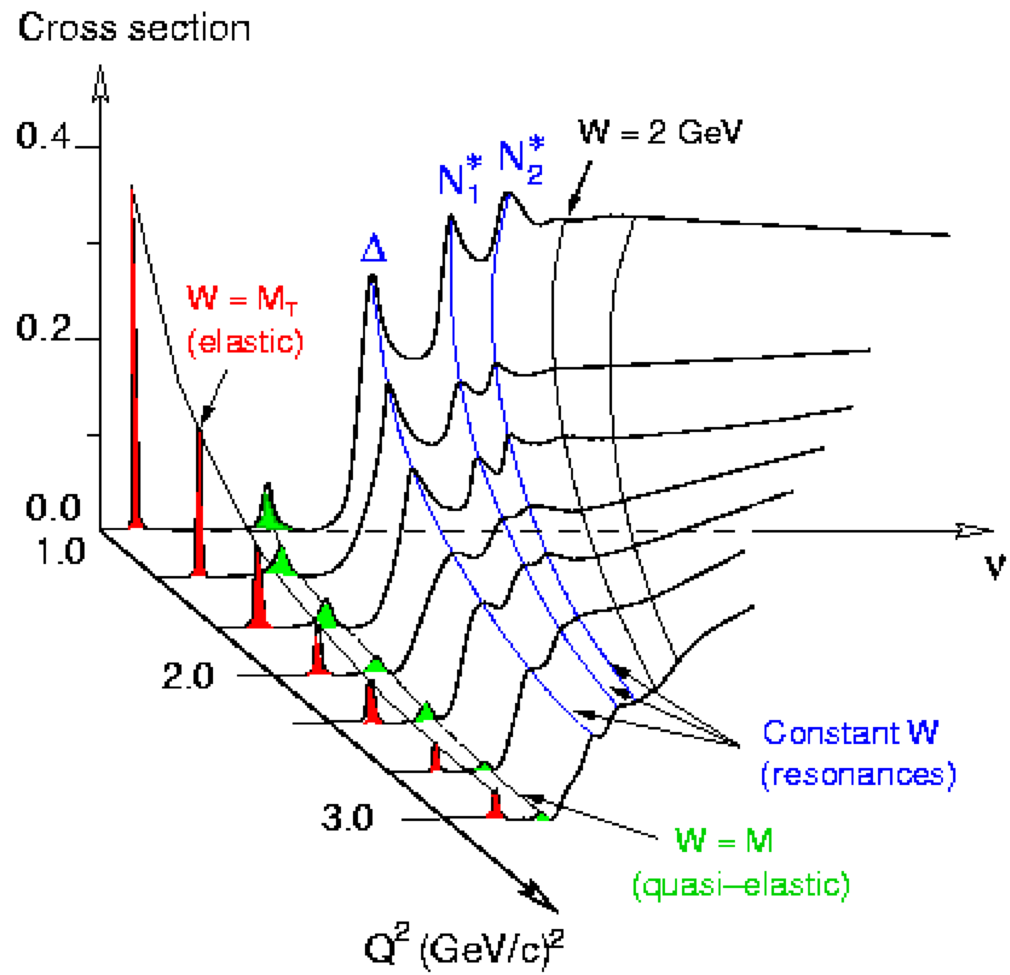
Exploring Nucleon Structure Using EM Probe (cont.)

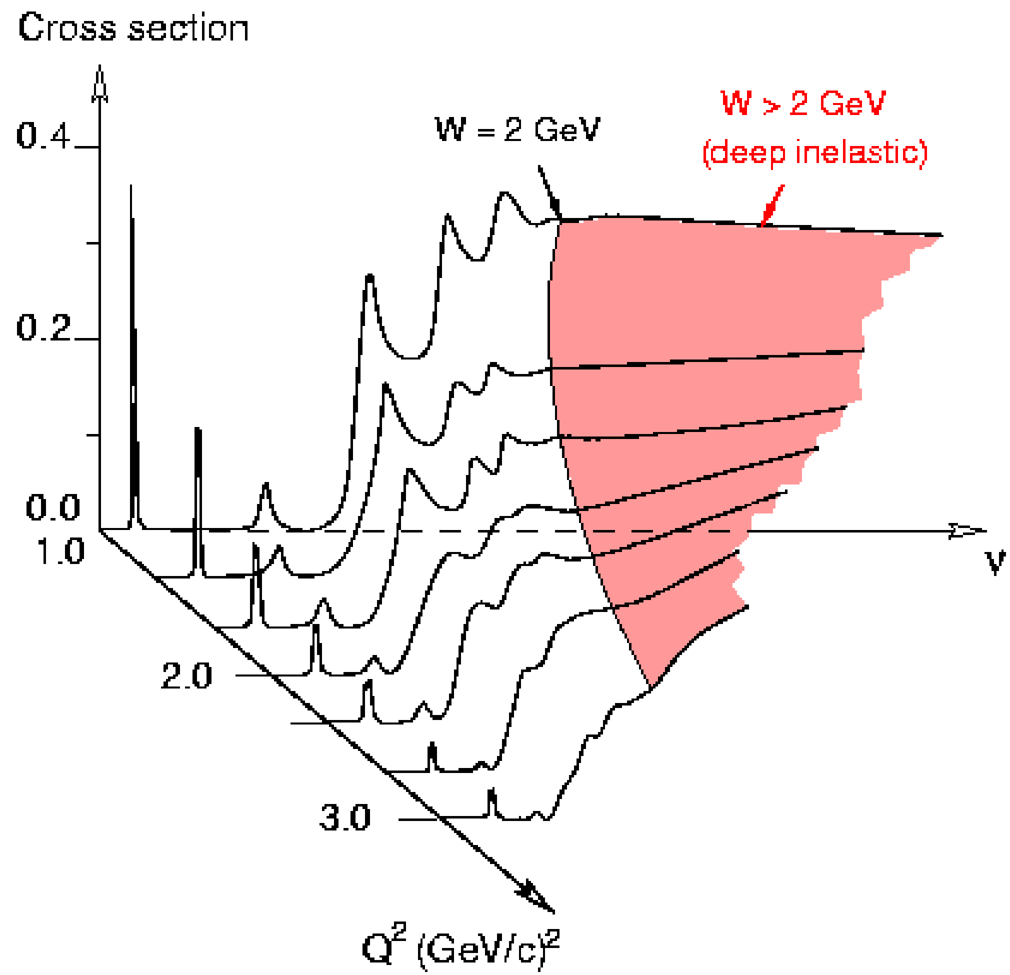
- Resonance region – quarks inside the nucleon react coherently (nucleon spectroscopy)

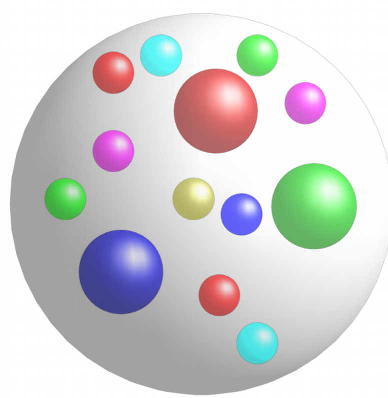




Exploring Nucleon Structure Using EM Probe (cont.)

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



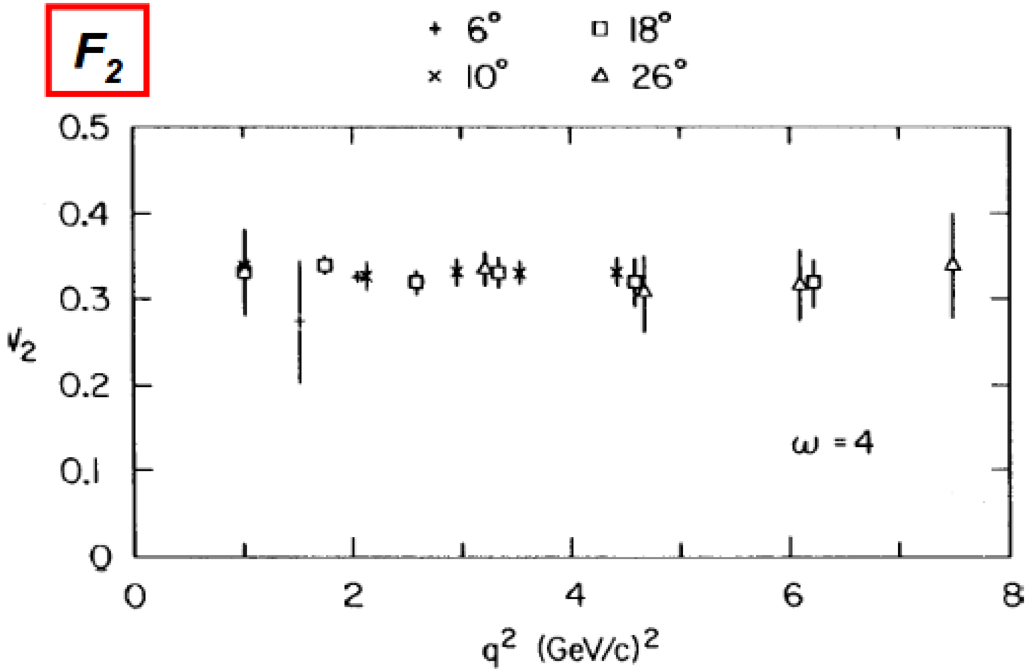


For DIS, perturbation theory starts to work !

Early Electron Scattering and Unpolarized DIS

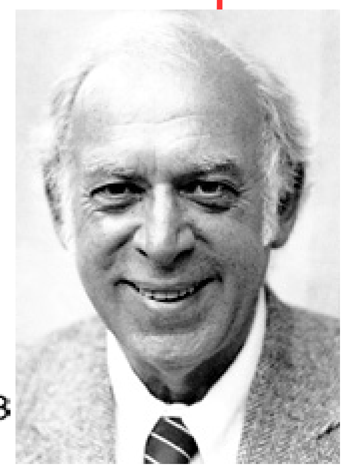
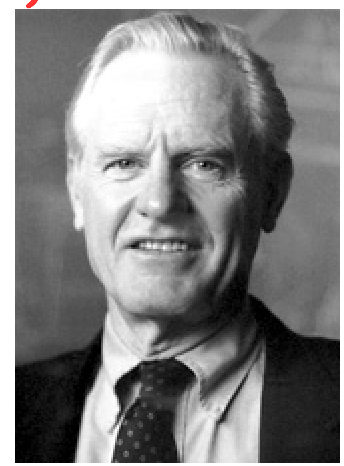
- 1968: First DIS data from SLAC, Friedman, Kendall, Taylor *et al.*

F_2



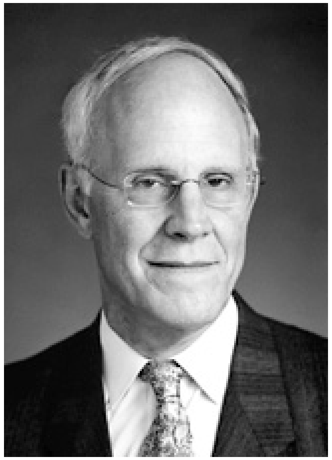
"scaling" (what you see no longer depend on the resolution of the probe)

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"

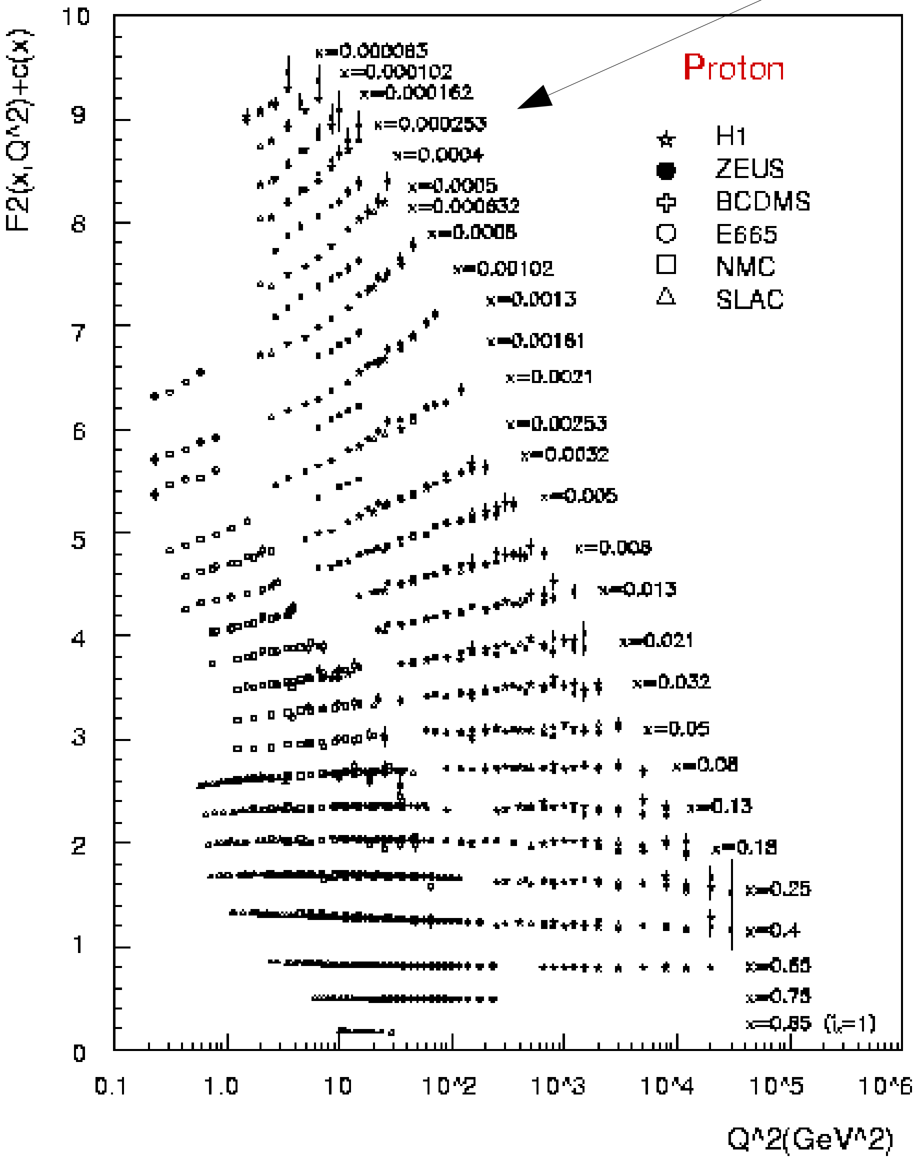


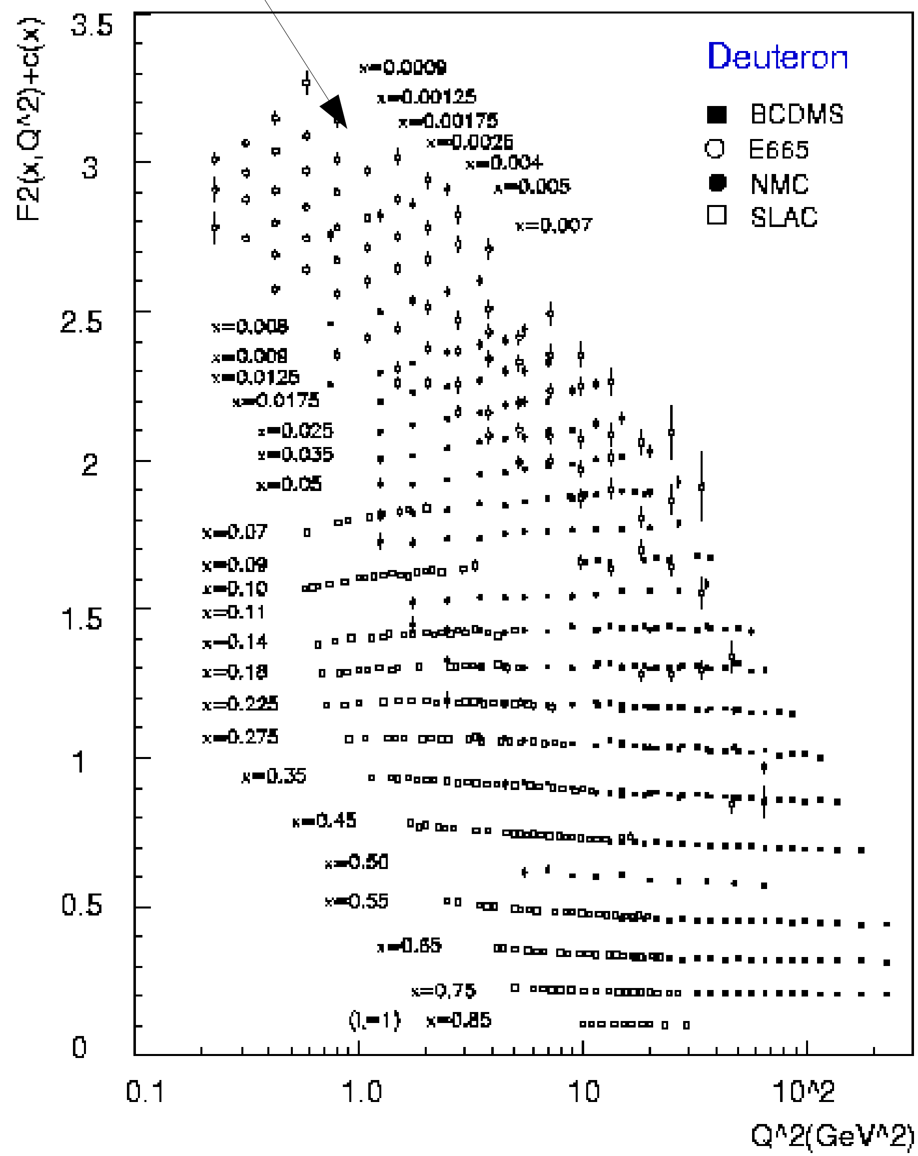
- 1972-1973: $$\alpha_s(Q^2) = \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$ 't Hooft, 1999
  - *Asymptotic freedom* Gross, Wilczek & Politzer
  - *QCD became a possible (and the leading) theory for the strong interaction.* 2004

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

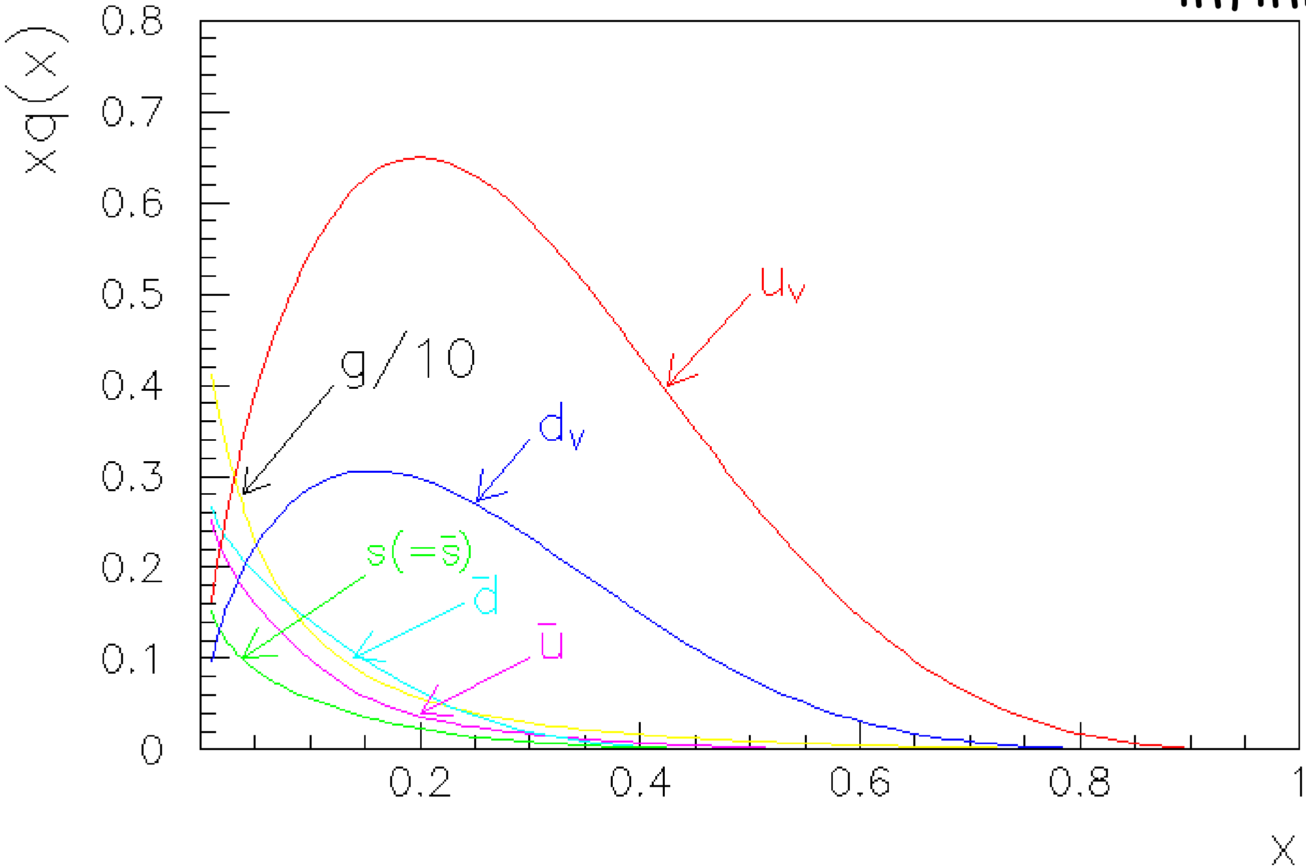
- 1933: Protons are not point-like (k_p=1.79); Estermann, Stern 1943
- 1950's: Nucleons have a structure; Hofstadter *et al.* 1961
- 1968: First DIS data from SLAC, Friedman, Kendall, Taylor *et al.* 1990
- 1969: nucleons are made of spin-1/2 point-like particles (quarks); DIS = incoherent sum of electron 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.

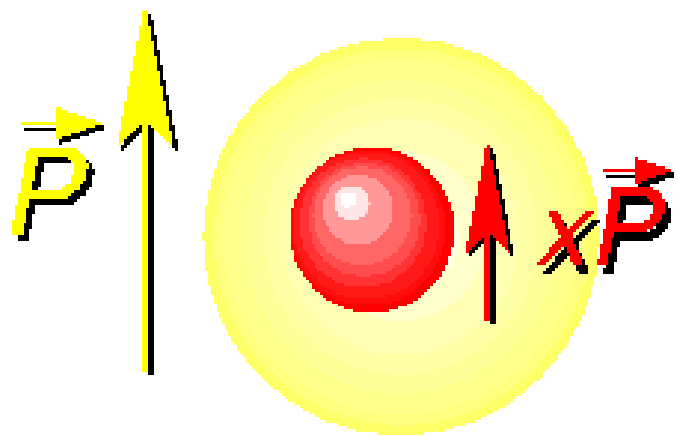
Current Knowledge of Nucleon Unpolarized Structure

(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 → ∞)

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

Today we focused on what was found by looking deeper and deeper into the atoms → nucleus → nucleon, with a focus on elastic scattering.

Next time we will focus on the nucleon spin and polarized PDF, spin at high x, and spin sum rules.

Lecture #2

Nucleon Spin Structure

Polarized PDF

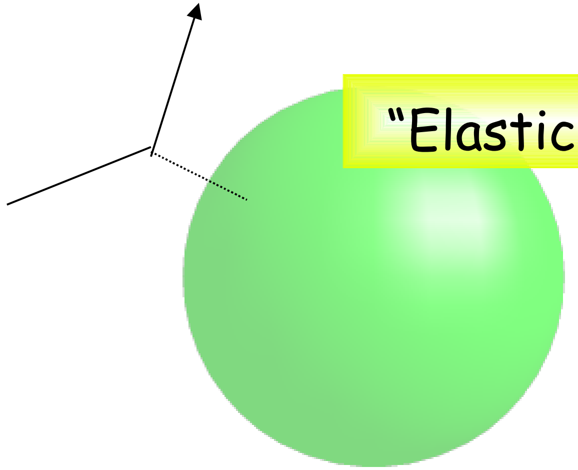
Spin at high x

Spin sum rules.

Three kinematic regions

We can select the physics by choosing carefully the angle and the momentum of scattered electrons

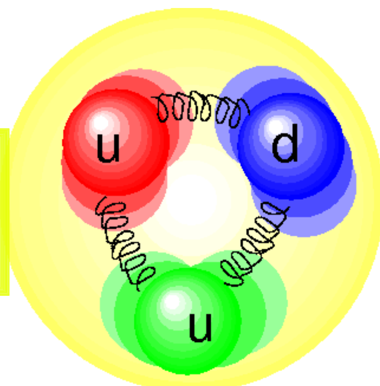
"Elastic": $W=M_t$ or M_p

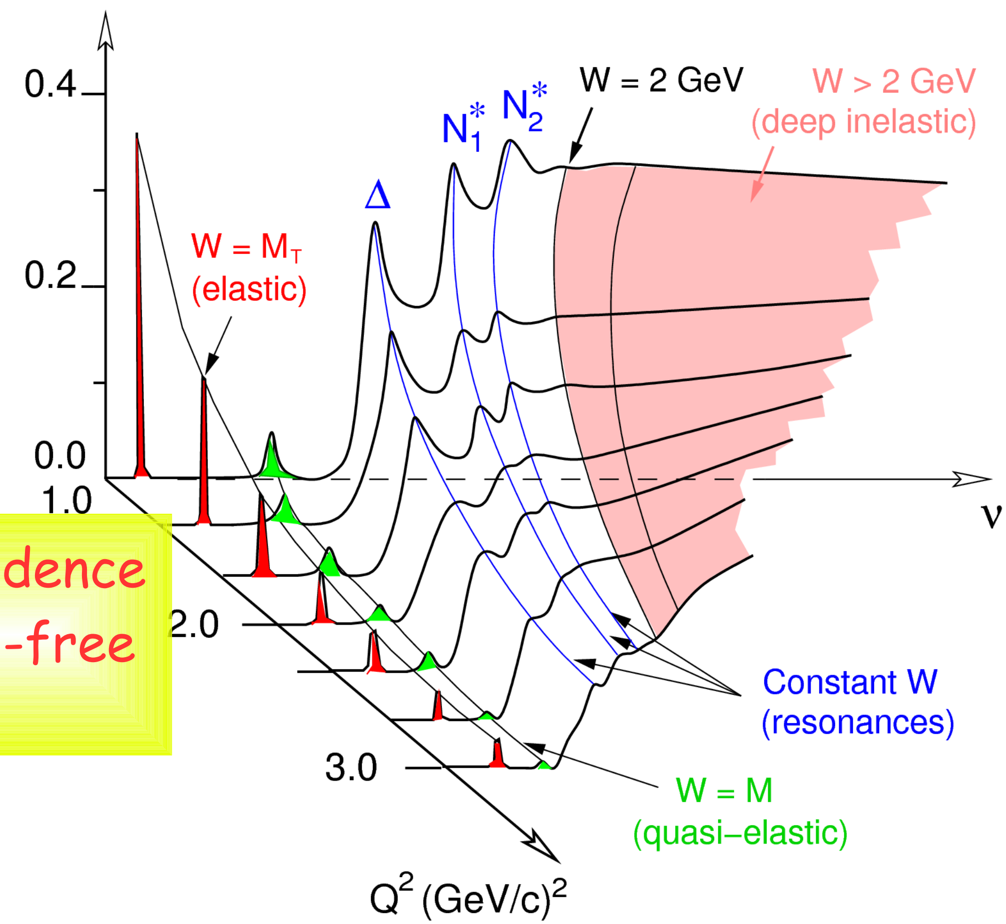


1961

From cross section we extract "elastic form factors"

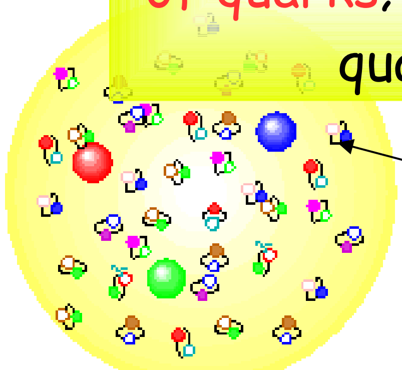
"Resonance": 1<W<2GeV





1999
2004

"Deep Inelastic": W>2 GeV, first evidence of quarks; directly probes the quasi-free quarks inside the nucleon.



10^{-18}m or smaller

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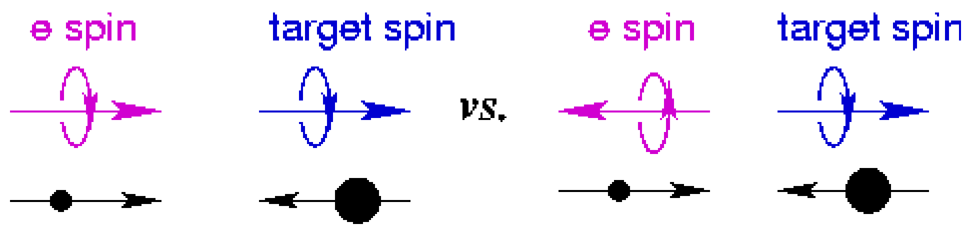
  - QCD became a possible (and the leading) theory for the strong interaction.

Polarized DIS (1980~present)

- Scattering cross section is spin-dependent (imagine throwing two small magnets together)

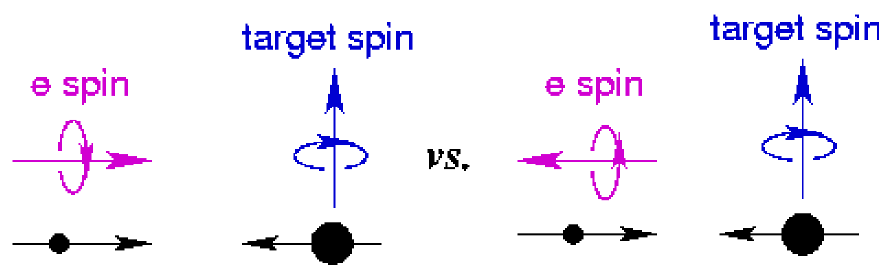
S N | N S vs. N S | N S

- 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

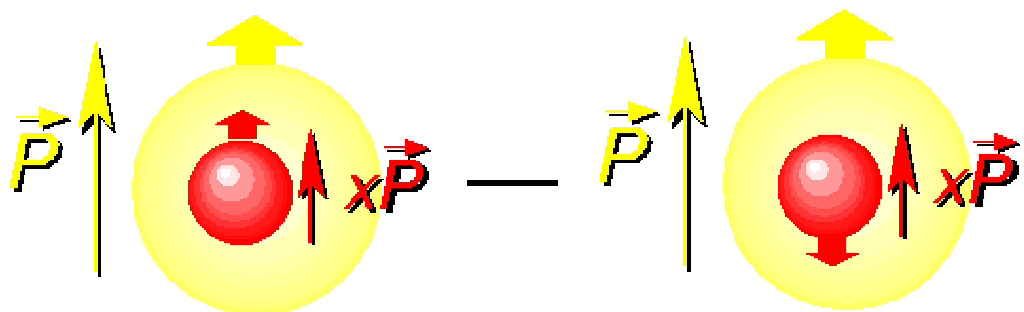


$$\frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega\, dE'} \propto \sigma_{point-like}[\alpha'' g_1(x,Q^2) + \beta'' g_2(x,Q^2)]$$

Polarized Structure Function and the Nucleon Spin Structure

- in QPM and the infinite momentum frame:

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



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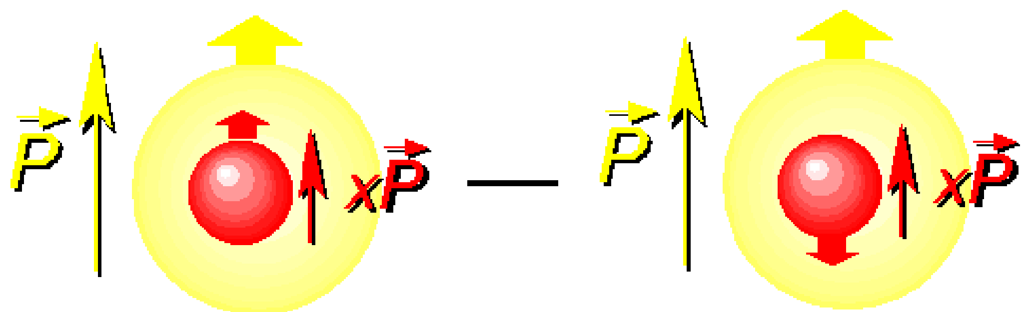
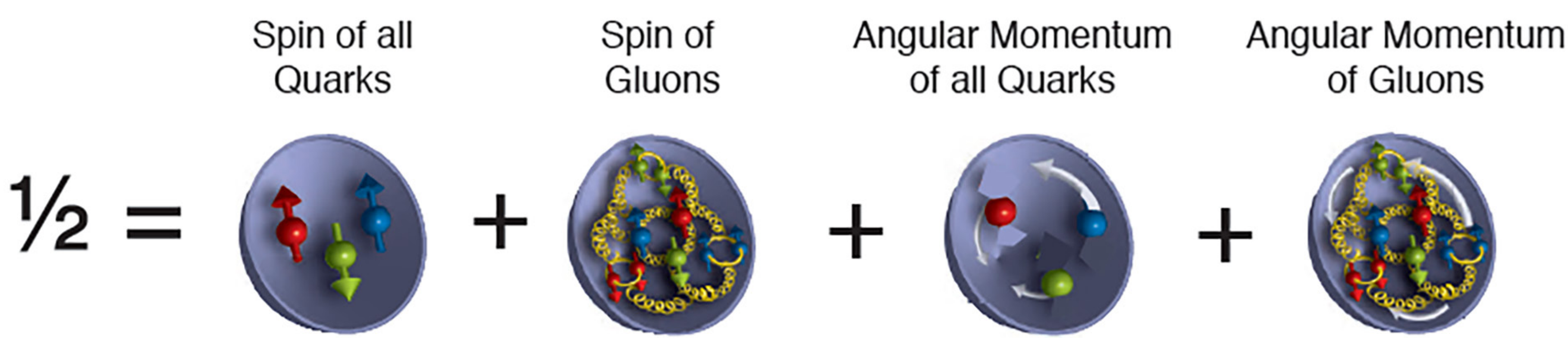
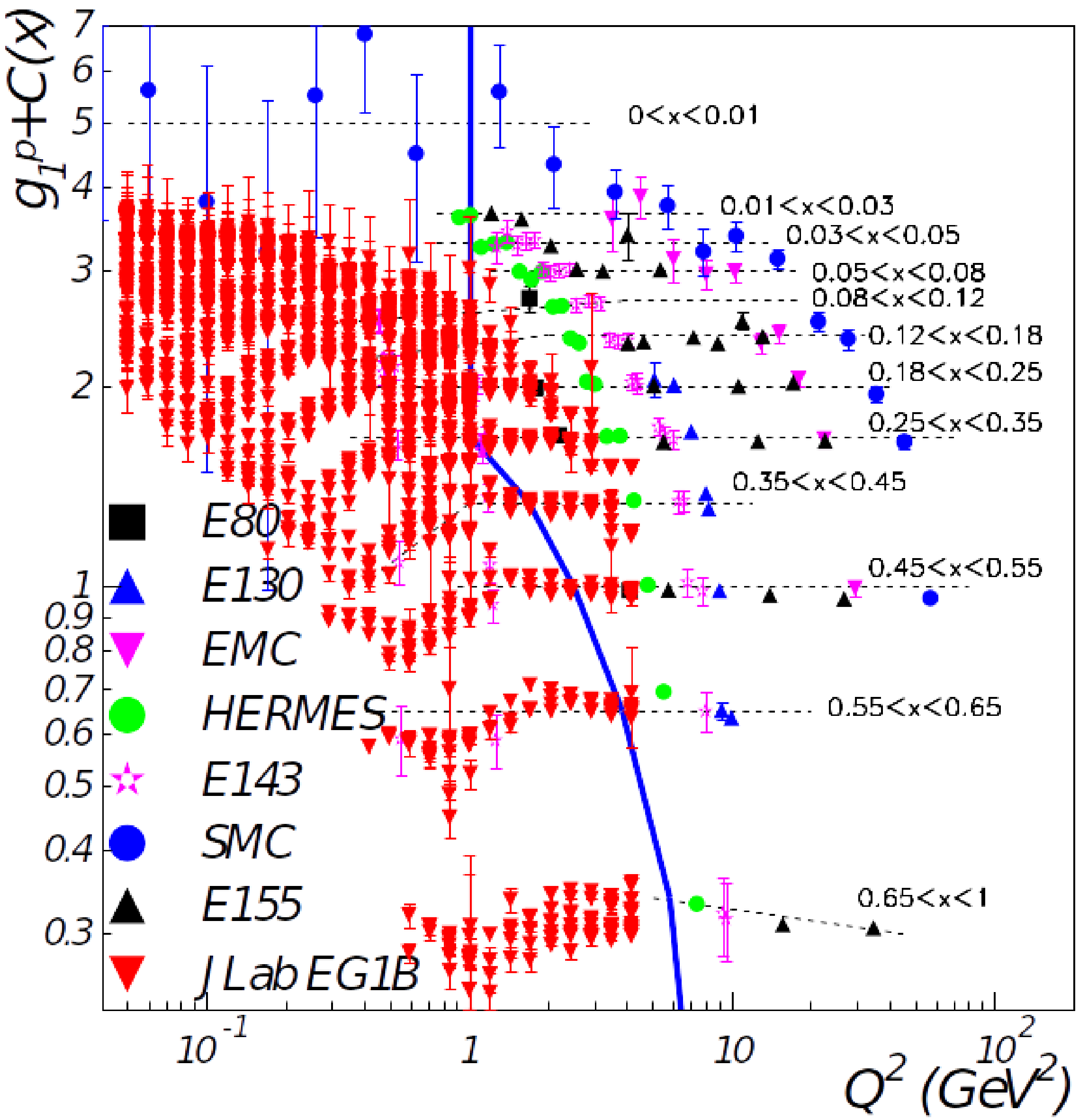




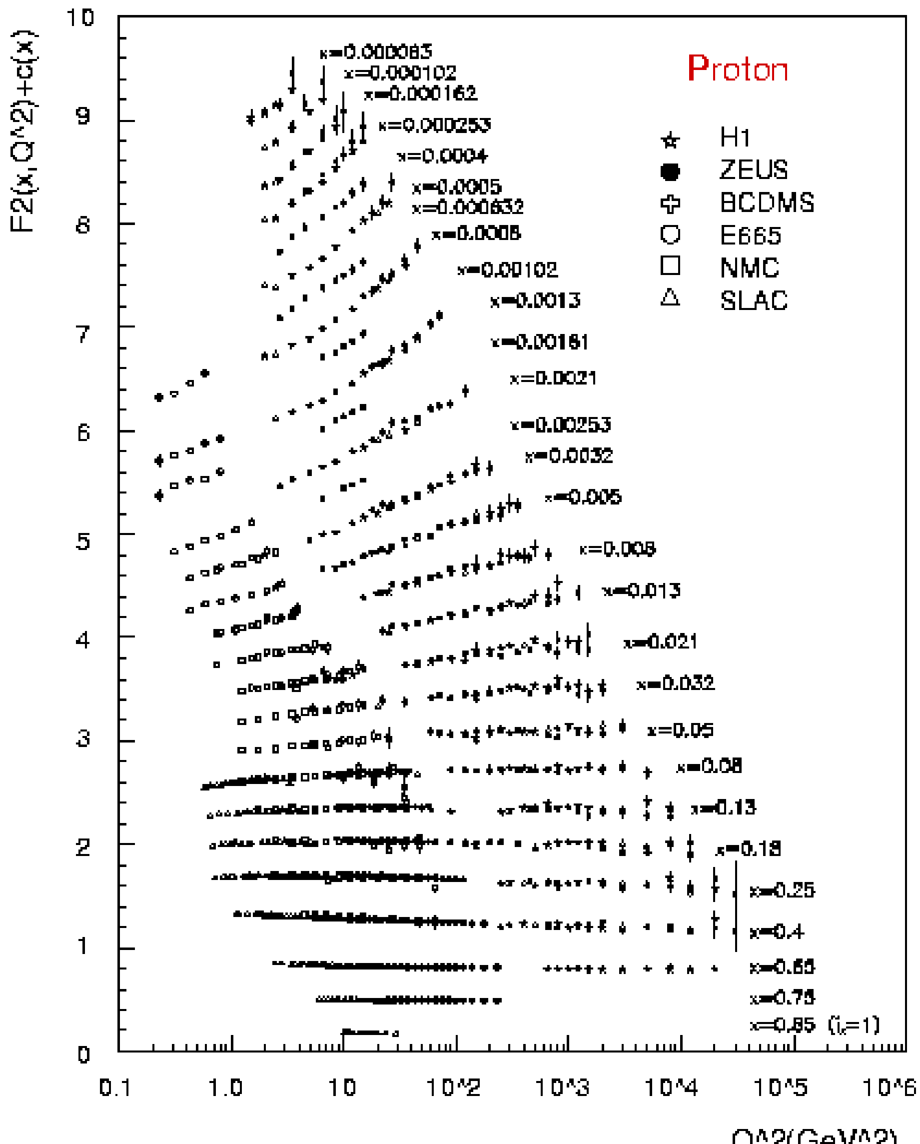


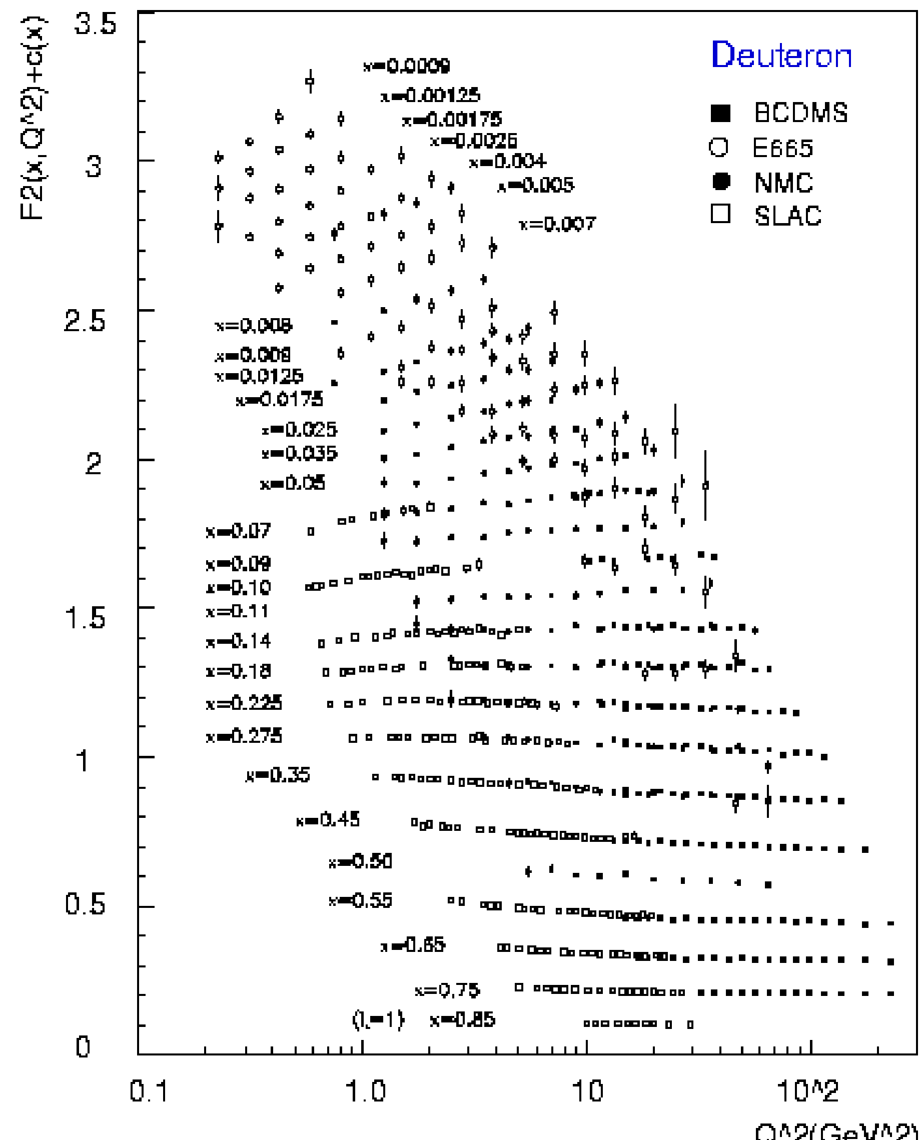
Similar to the unpolarized case, "scaling violation" agree with pQCD (DGLAP equations)

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 (though some phenomena do)
- Strong interaction: asymptotic freedom vs. confinement

(high Q2, small distance)   (low Q2, large distance)

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? (from short to long distances, with the transition in between) – 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

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- 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

focus of this talk

Lepton scattering spin structure experiments (mostly inclusive):

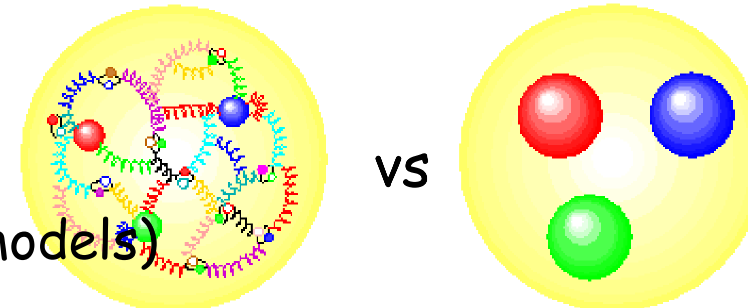
JLab's focus is high precision and low to intermediate Q^2 values

Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	[244]	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	[245]	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	[246, 247]	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	[248, 249]	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	[253, 254]	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	[256]	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	[257]	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	[258, 259]	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	[251]	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	[280]	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	[260, 261, 262, 263]	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	[264]	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	[265]	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	[266, 267]	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	[268]	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	[269]	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	[271]	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	[270]	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	[272, 273]	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	[278]	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	[72]	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	[309]	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

Nucleon Spin Structure At High x

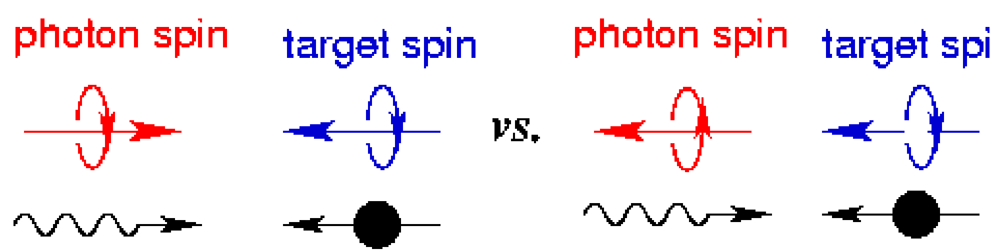
Nucleon (spin) Structure at High x_{Bj}

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



The far valence domain (x>0.5)

- is 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 $\Delta d/d$



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

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

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

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

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

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

(see Griffiths p.188)

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.

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

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 splitting, etc.
– but the breaking of SU(6) may not be that big.

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

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

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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

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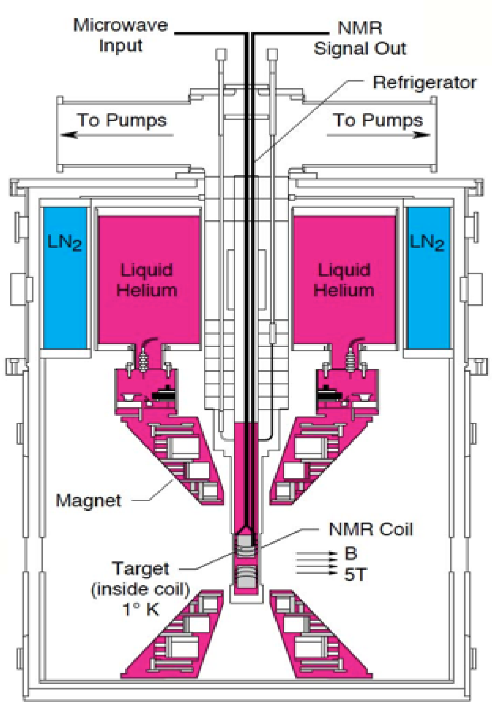
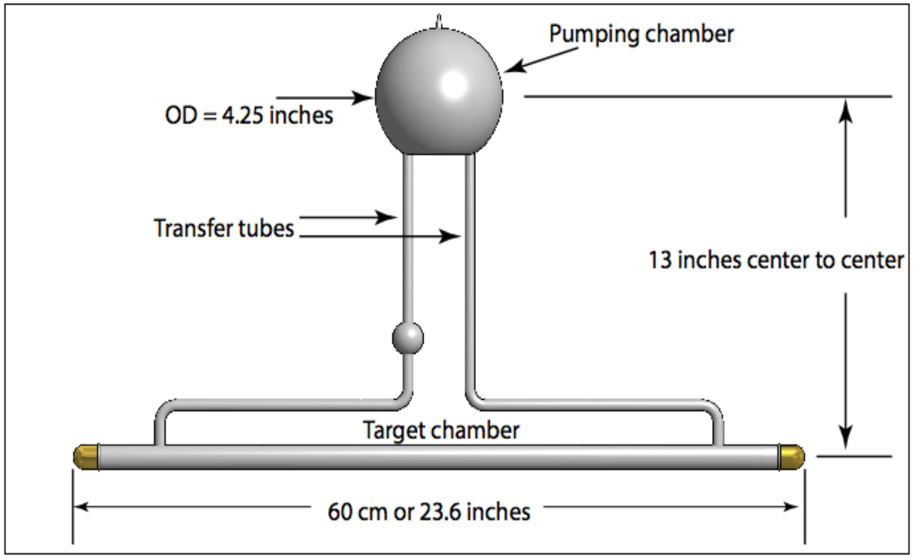
Experimental Tools - Polarized Beam and Polarized Targets

Polarized electron beam: available at JLab, (previously) SLAC, MAMI, etc;

Polarized target for proton study: NH3

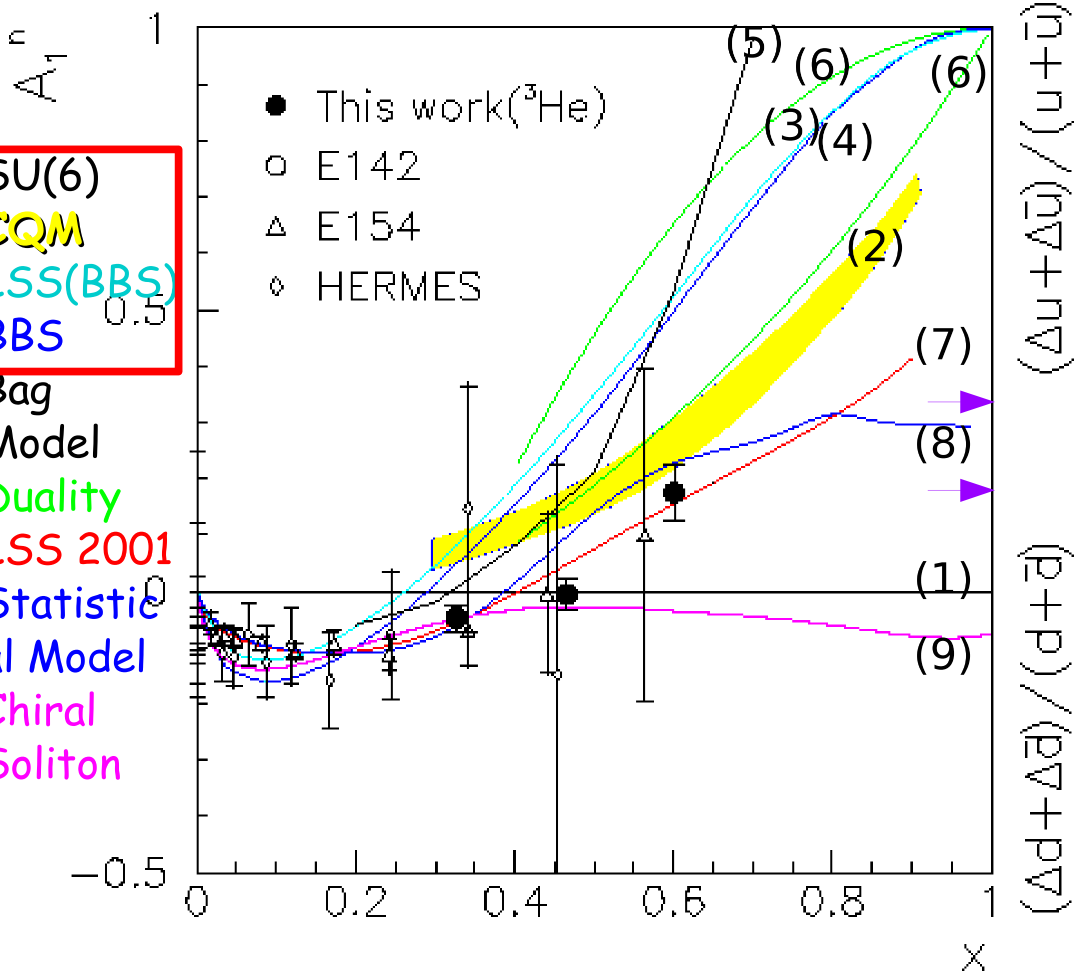
Polarized target for neutron study: ND3, 3He.

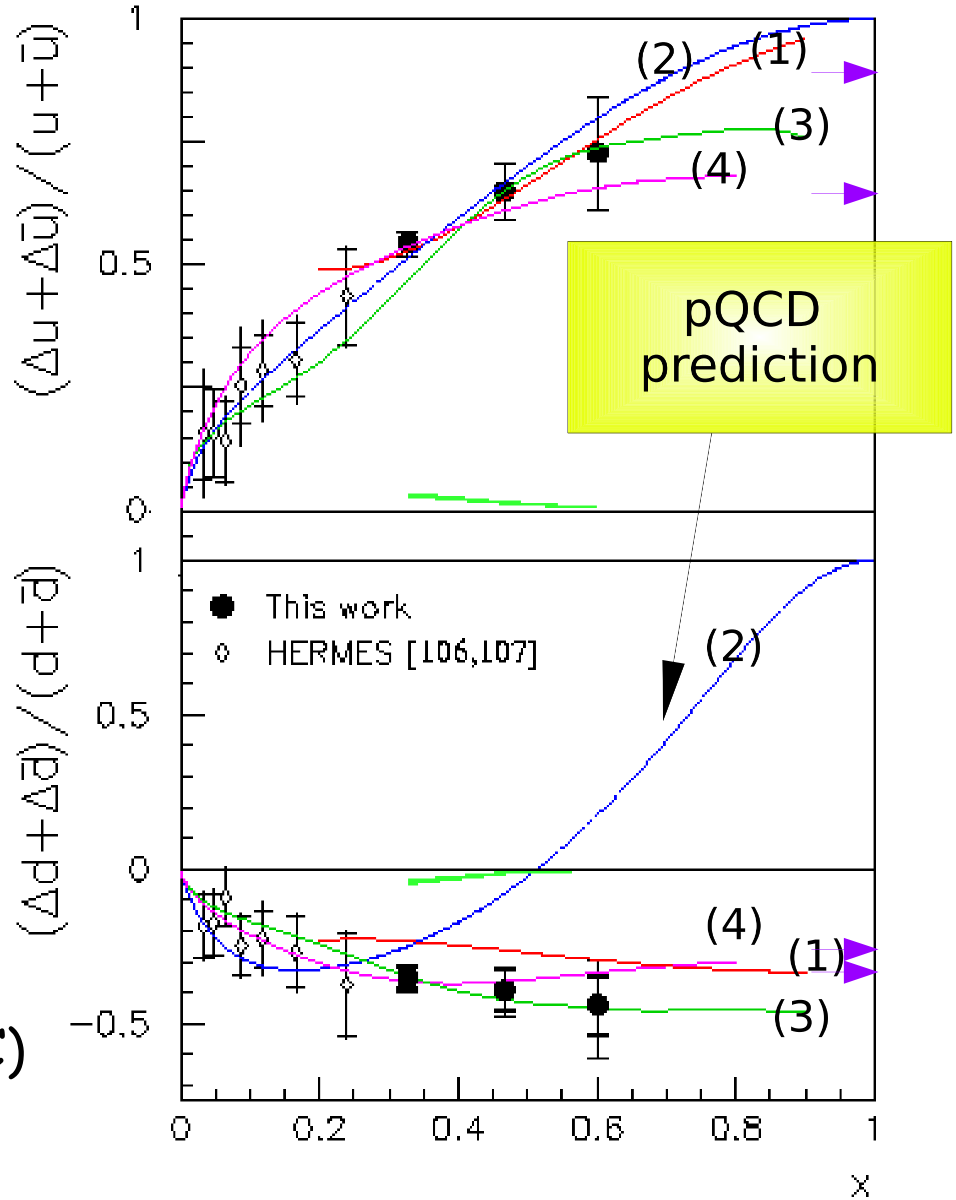




The 6 GeV Hall A Neutron A1 Measurement (2001)

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



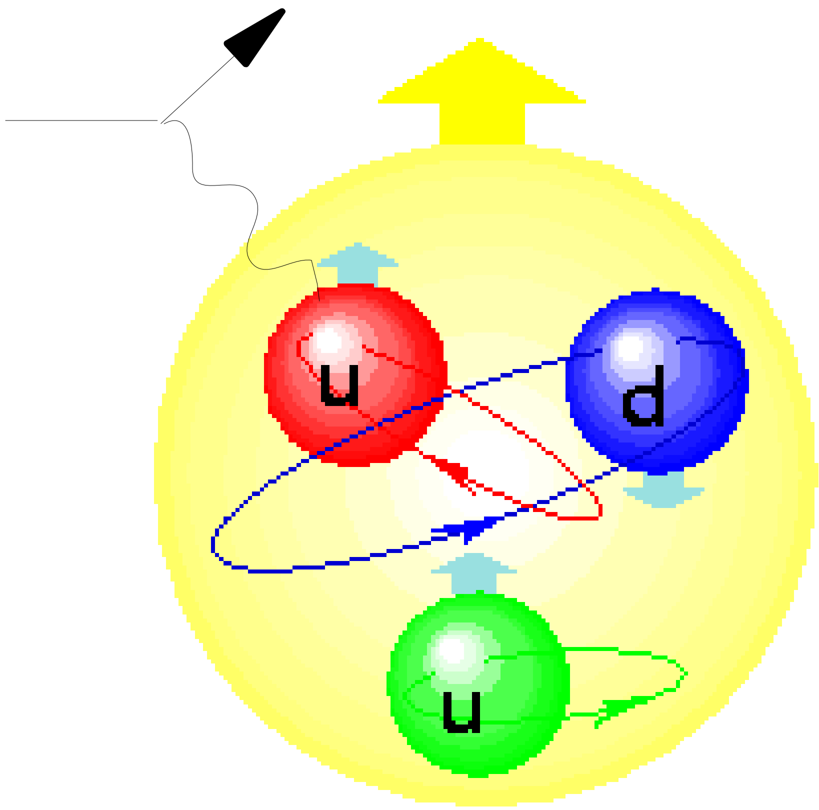


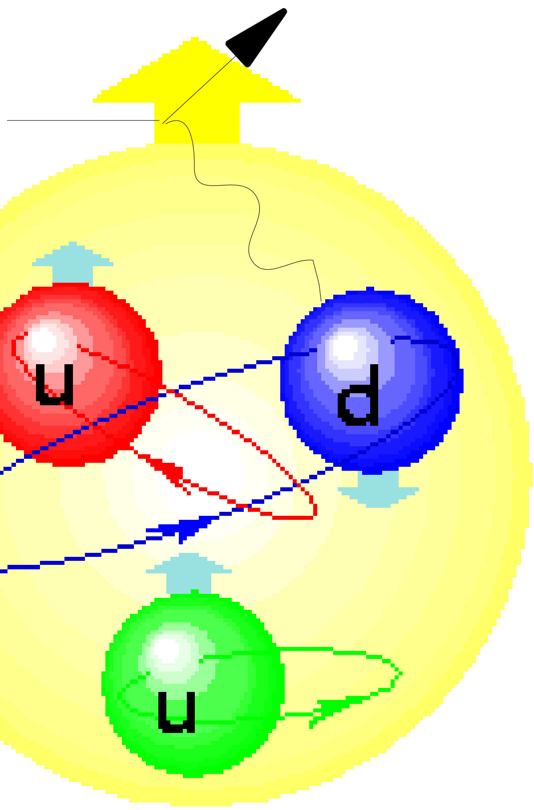
(Deutron data not shown: E143, E155, SMC)

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

What Can We Learn From $\Delta q/q$ Results?





Public Media Articles on A_1^n Results

- CERN Courier
  http://www.cerncourier.com/main/c
  0/16
- APS — DNP website
  http://dnp.nscl.msu.edu/current/sp
- Physics Today Update
  http://www.physicstoday.org/vol-57
  html
- Science On-line article
  http://sciencenow.sciencemag.org/cgi/content/
  full/2003/1223/2
- Science News article
  https://www.sciencenews.org/article/topsy-turvy-neutrons-and-protons-quarks-take-wrong-turns
- Physics News Update:

News: Physics

Topsy Turvy: In neutrons and protons, quarks take wrong turns

By Peter Weiss 8:43am, December 23, 2003

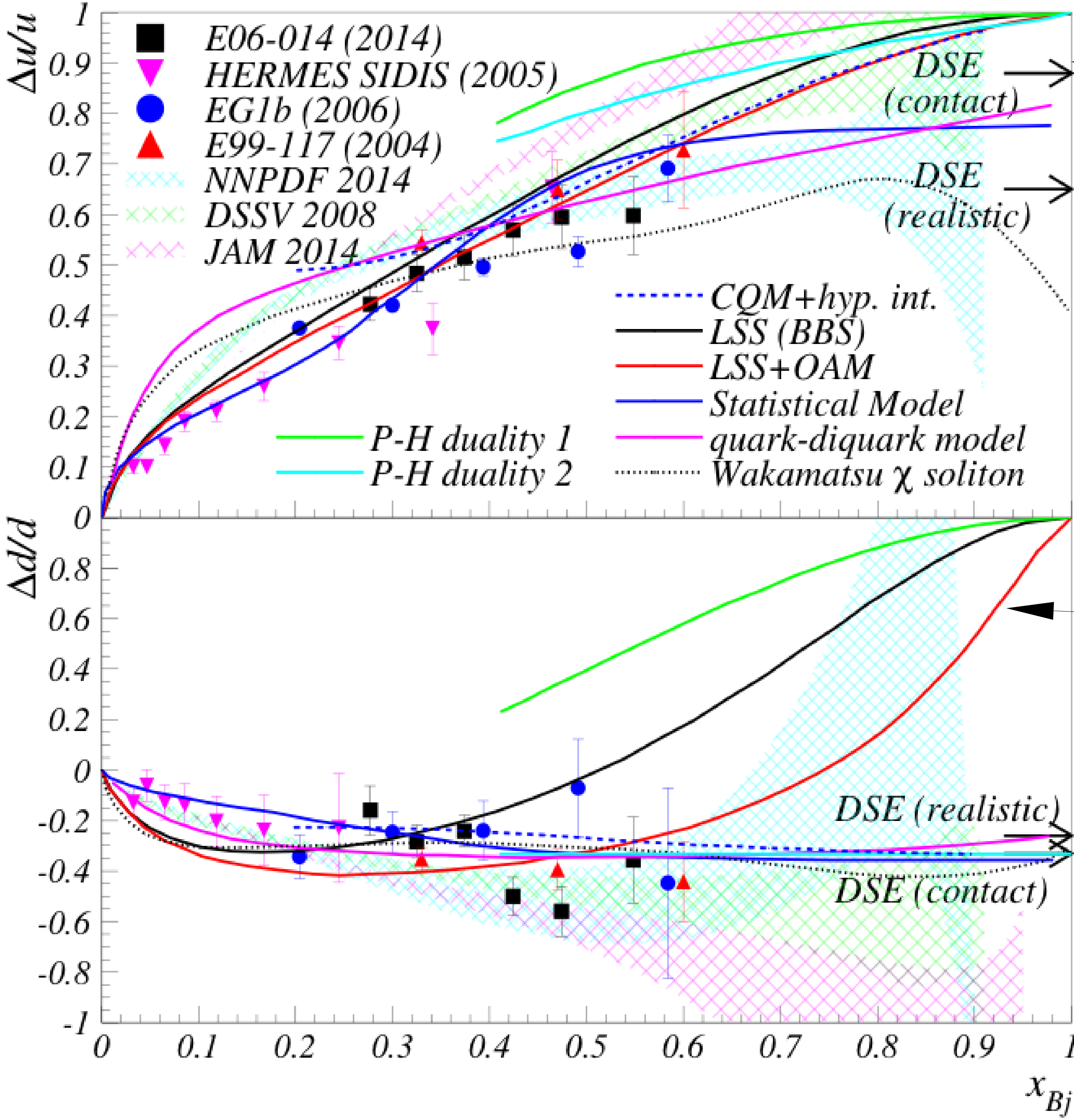
Physicists peering inside the neutron are seeing glimmers of what appears to be an impossible situation. The vexing findings pertain to quarks, which are the main components of neutrons and protons. The quarks, in essence, spin like tops, as do the neutrons and protons themselves.

Now, experimenters at the Thomas Jefferson National Accelerator Facility in Newport News, Va., have found hints that a single quark can briefly hog most of the energy residing in a neutron, yet spin in the direction opposite to that of the neutron itself.

"That's very disturbing," comments theoretical physicist Xiangdong Ji of the University of Maryland at College Park.

SCIENCE NEWS

- **The JLab Hall A data were quoted by the 2007 NSAC long range plan as one of the "most important accomplishments since the 2002 LRP";**
- Extensions of these measurements are **flag-ship** experiments for JLab 11 GeV.

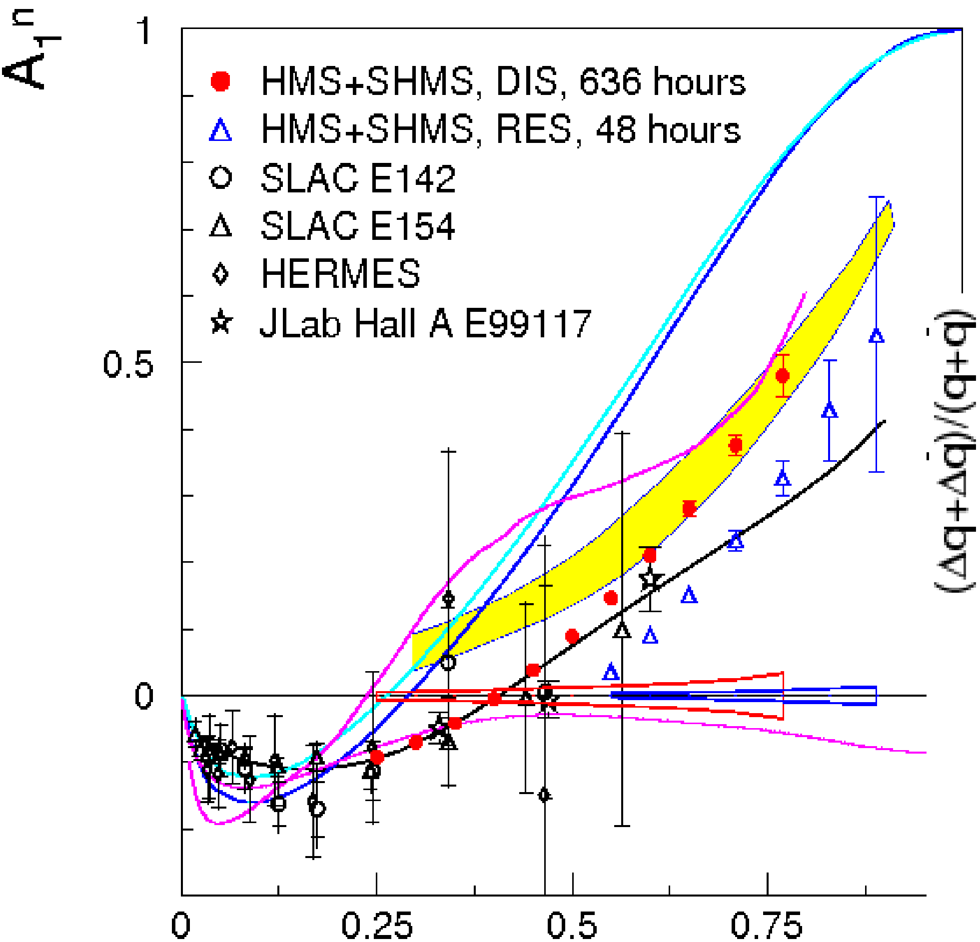


A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

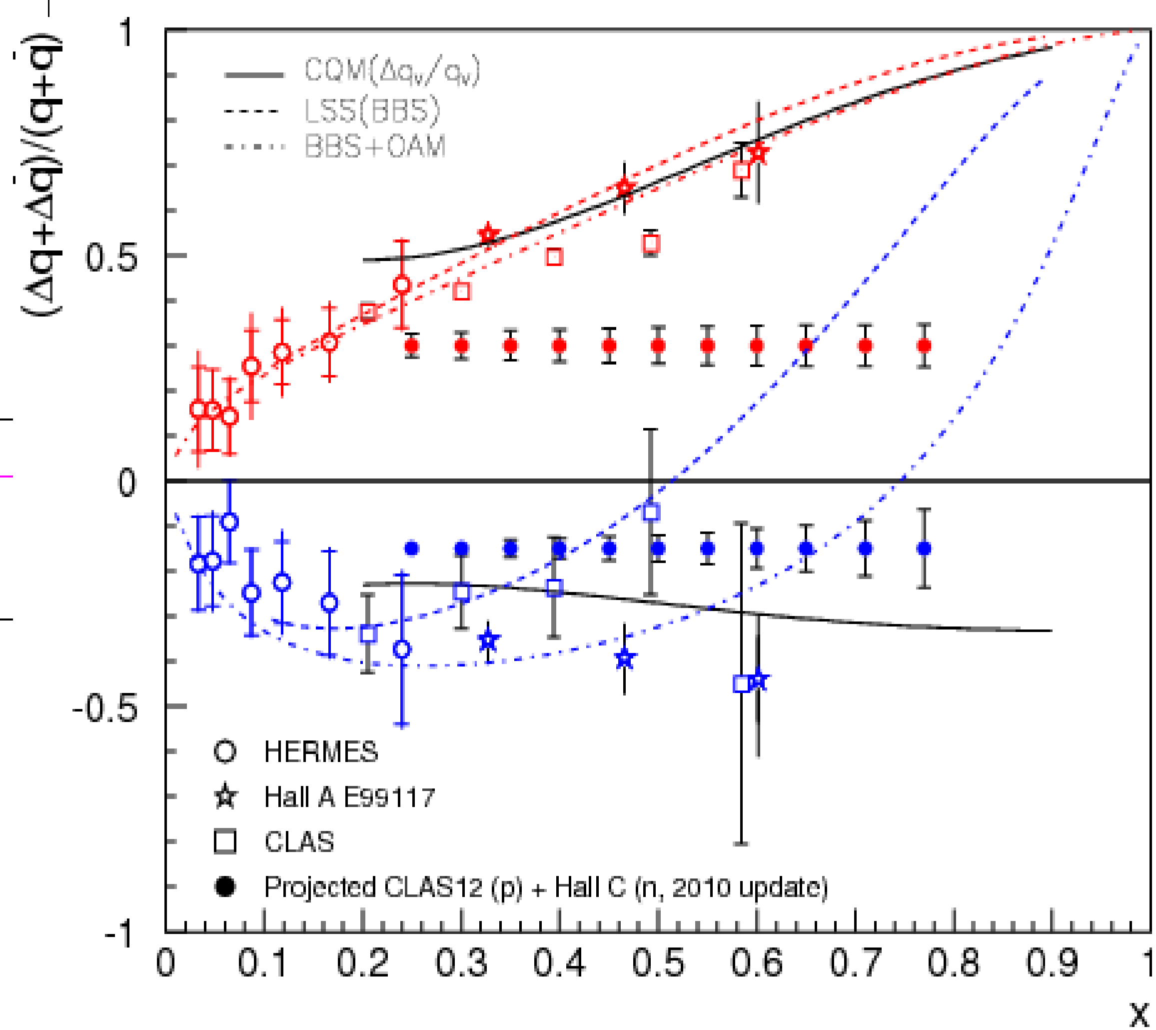
pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at x→1

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

Expected Results from 11 GeV Hall C (2019-2020)



- Combined results from Hall C (neutron) and CLAS12 (proton):



Fully approved in August 2010, rated A. Will run in fall 2019 – spring 2020

Spin Sum Rules
Moments of Spin Structure Functions

- Measurements of S.F. moments at low Q2 provide important tests for effective theories that deal with non-perturbative QCD ("If we can't expand w.r.t. α_s, we find something else small to expand on").

(Some) Moments and Sum Rules

- Quark spin contribution to the nucleon spin: $\sum_f \Delta q_f$

- Bjorken Sum Rule: (current algebra, isospin symmetry)

$$\int (g_1^p - g_1^n)\, dx = \frac{1}{6} g_A \left(1 + \frac{\alpha_S(Q^2)}{\pi} + \ldots\right) + \text{non-pertubative corrections (higher twist)}$$

axial charge

- GDH Sum Rule (real photon):

(unitarity)

anomalous magnetic moment

$$\int_{\nu_{th}}^{\infty} (\sigma^{1/2} - \sigma^{3/2}) \frac{d\nu}{\nu} = -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

- GDH Sum Rule (virtual photon): spin dependent DDVCS amplitude

$$\frac{16\alpha\pi^2}{Q^2}\int_0^1 g_1\, dx = 2\alpha\pi^2 S_1 \xrightarrow[Q^2 \to 0]{} -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

low-to-intermediate Q²: chiral PT, OPE

Higher Moments - Spin Polarizabilities

- Generalized forward spin polarizability:

$$\gamma_0 = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right] dx$$

- Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 \left[g_1 + g_2 \right] dx$$

- Twist-3 term d_2:

$$d_2(Q^2) = \int_0^1 x^2 \left[2 g_1(x,Q^2) + 3 g_2(x,Q^2) \right] dx = 3 \int_0^1 x^2 \left[g_2(x,Q^2) - g_2^{WW}(x,Q^2) \right] dx$$

Calculations exist or possible from lattice QCD, Dyson-Schwinger Equations, or Chiral PT

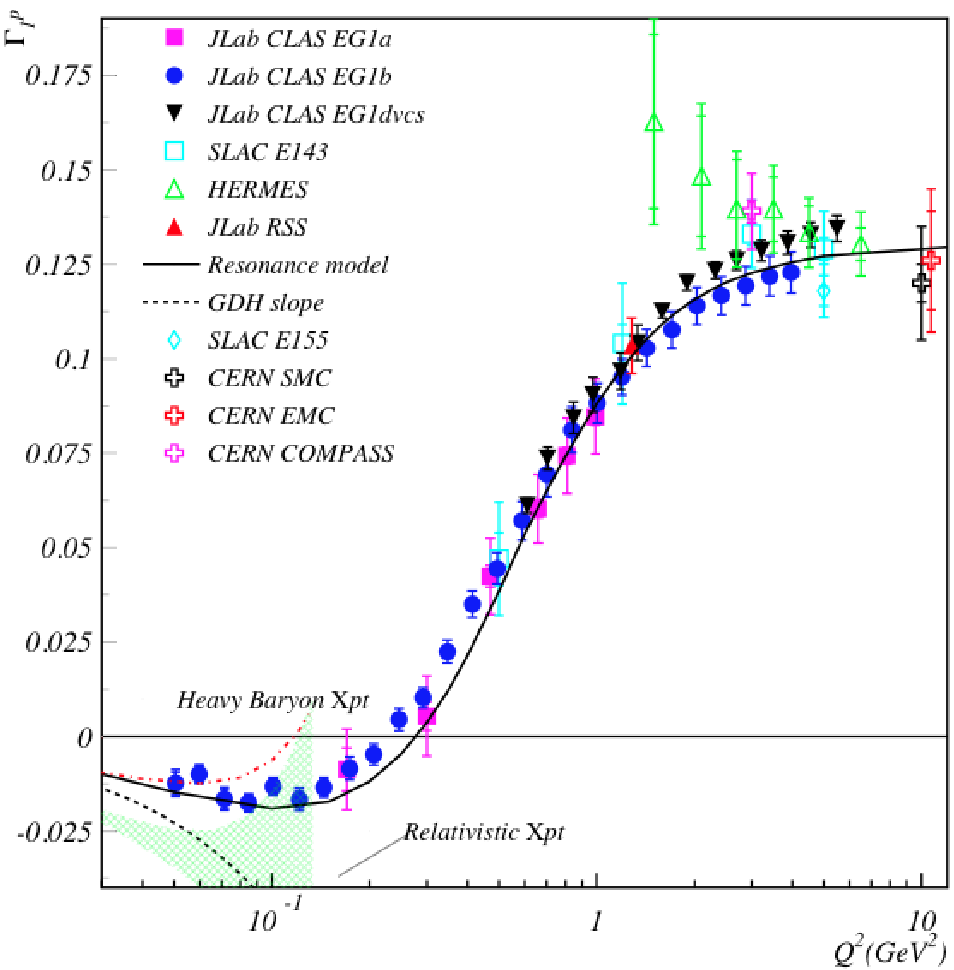
Lepton scattering spin structure experiments (mostly inclusive):

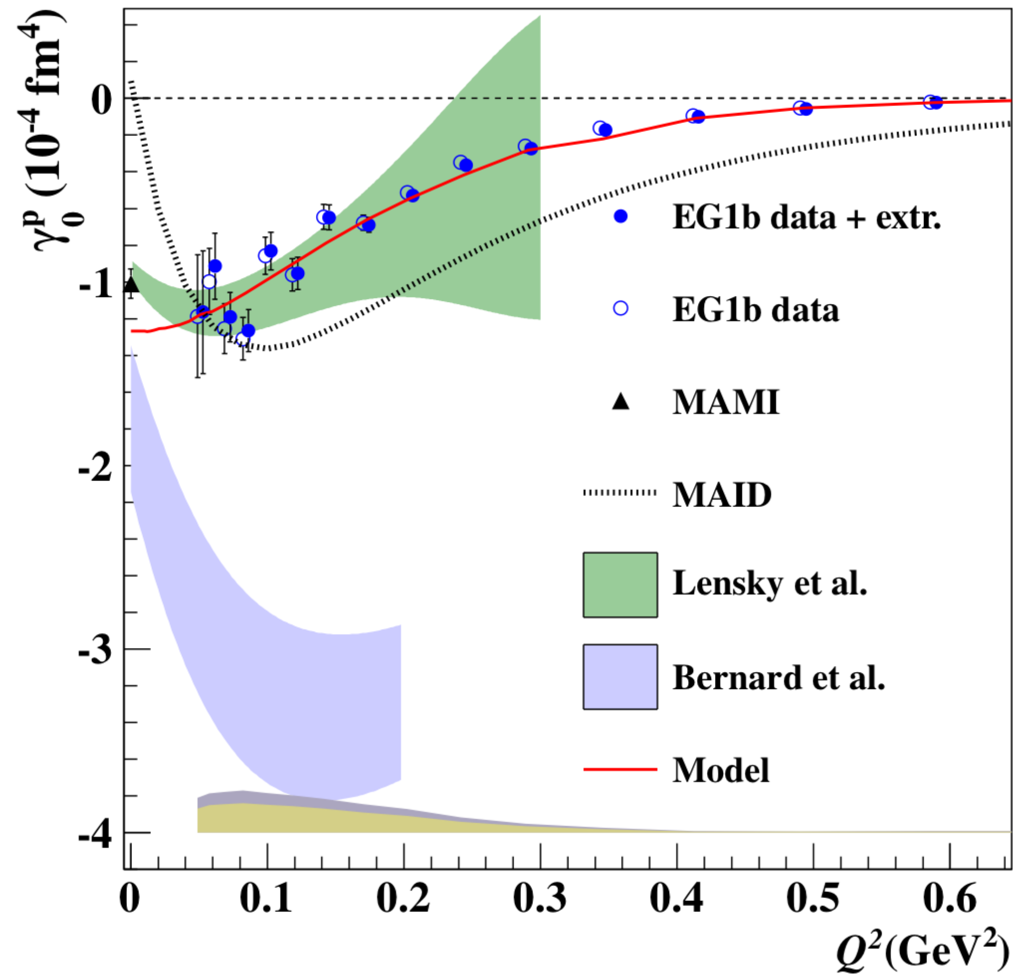
Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	[244]	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	[245]	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	[246, 247]	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	[248, 249]	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	[253, 254]	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	[256]	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	[257]	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	[258, 259]	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	[251]	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	[280]	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	[260, 261, 262, 263]	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	[264]	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	[265]	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	[266, 267]	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	[268]	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	[269]	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	[271]	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	[270]	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	[272, 273]	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	[278]	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	[72]	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	[309]	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

JLab's focus is high precision and low to intermediate Q^2 values

(Recently Published and Preliminary) Results on Moments of Structure Functions in the low to intermediate Q^2 region

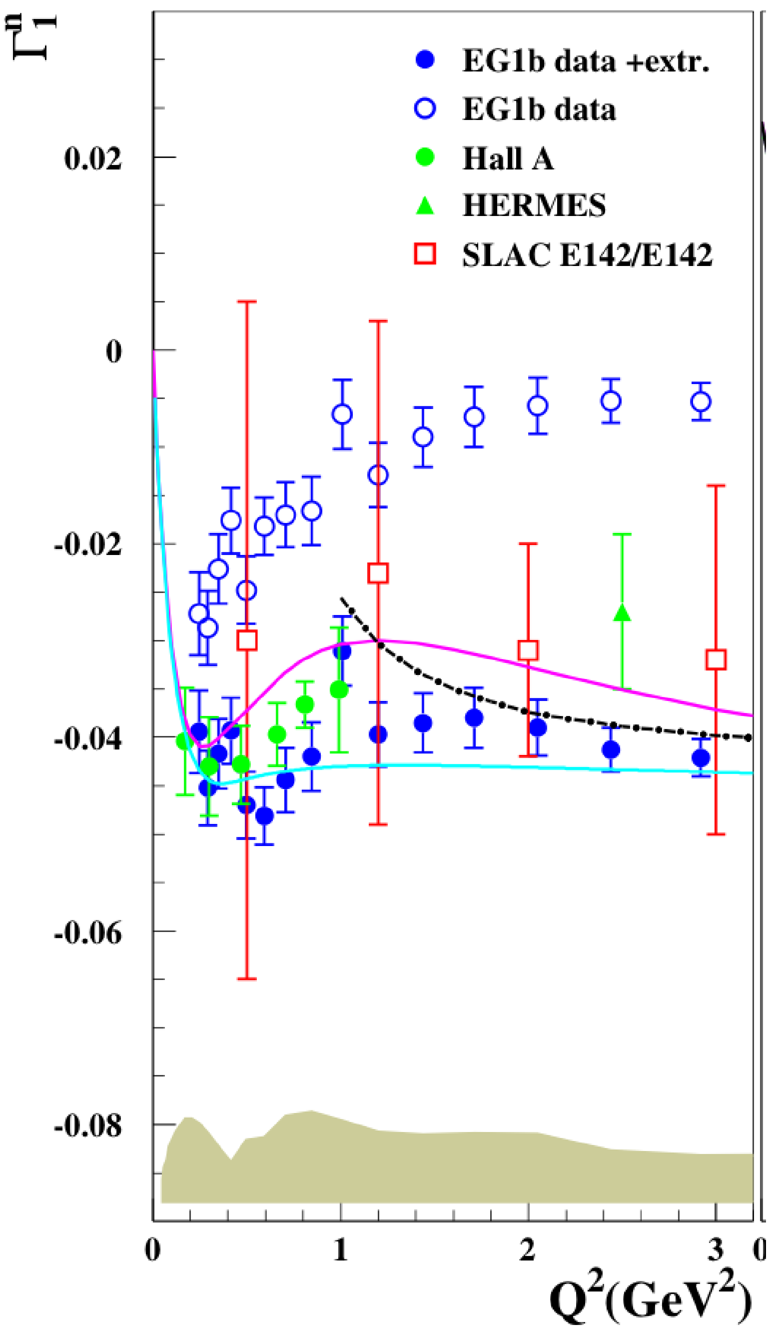
Existing data (proton) – up to 2017

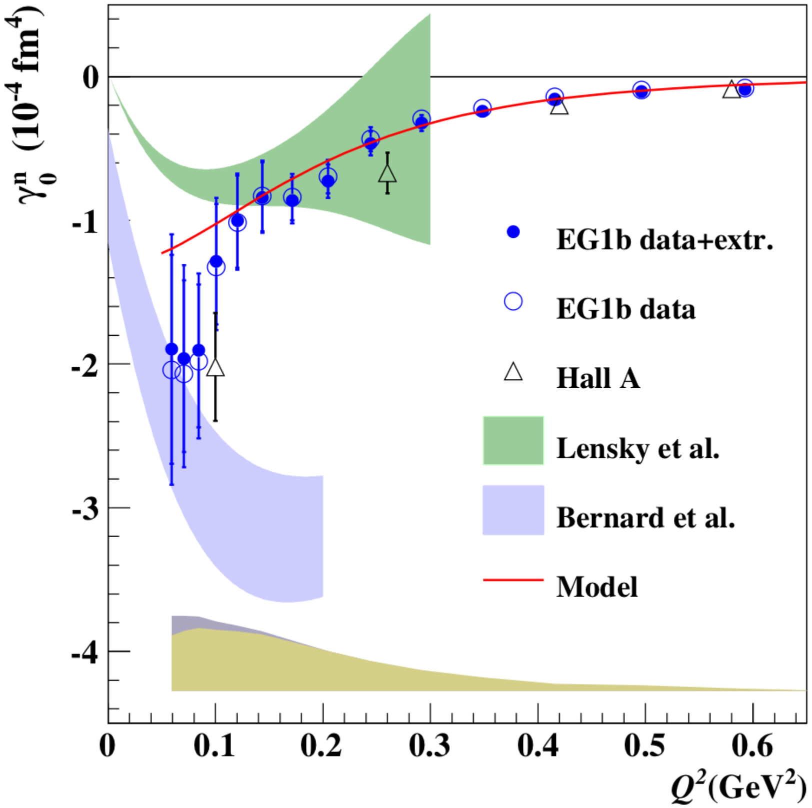


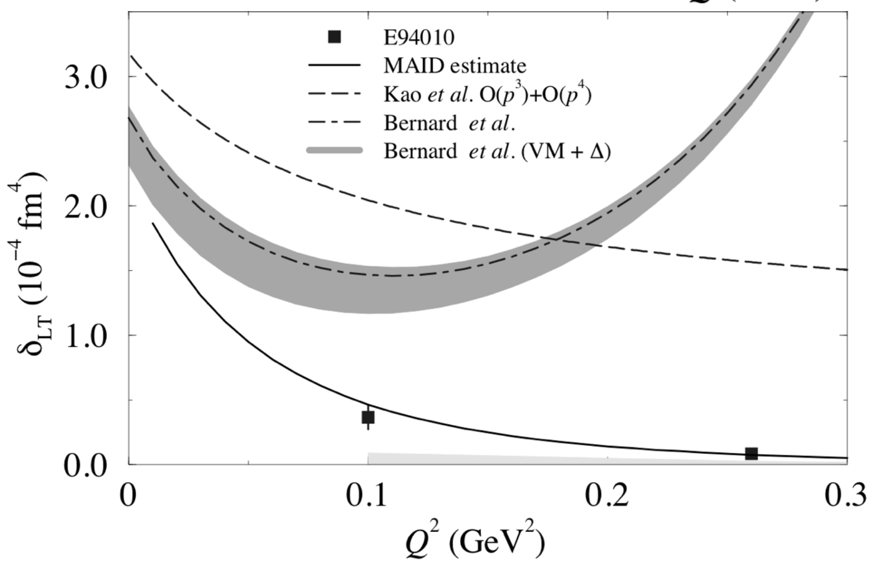


Recently published
Fersch et al. PRC 96 065208 (2017)

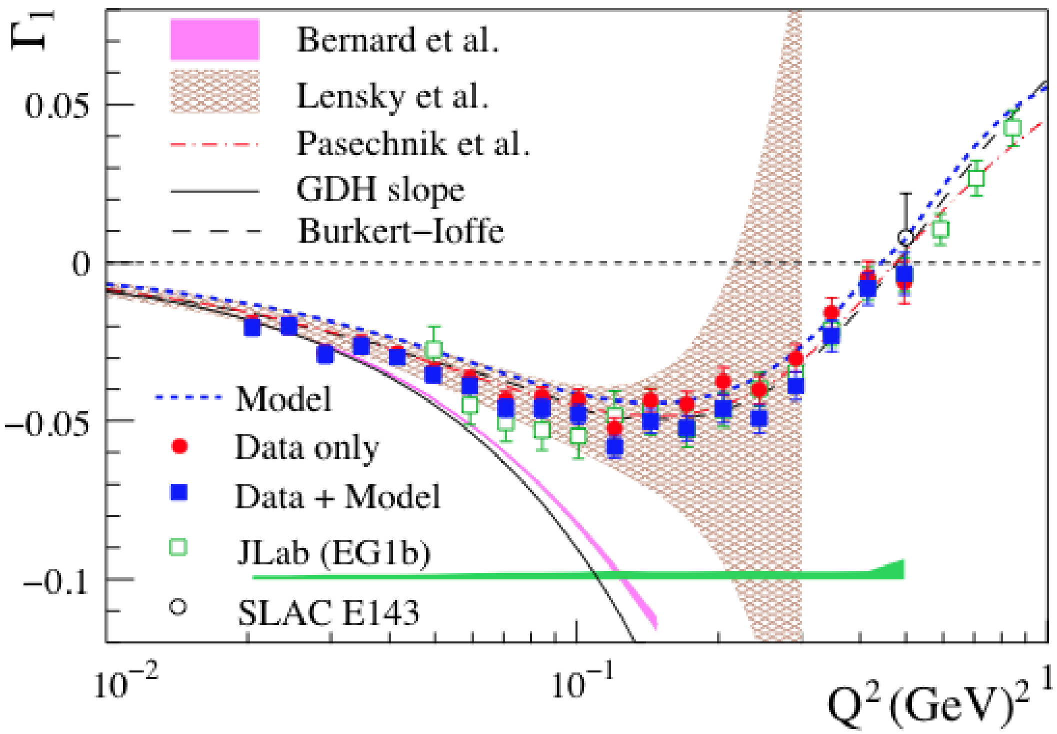
Existing data (neutron) – up to 2017

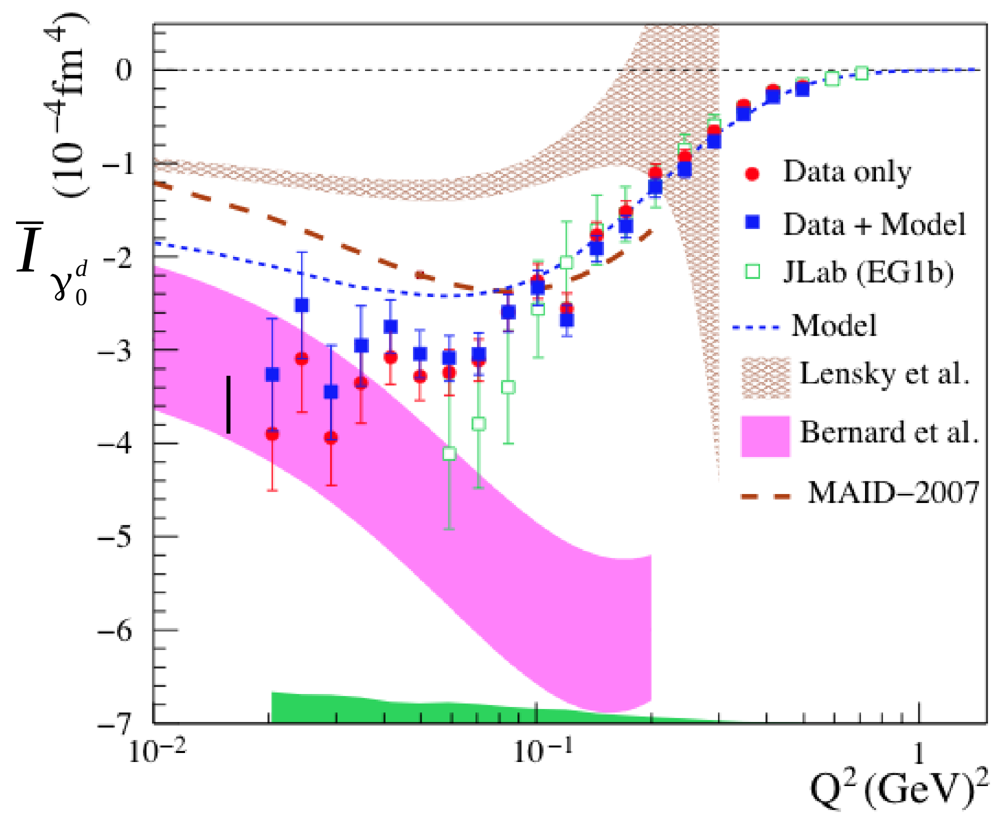






New deuteron results from EG4 (Hall B)





Just Published.

Adhikari et al. PRL 120, 062501 (2018)

E97-110 preliminary neutron(^{3}He) results on $\int g_1\, dx$

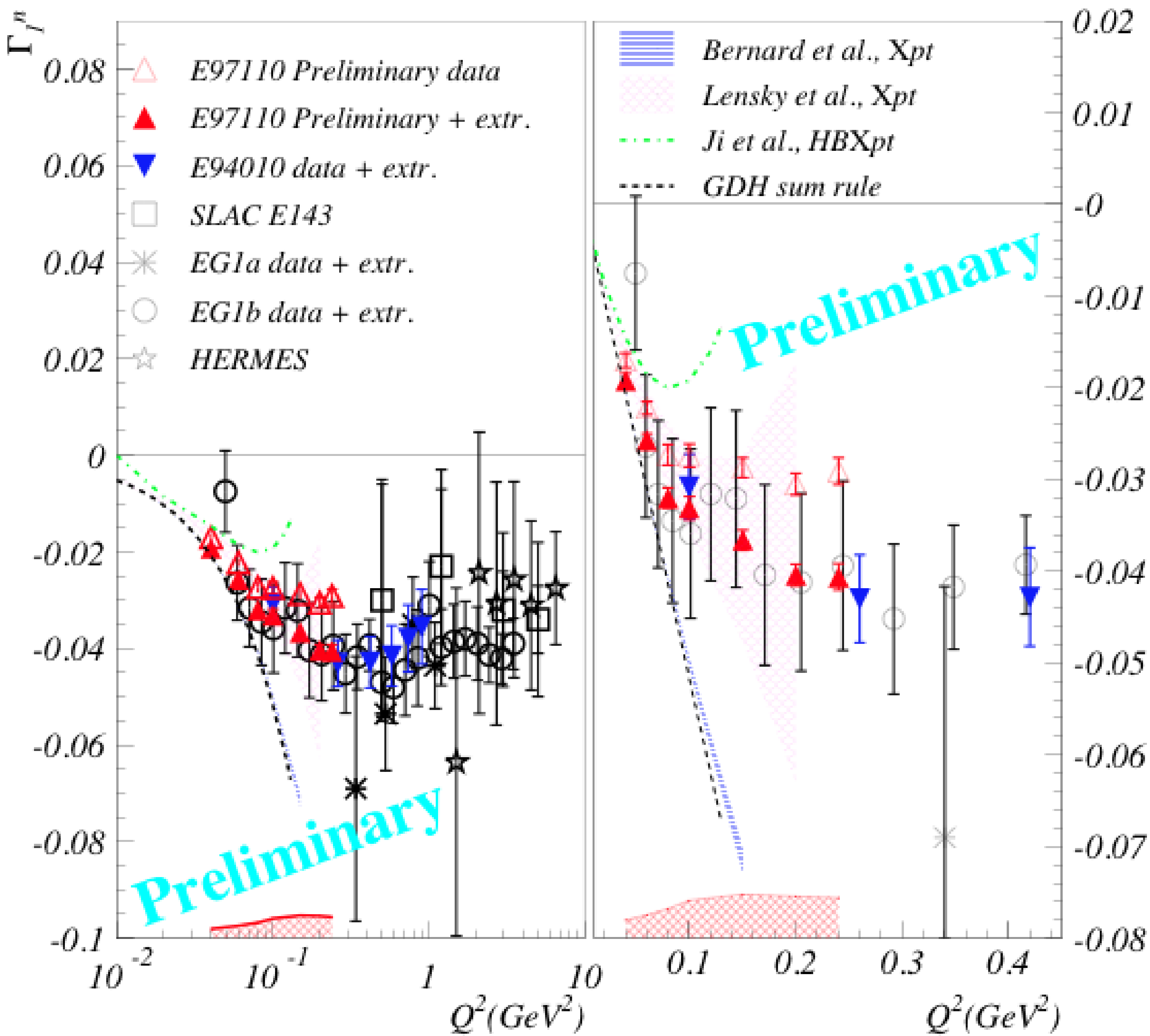
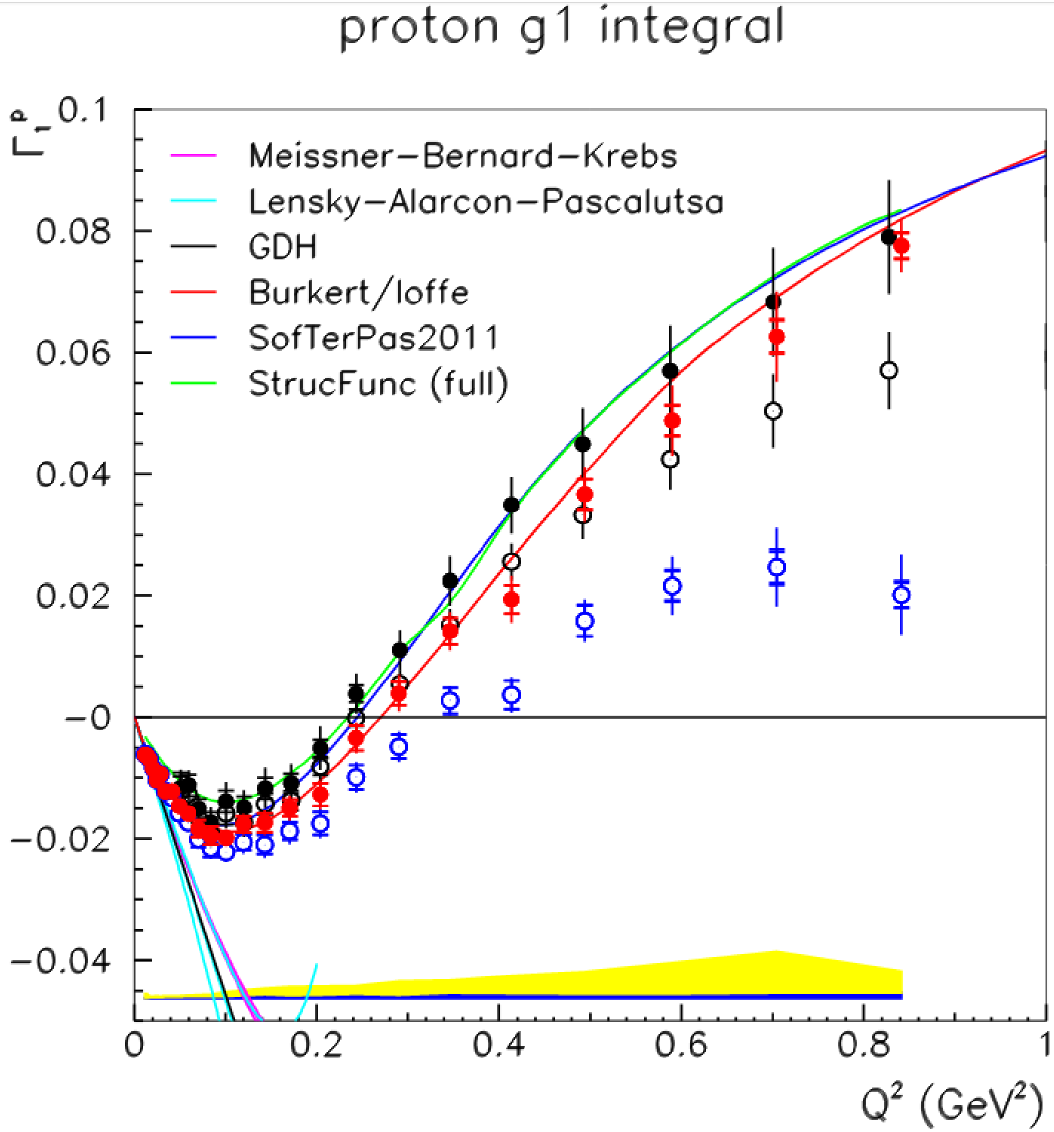


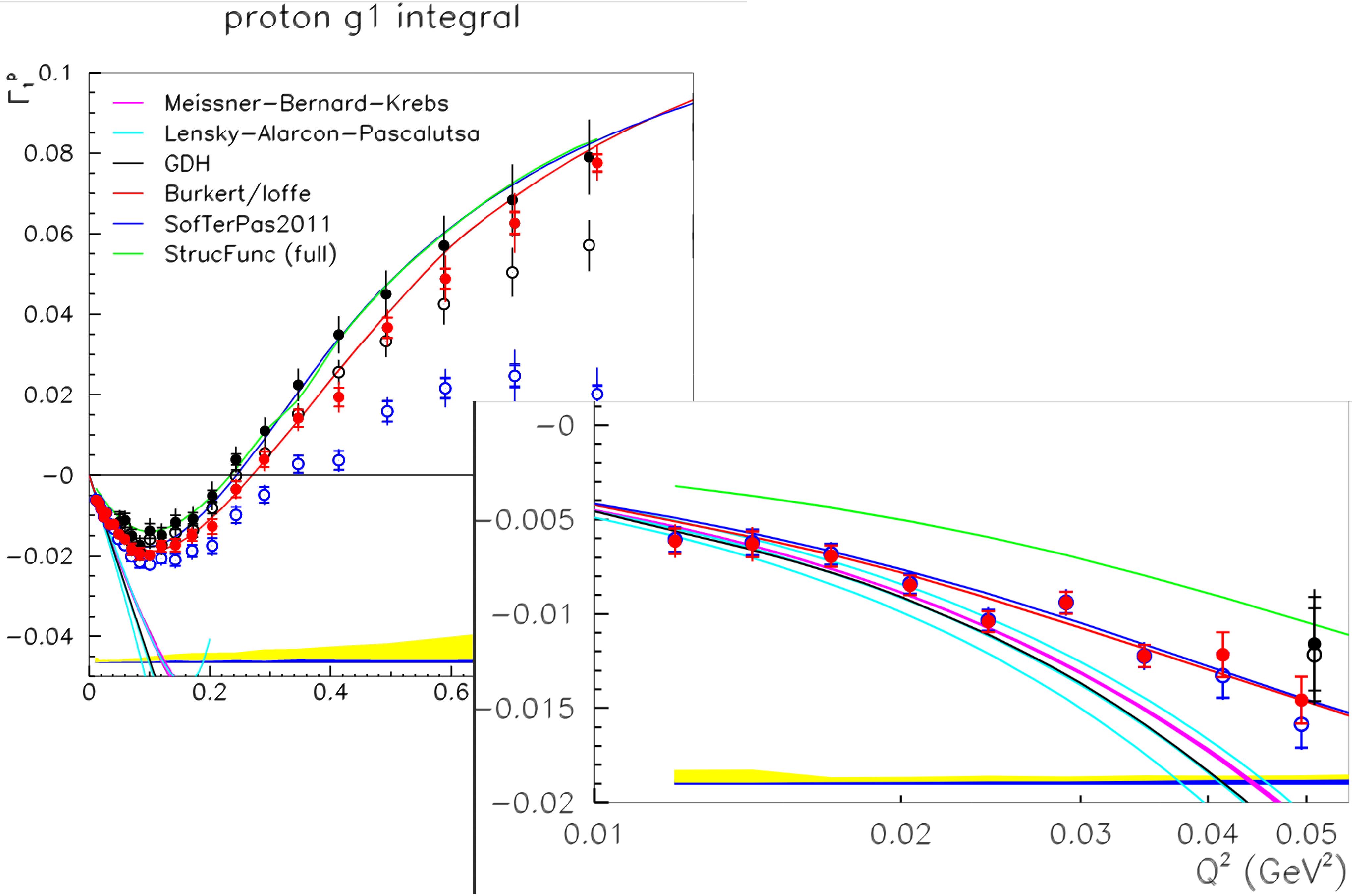
Figure credit:
V. Sulkosky

draft paper in prep

New proton (preliminary) results from EG4



New proton (preliminary) results from EG4



Test of Chiral Perturbation Theory

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$	d_2^n
Ji 1999 [194, 196]	X	X	A	X	-	-	-	-	-	-
Bernard 2002 [192, 193]	X	X	A	X	X	A	X	X	X	X
Kao 2002 [197]	-	-	-	-	X	A	X	X	X	X
Bernard 2012 [198]	X	X	A	X	X	A	X	X	X	-
Lensky 2014 [199]	X	A	A	A	A	X	X	X	$\sim$ A	A

A = good agreement between chPT prediction and data
X = not that well

(Data guiding chPT calculations)

Table credit: A. Deur, S.J. Brodsky, G.F. de Teramond, review article in progress

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
- 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 two examples of such study: (1) 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. (2) Moments of spin structure functions will test predictions from effective theories such as chiral perturbation theory, for the non-perturbative regime.
- For testing the Standard Model in the electroweak sector using electron scattering, come back later!