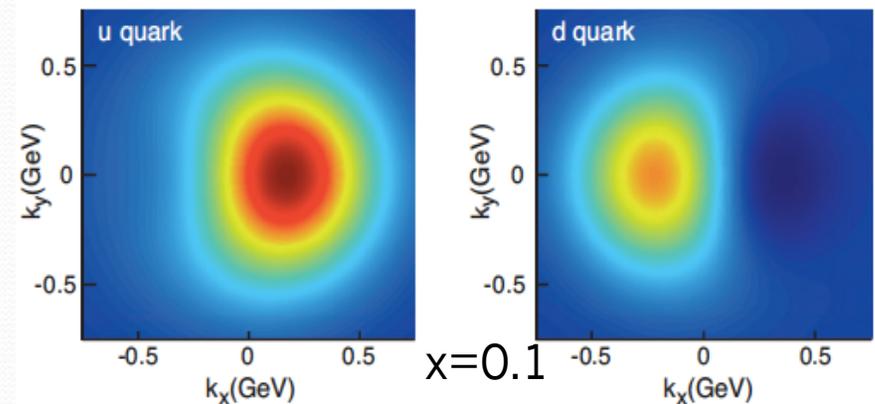


# Nucleon 3-D Structure

Jian-ping Chen (陈剑平), Jefferson Lab, Virginia, USA

Weihai HEP School, August 16-25, 2018

- *I: Introduction and Overview*
- *II: Nucleon Structure Study: From 1-D to 3-D*
- *III: 3-D Structure: Generalized Parton Distributions (GPDs) and Transverse-Momentum Dependent Distributions (TMDs)*



# Nucleon 3-D Structure

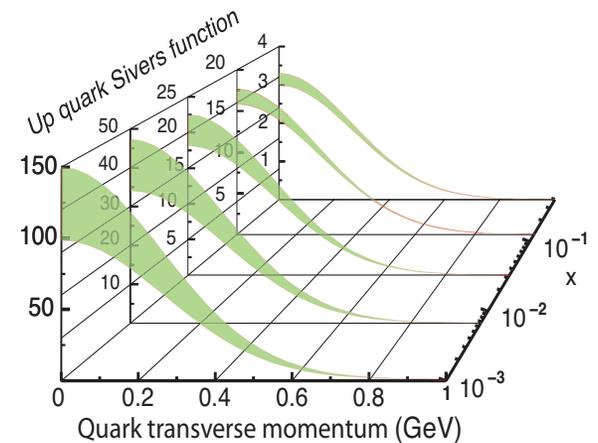
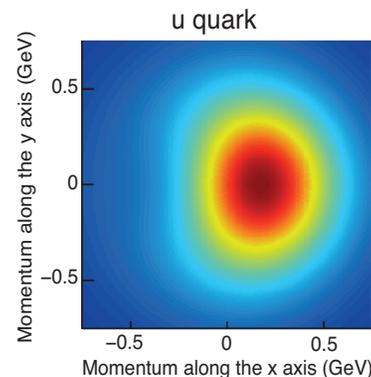
## *I: Introduction and Overview*

- Introduction and History
- Electron As A Clean Probe
- Facilities:

**Fixed Target:** SLAC, HERMES, COMPASS, Jefferson Lab, ...

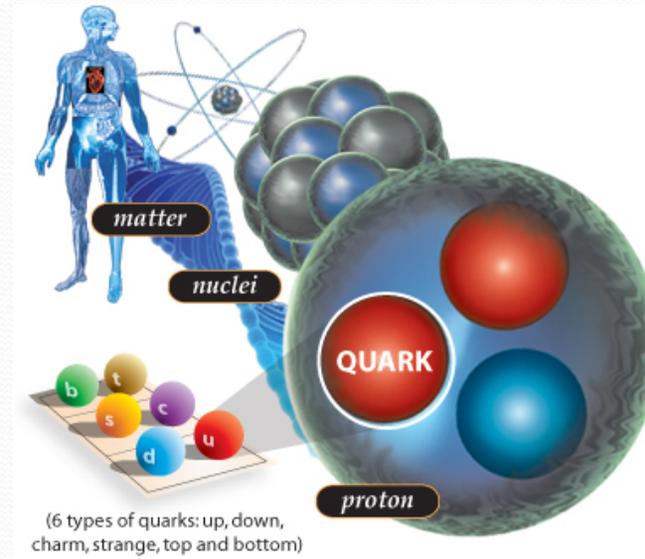
**Electron-Ion Collider :** HERA, **Future EIC:** JLEIC, e-RHIC, EicC, LHeC

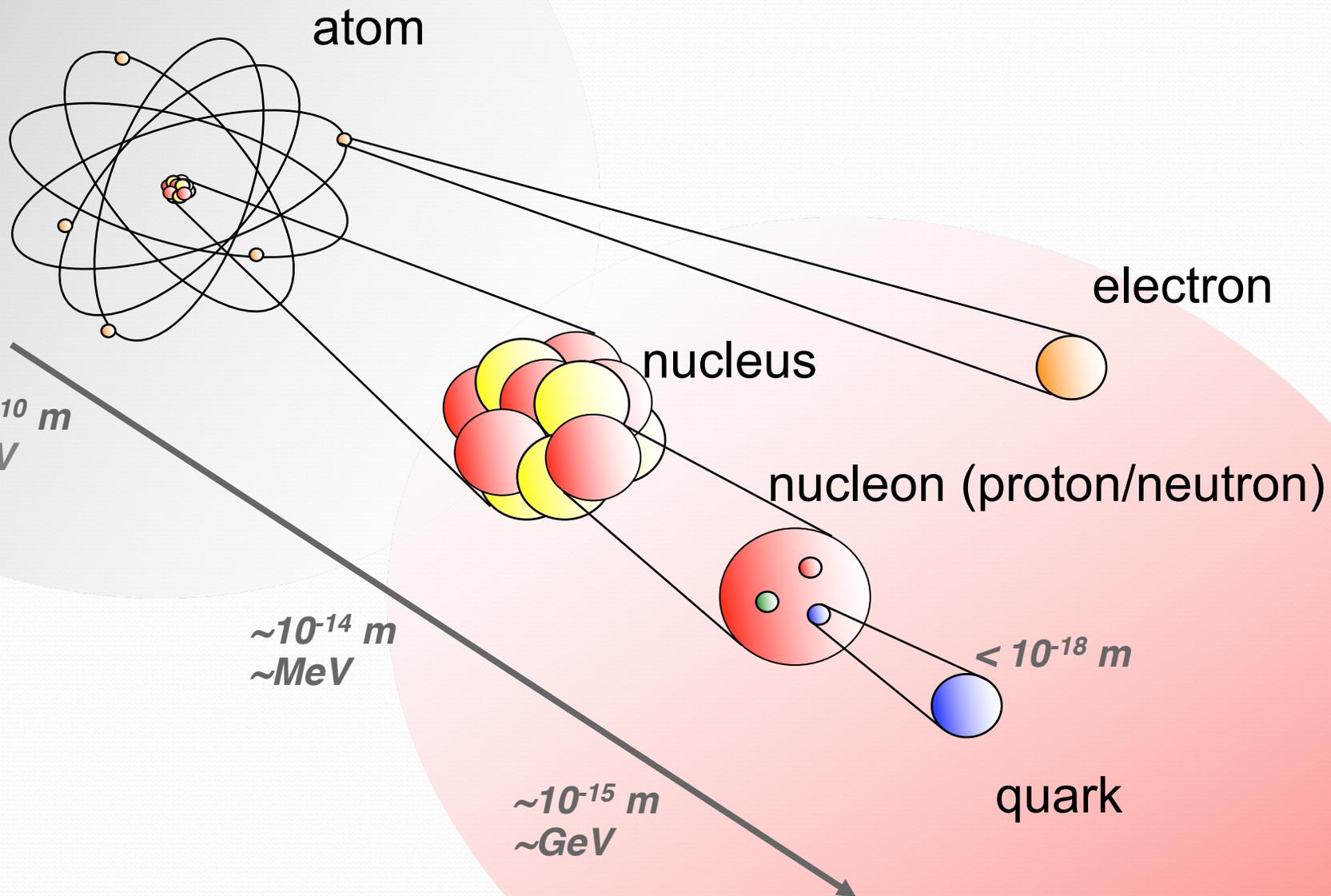
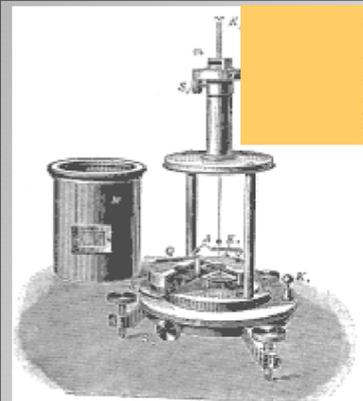
- e-N/e-A Experiments



# Introduction and History

## Nucleon Structure and Strong Interaction (QCD)

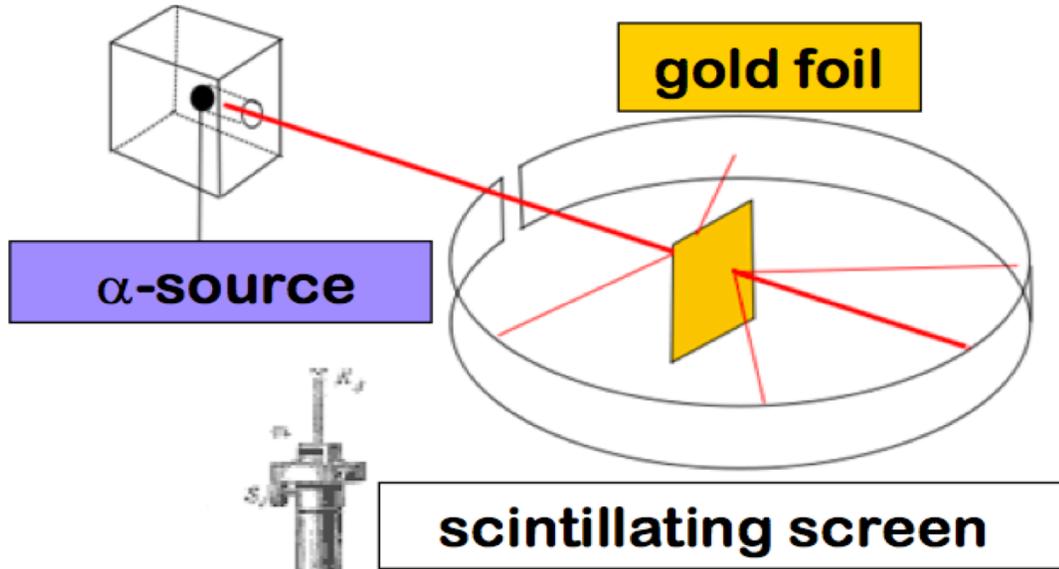




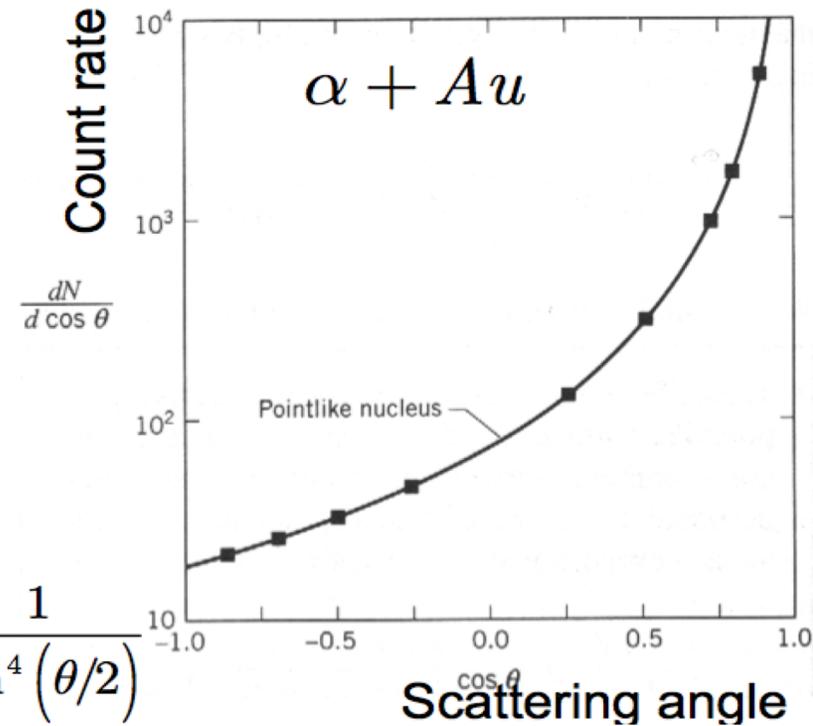
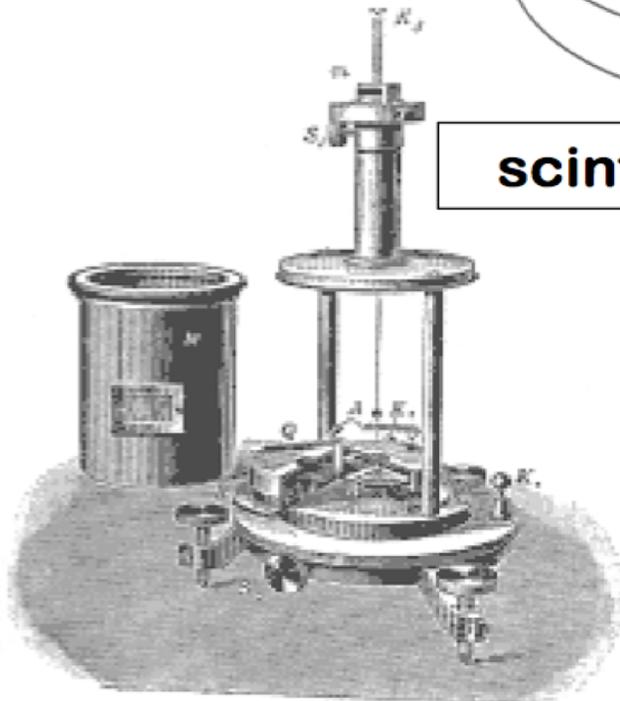
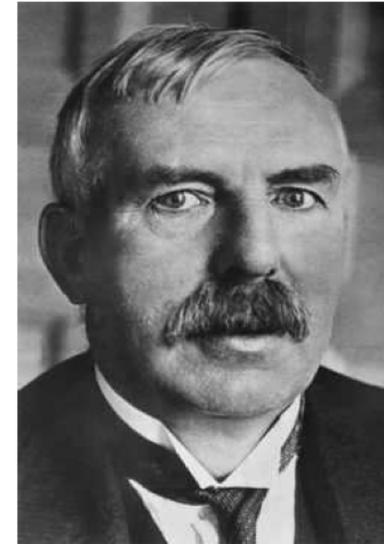
# Rutherford Scattering

Discovery of Nucleus

~5 MeV



Ernest Rutherford,  
Nobel Prize 1908



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

Scattering off a hard sphere;  $r_{\text{nucleus}} \sim 10^{-4} r_{\text{atom}} \sim 10^{-14} \text{ m}$

# Discovery of (Electron) Spin

- 1896 Zeeman Effect : effect of a magnetic field on light  
-> atomic level splitting due to electron spin

- 1922 Stern-Gerlach experiment  
silver beam split

in inhomogeneous field

Bohr magneton:  $\mu_e = e\hbar/2m_e c$

- 1925 spinning electron

Uhlenbeck and Goudsmit, Pauli

spin: internal property,  $S_e = 1/2$

- 1928 Dirac equation

relativistic effect: spin  $\leftrightarrow$  magnetic moment



Postcard from Gerlach to Bohr



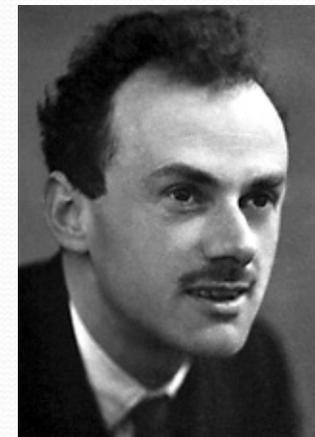
Pieter Zeeman

**Nobel Prize 1902**



Wolfgang Pauli  
for "Pauli Principle"

**Nobel Prize 1945**



Paul Dirac

**Nobel Prize 1933**

# Anomalous Magnetic Moment (of Proton)

## ■ 1933 Otto Stern

Magnetic moment of the proton

-- expected:  $\mu_p = e\hbar/2m_p c$  (since  $S_p = 1/2$ )

-- measured:  $\mu_p = e\hbar/2m_p c(1 + \kappa_p)$  !

anomalous magnetic moment (a.m.m)  $\kappa_p = 1.5 \pm 10\%$

➤ first (indirect) evidence proton has structure



Otto Stern  
Nobel Prize 1943

## ■ 1943 Nobel Prize awarded to Stern

for 'development of the molecular ray method and his discovery of the magnetic moment of protons'

now:  $\kappa_p = 1.792847386 \pm 0.000000063$

and  $\kappa_n = -1.91304275 \pm 0.000000045$

# Neutron, Mesons and Quark Model



James Chadwick  
**Nobel Prize 1935**



Cecil Frank Powell  
**Nobel Prize 1950**



Murray Gell-Mann  
**Nobel Prize 1969**



Hideki Yukawa  
**Nobel Prize 1949**

- 1932: Discovery of the neutron by Chadwick  
proton, neutron: basic building blocks for nuclei
- 1935: Yukawa “strong” force  $\rightarrow \pi$  meson
- 1937: Discovery of “meson”
- 1946: Powell, “ $\pi$  and  $\mu$  mesons”  
 $\mu$  mesons  $\rightarrow$  muon

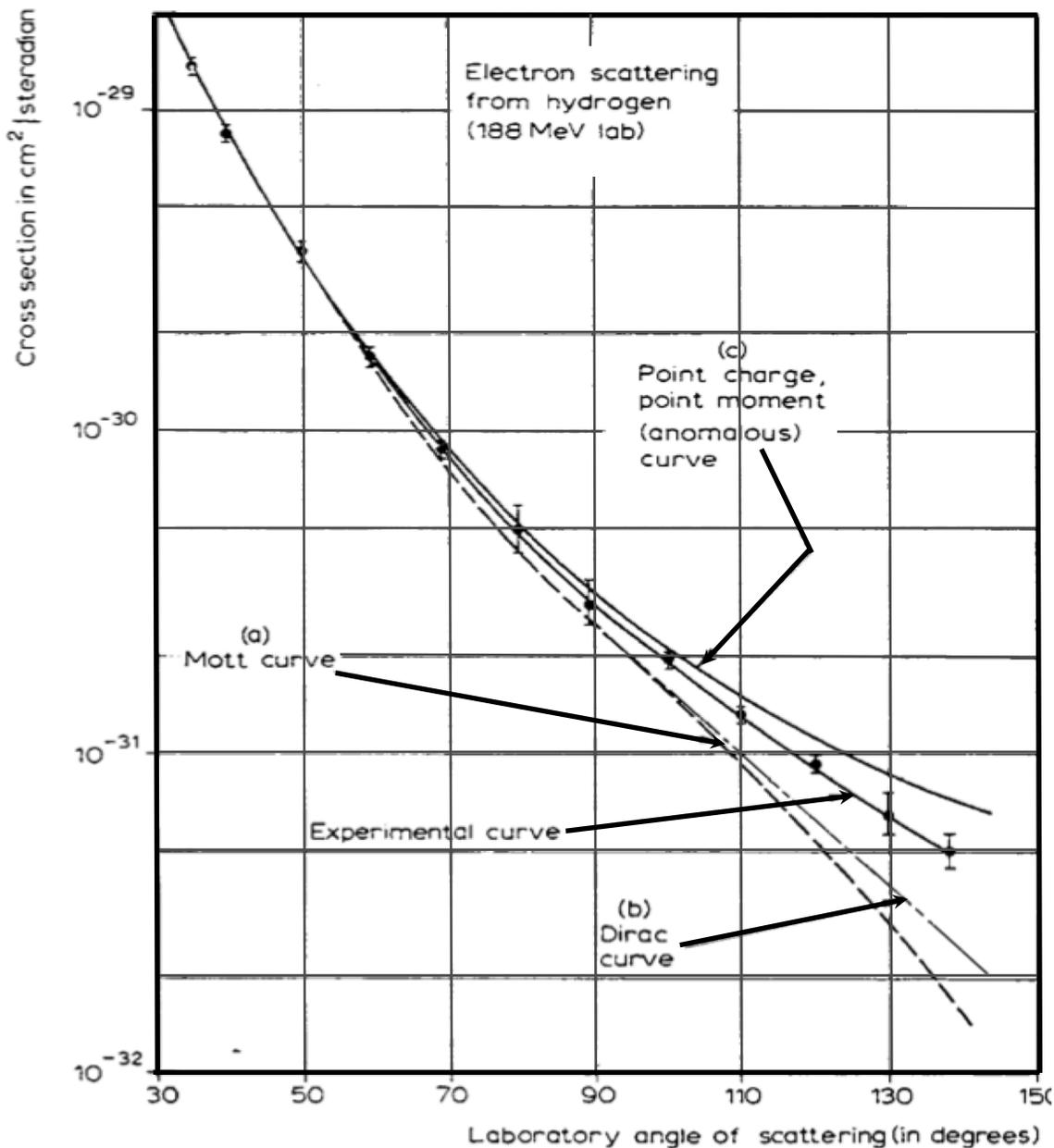
## Zoo of hadrons !

- 1964 Gell-Mann  
Classify strong interacting particles (hadrons)  
with a simple quark model

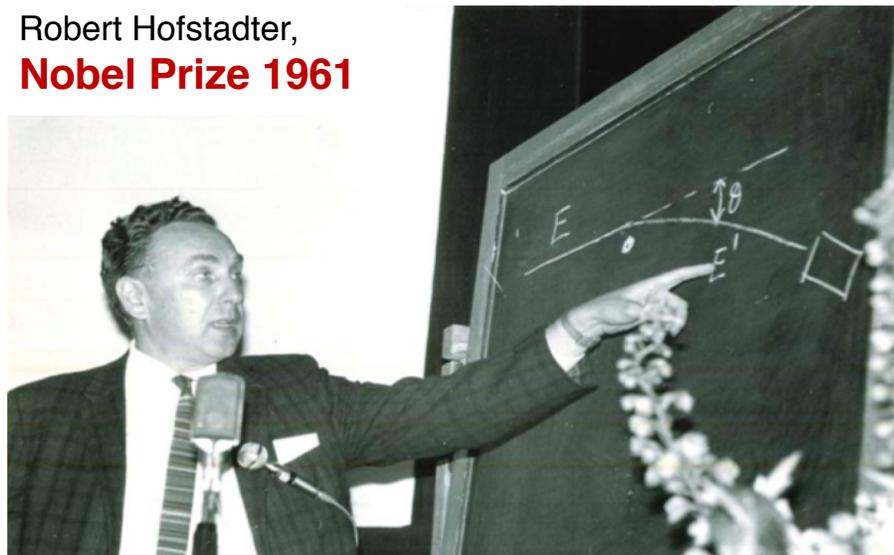
# Elastic Electron Scattering

~200 MeV

Discovery: Proton Has Structure



Robert Hofstadter,  
Nobel Prize 1961



Scattering off a spin-1/2 Dirac particle:

$$\frac{d\sigma}{d\Omega} = \left( \frac{\alpha}{4ME \sin^2(\theta/2)} \right)^2 \frac{E'}{E} \left[ \frac{q^2}{2M} \sin^2(\theta/2) + \cos^2(\theta/2) \right]$$

The proton has an anomalous magnetic moment,

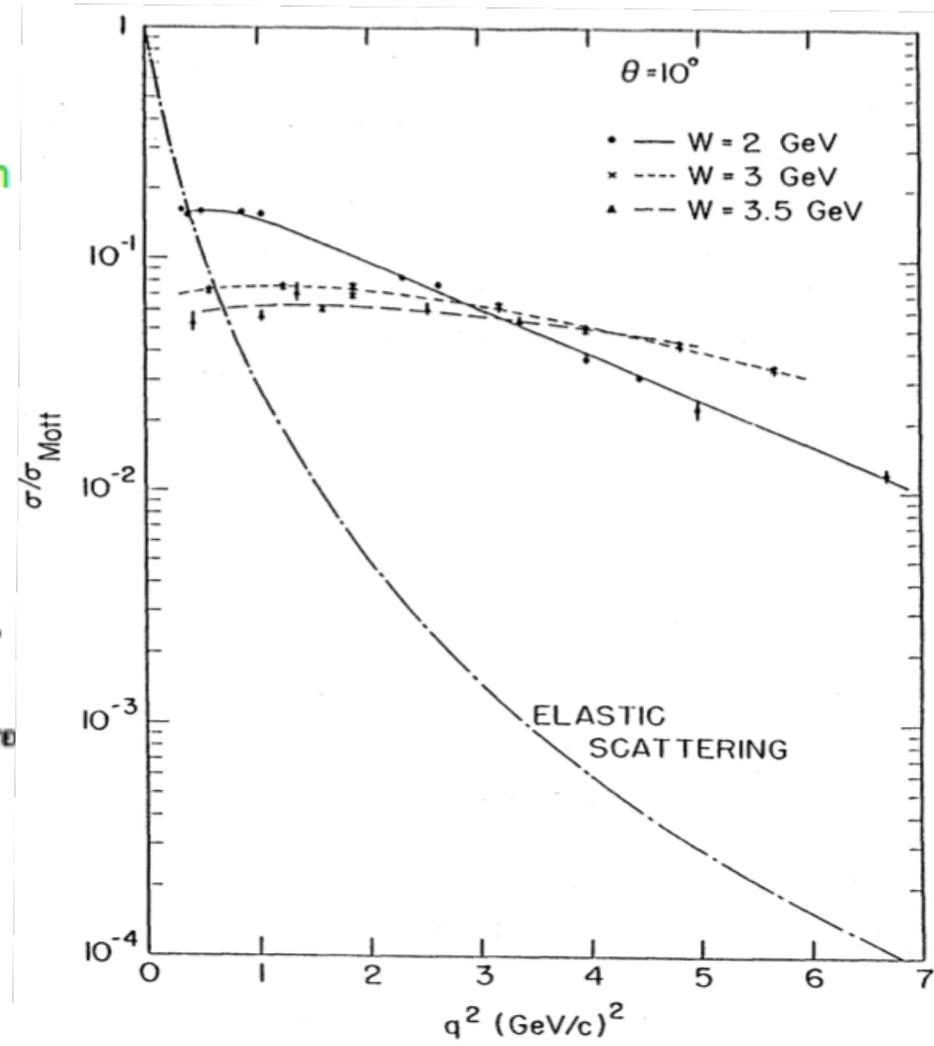
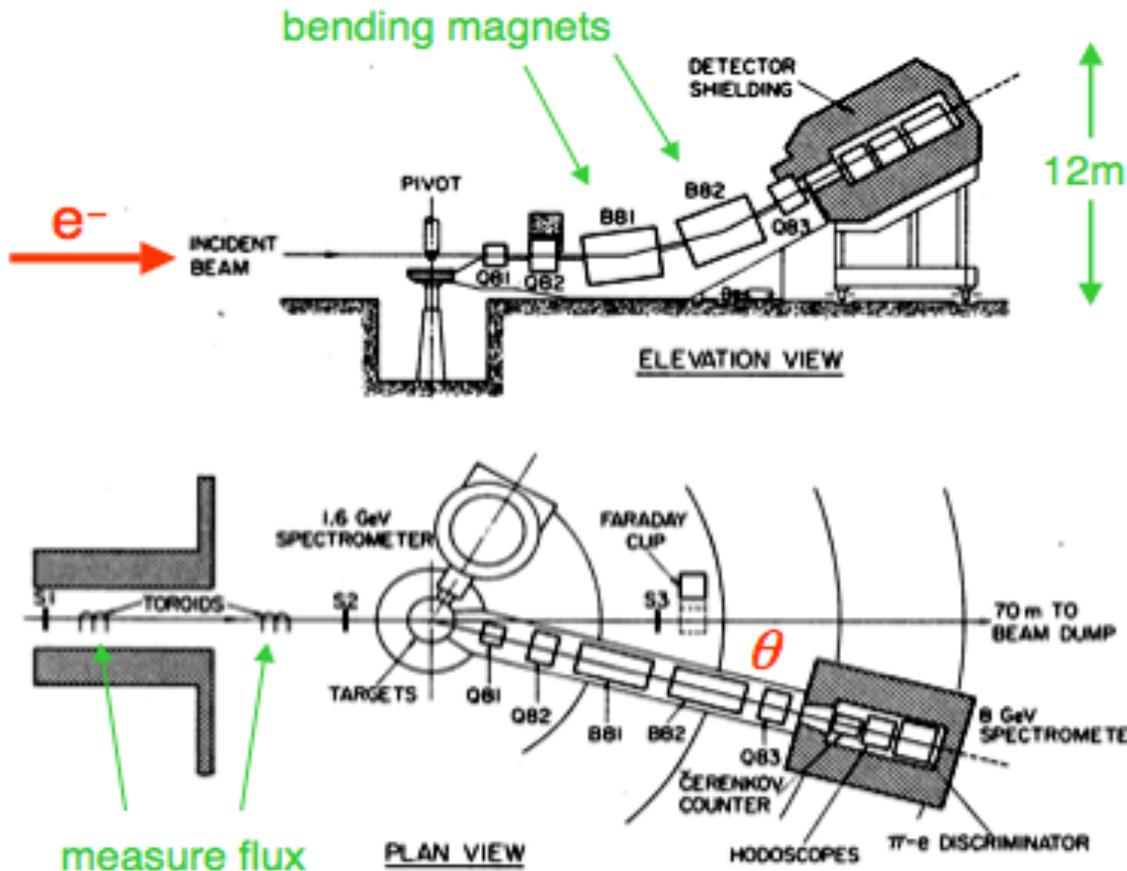
$$g_p \neq 2, \quad g_p \simeq 5.6$$

and, hence, internal (spin) structure.

# Deep-Inelastic Electron Scattering

$\sim 10$  GeV

Discovery of Quarks (Partons)

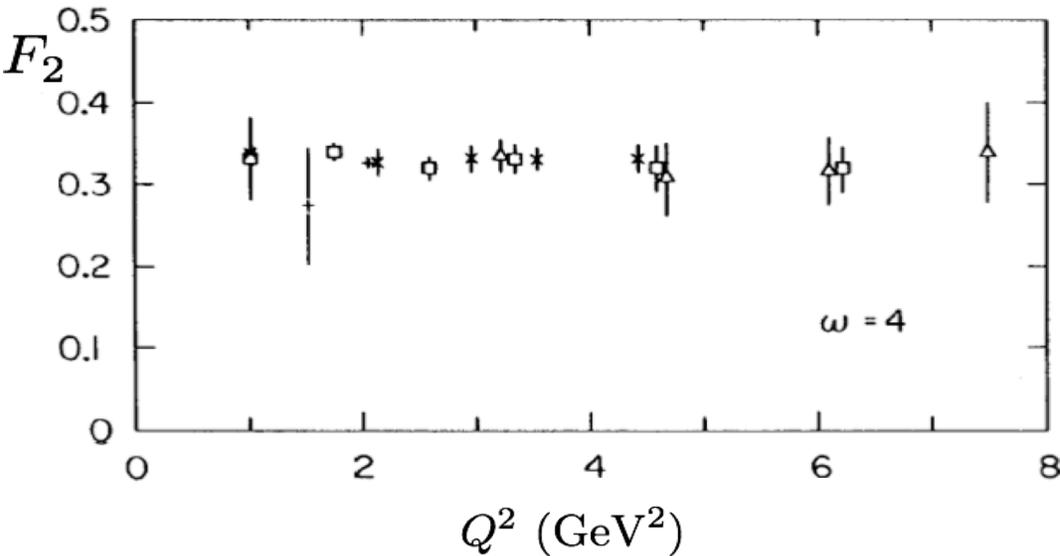


# Deep-Inelastic Electron Scattering

## Discovery of Quarks (Partons)

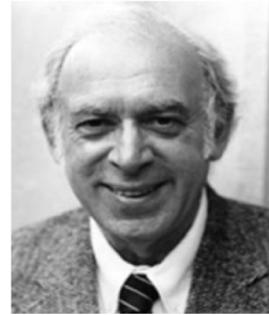
**Bjorken scaling:**

+ 6°    □ 18°  
 × 10°    △ 26°



*Point particles cannot be further resolved; their measurement does not depend on wavelength, hence  $Q^2$ ,*

*Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.*



J.T. Friedman



R. Taylor

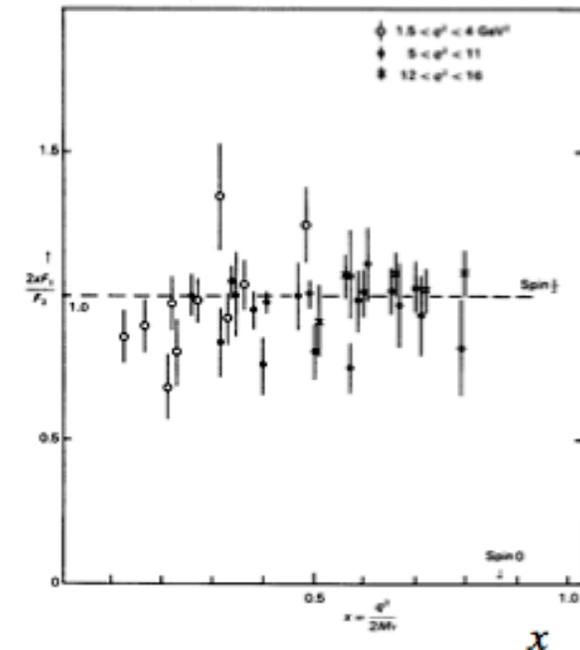


H.W. Kendall

**Nobel Prize 1990**

**Callan-Gross relation:**

$$\frac{2xF_1}{F_2}$$



spin 1/2

spin 0

# *Birth of QCD*

- Problems with simple quark model:
  1. pion mass is light ( $\sim 140$  MeV) compared with nucleon (1 GeV) and  $\rho$  meson (770 MeV)  
→ spontaneous breaking of chiral symmetries  
quark mass  $\sim 300$  MeV ?
  2. Pauli principle → new degree of freedom: color  
no free quarks observed !
- 1972-73 Gell-Mann, Fritzsche, Leutwyler,  
Gross, Politzer, Wilczek  
SU(3) color gauge field → QCD

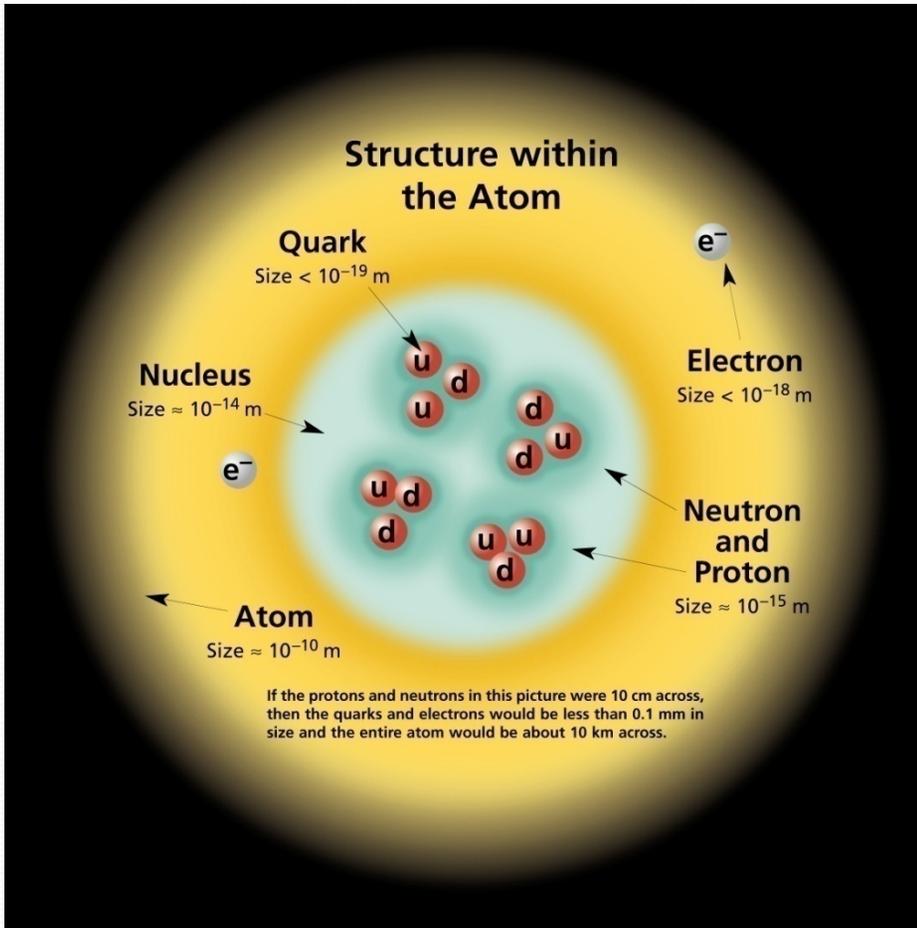


David Gross, H. David Politzer, Frank Wilczek  
**Nobel Prize 2004**

# What Is the World Made of?

Visible Matter → Atom → Electrons + Nucleus

Nucleus → Nucleons(proton,neutron) → Quarks: proton=uud, neutron=udd



FERMIONS			matter constituents spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$< 1 \times 10^{-8}$	0	<b>u</b> up	0.003	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.006	-1/3
$\nu_\mu$ muon neutrino	$< 0.0002$	0	<b>c</b> charm	1.3	2/3
<b><math>\mu</math></b> muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ tau neutrino	$< 0.02$	0	<b>t</b> top	175	2/3
<b><math>\tau</math></b> tau	1.7771	-1	<b>b</b> bottom	4.3	-1/3

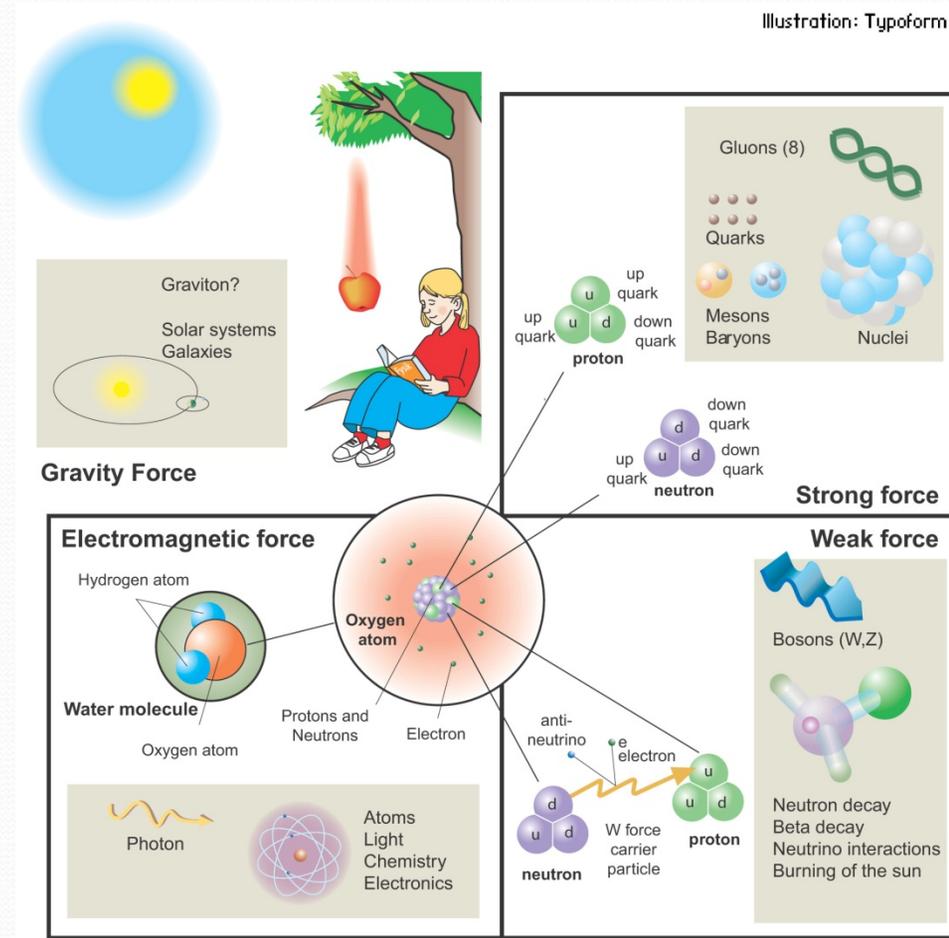


So everything is made of quarks and leptons, eh? Who would have *thought* it was so simple?

# What Holds the World Together?

## Four Known Interactions

- Gravitational Interaction (graviton?)  
long range, always attractive  
strength, extremely weak,  $\sim 10^{-40}$
- Electromagnetic Interaction ( $\gamma$ )  
long range, electric charge (e)  
strength (coupling constant),  $\alpha = 1/137$
- Weak Interaction (W, Z)  
short range, weak charge  
strength,  $10^{-4} \sim 10^{-7}$
- Strong Interaction (gluons)  
short range, color charge,  
strength, running coupling,  $\alpha_s = 0.1 \sim 1$   
*confinement*



# Standard Model

## Electro-weak and Quantum Chromodynamics (QCD)

FERMIONS			matter constituents spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0	<b>u</b> up	0.003	2/3
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$\nu_\tau$ tau neutrino	$<0.02$	0	<b>t</b> top	175	2/3
<b><math>\tau</math></b> tau	1.7771	-1	<b>b</b> bottom	4.3	-1/3

BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
<b>W<sup>-</sup></b>	80.4	-1			
<b>W<sup>+</sup></b>	80.4	+1			
<b>Z<sup>0</sup></b>	91.187	0			

## PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	<b>W<sup>+</sup> W<sup>-</sup> Z<sup>0</sup></b>	$\gamma$	Gluons	Mesons
Strength relative to electromag for two u quarks at:	$10^{-41}$	0.8	1	25	Not applicable to quarks
	$10^{-41}$	$10^{-4}$	1	60	
	for two protons in nucleus	$10^{-36}$	$10^{-7}$	1	Not applicable to hadrons

# What Are the Challenges?

- Success of the Standard Model

Electro-Weak theory tested to very good level of precision

Discovery of Higgs particle

Strong interaction theory (QCD) tested in the high energy (short distance) region

- Major challenges:

Understand QCD in the strong region (distance of the nucleon size)

Understand quark-gluon structure of the nucleon

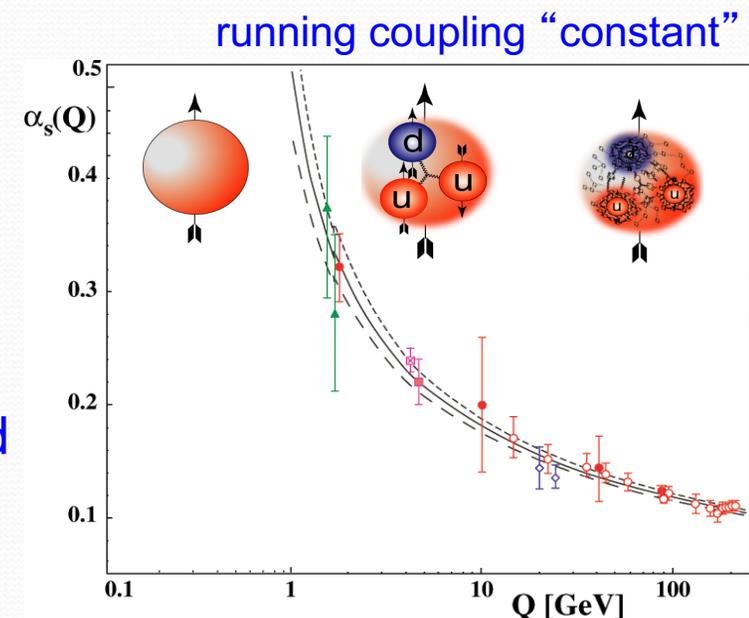
Confinement

- Beyond Standard Model

Energy frontier: LHC search Beyond SM

Precision tests of Standard Model at low energy

Precision information of nucleon structure needed



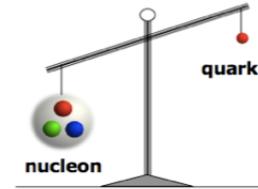
# Nucleon Structure: A Universe Inside

- Nucleon: proton = (uud), neutron = (udd) + sea quarks + gluons
- Nucleon: **99% of the visible mass in universe**

## ➤ Proton mass “puzzle”:

Quarks carry  $\sim 1\%$  of proton's mass

*How does glue dynamics generate the energy for nucleon mass?*



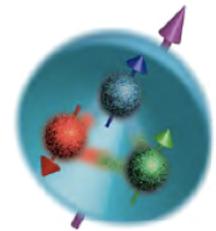
$$m_q \sim 10 \text{ MeV}$$

$$m_N \sim 1000 \text{ MeV}$$

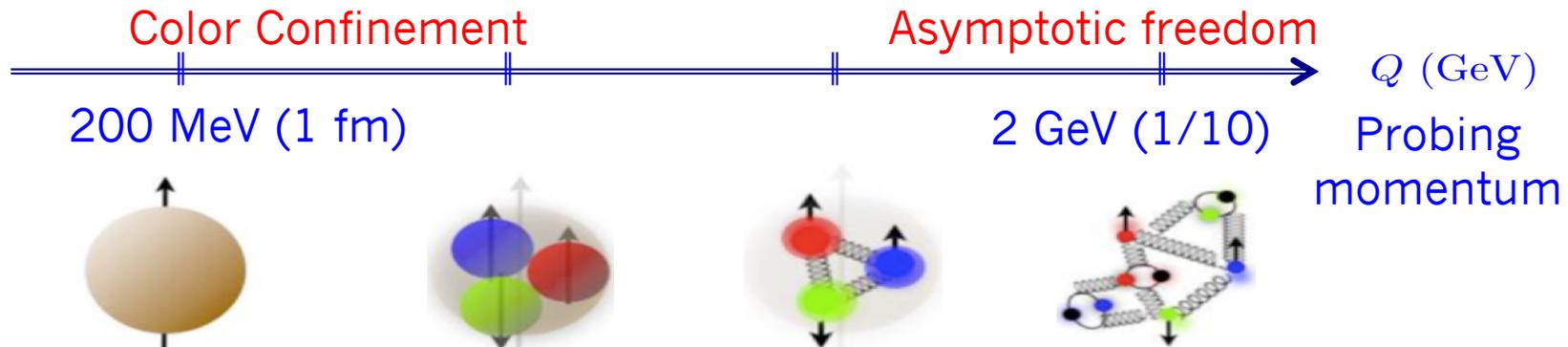
## ➤ Proton spin “puzzle”:

Quarks carry  $\sim 30\%$  of proton's spin

*How does quark and gluon dynamics generate the rest of the proton spin?*



## ➤ 3D structure of nucleon: 3D in momentum or (2D space +1 in momentum)



*How does the glue bind quarks and itself into a proton and nuclei?  
Can we scan the nucleon to reveal its 3D structure?*

# Recent Theoretical Developments

- **Dynamical Chiral Symmetry Breaking  $\leftrightarrow$  Confinement**

- Responsible for  $\sim 99\%$  of the nucleon mass
- Higgs mechanism is (almost) irrelevant to light quarks

- **Recent development in theory**

- Lattice QCD
- Bound State QCD: Dyson-Schwinger
- Ads/CFT: Holographic QCD
- QCD Dynamics
- .....

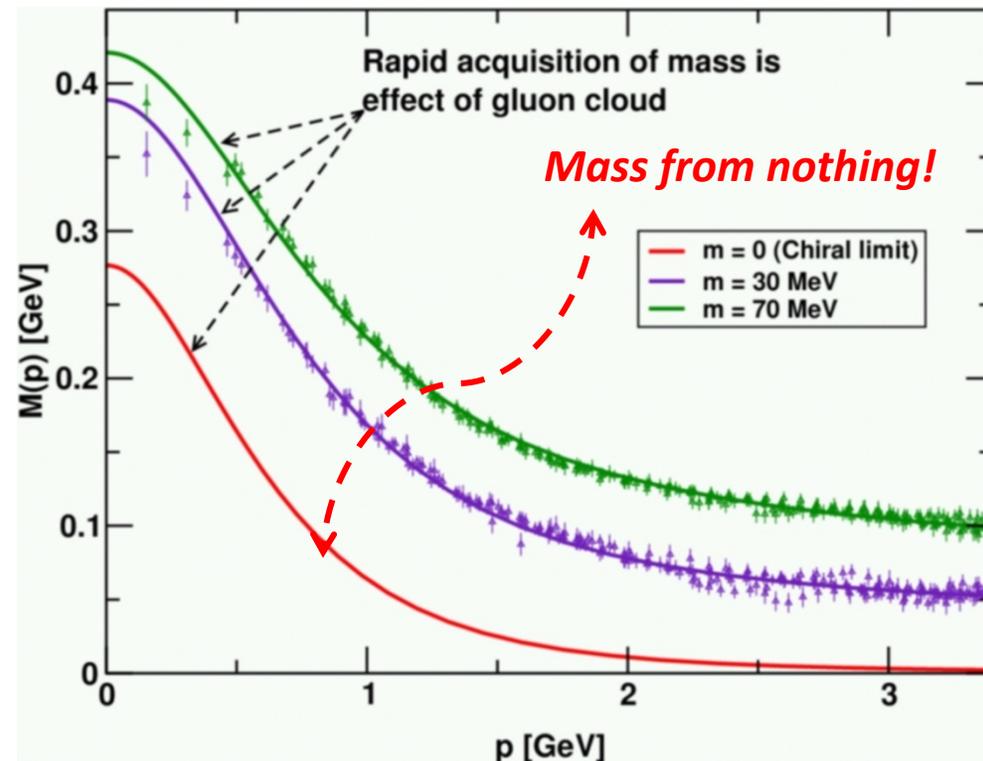
- **Direct comparison becomes possible**

- **LQCD: Moments of PDFs**
- **x-dependence of PDFs, TMDs, GPDs**

X. Ji, PRL 111, 039103 (2013)

H. W. Lin, et al., Phys. Rev. D 91, 054510 (2015)

- **Quasi-PDF, Pseudo-PDF, .....**

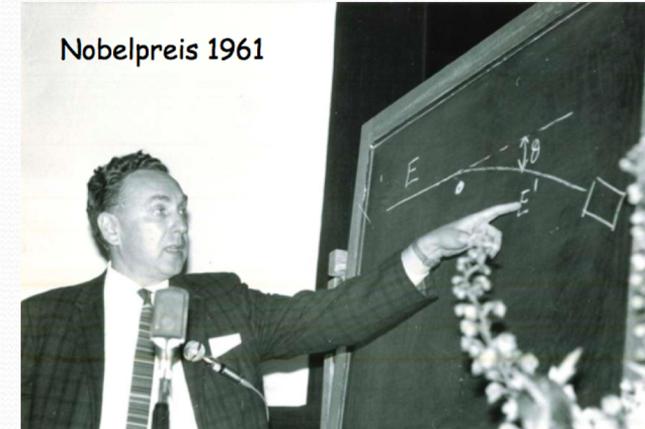


# Electron Scattering and e-p/e-A colliding

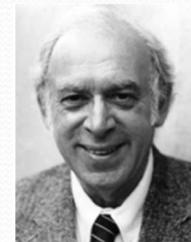
**A Clean Probe To Study Nucleon Structure and QCD**

# Electron Scattering and Nucleon Structure

- Clean probe to study nucleon structure  
only electro-weak interaction, well understood
- Elastic Electron Scattering: Form Factors  
→ 60s: established nucleon has structure (Nobel Prize)  
electrical and magnetic distributions
- Resonance Excitations  
→ internal structure, rich spectroscopy (new particle search)  
constituent quark models
- Deep Inelastic Scattering  
→ 70s: established quark-parton picture (Nobel Prize)  
parton distribution functions (PDFs)  
polarized PDFs : Spin Structure



Robert Hofstadter,  
**Nobel Prize 1961**



J.T. Friedman



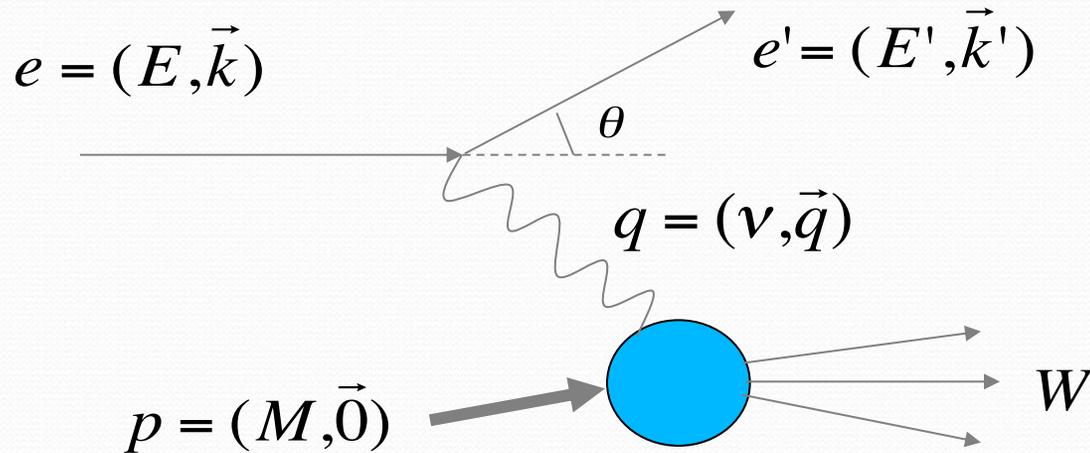
R. Taylor



H.W. Kendall

**Nobel Prize 1990**

# Inclusive Electron Scattering



4-momentum transfer squared

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

Invariant mass squared

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

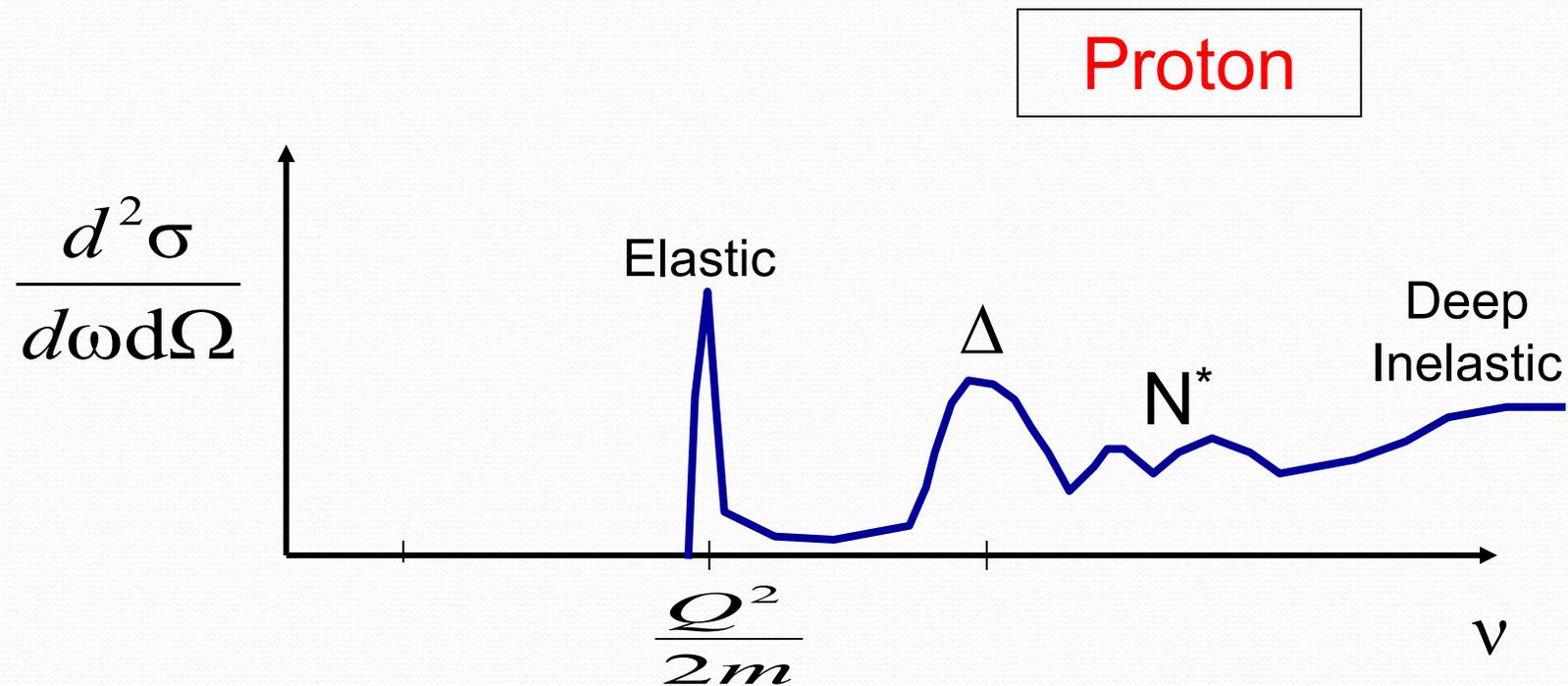
Unpolarized:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_M \left[ \frac{1}{\nu} F_2(\nu, Q^2) + \frac{2}{M} F_1(\nu, Q^2) \tan^2 \frac{\theta}{2} \right]$$

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

$F_1$  and  $F_2$ : information on the nucleon/nuclear structure

# Typical Electron Scattering Spectra at Fixed $Q^2$



# Facilities for e-N and e-A

**JLab 12 Program and Future EIC**

# Experimental Facilities for e-N (e-A)

- SLAC: Fixed target, 20/50 GeV (polarized) electron beam, polarized p, d and  $^3\text{He}$
- CERN: EMC/NMC/SMC/COMPASS  
Fixed target,  $\sim 200$  GeV polarized  $\mu$  beam on polarized p, d
- DESY: HERA, unpolarized e-p collider. 27.5 GeV x 920 GeV  
HERMES, fixed target, polarized e-/e+ 27 GeV beam,  
polarized internal p, d,  $^3\text{He}$
- JLab: fixed target, 6/12 GeV polarized e beam, polarized p,d, $^3\text{He}$   
highest luminosity  $10^{39}$ .
- Low energy facilities: Mainz, MIT-Bates, Saclay, NIKHEF, ...
- Future EIC: e-RHIC, JLEIC, EIC@China (EicC), LHeC, ...

# Jefferson Lab at a Glance

## CEBAF

- **High-intensity** electron accelerator based on **CW SRF** technology
- $I_{\max} = 200 \mu\text{A}$
- $\text{Pol}_{\max} = 90\%$
- $E_{\max} = 6 \text{ GeV}$ : 1995-2012
- **Energy Upgrading to 12 GeV (2012-2017)**
- **12 GeV data taking started**

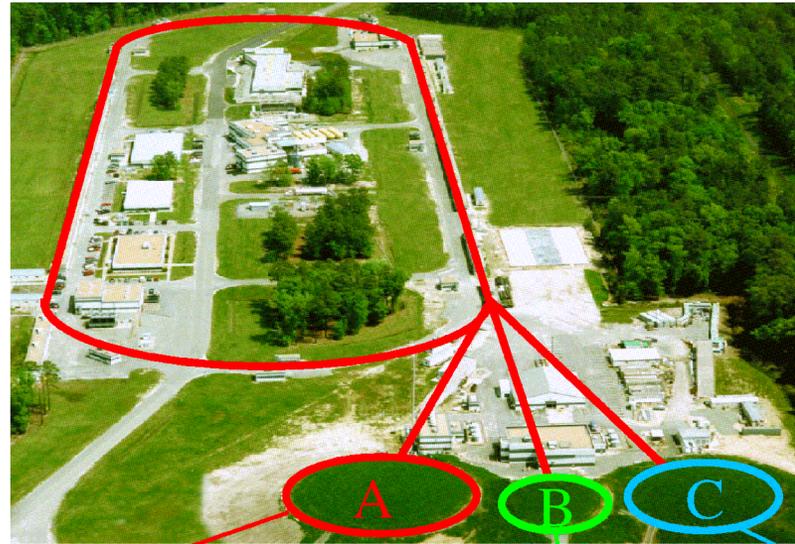
- **~ 1400 Active Users**
- **Produces ~1/3 of US PhDs in Nuclear Physics**



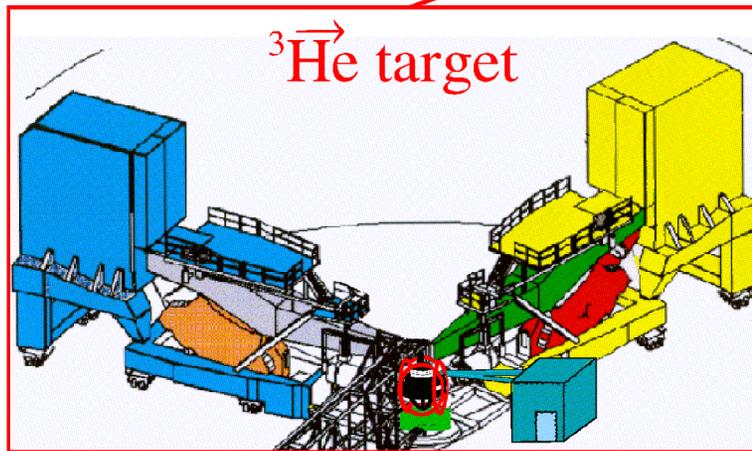
# Thomas Jefferson National Accelerator Facility

Newport News, Virginia, USA

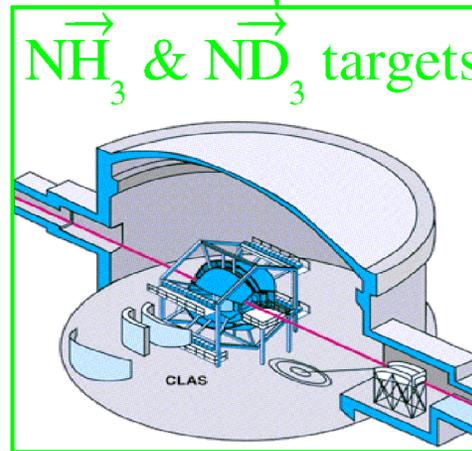
6 GeV polarized  
CW electron beam  
Pol=85%, 200 $\mu$ A  
Luminosity  $\sim 10^{39}$



Upgrading to 12 GeV  
nearly complete



Hall A: two HRS'

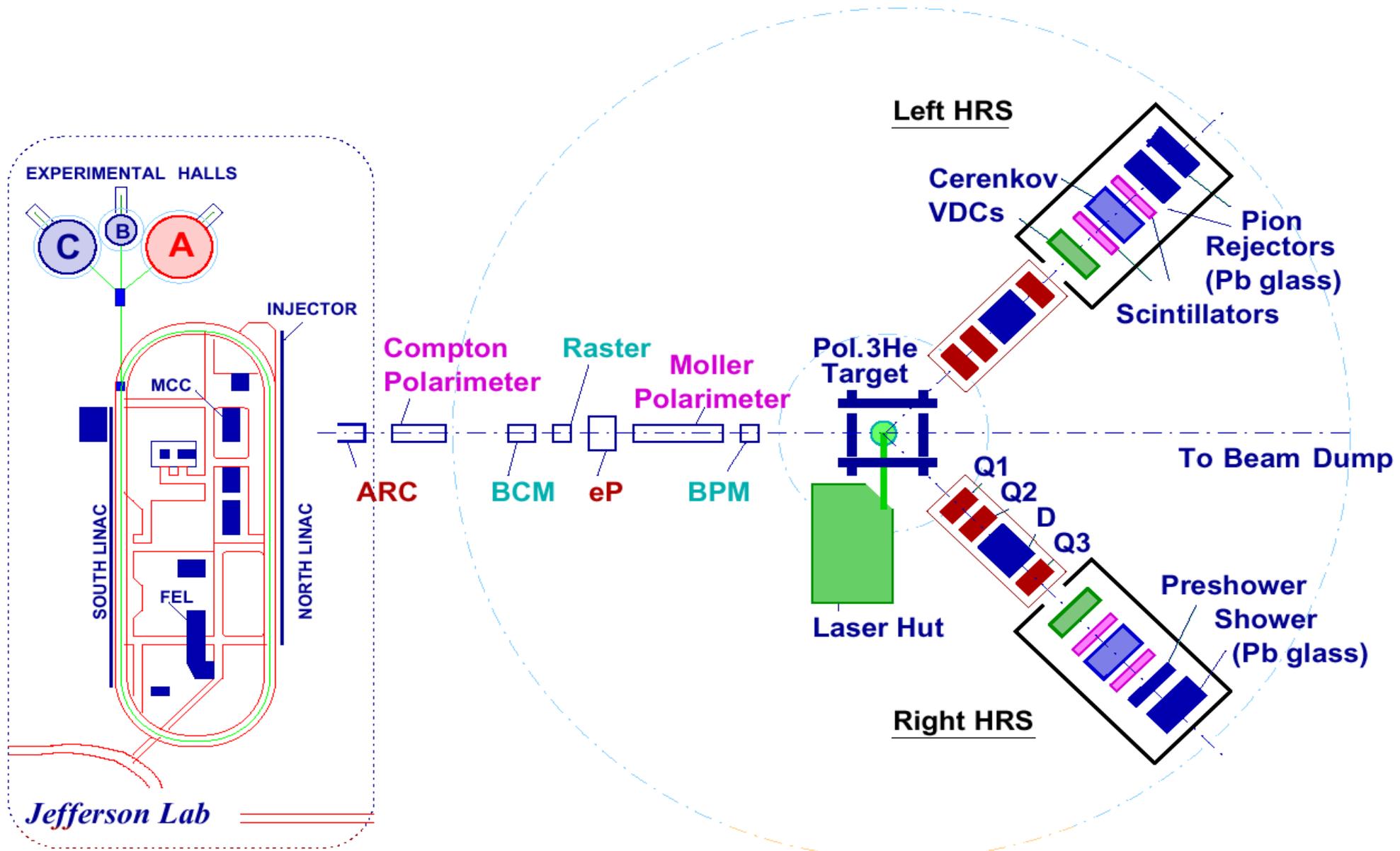


Hall B: CLAS



Hall C: HMS+SOS

# Jefferson Lab Hall A Experimental Setup for inclusive polarized $n$ ( $^3\text{He}$ ) Experiments

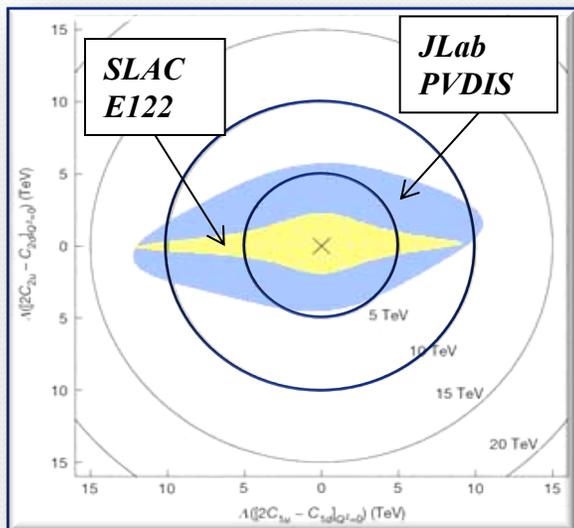


# JLab 2014

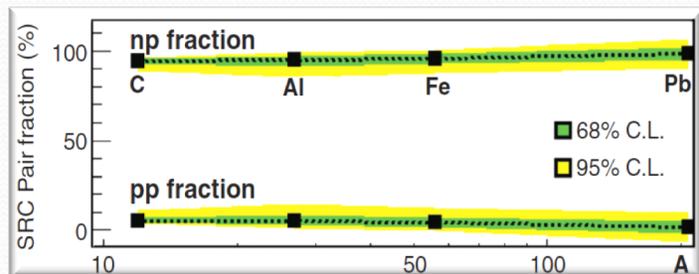
# Near-Future

# Future

Nature 506, 67 (6 February 2014)  
Parity Violating DIS



Science 346, 614 (October 2014)  
Short Range NN Correlations



Decade of Experiments Approved  
Eager to Start 12 GeV Science!

**Jefferson Lab**  
Thomas Jefferson National Accelerator Facility

Physics Opportunities with  
the 12 GeV Upgrade at Jefferson Lab

- **Confinement**
- **Hadron Structure**
- **Nuclear Structure**
- **Fundamental Symmetries**

*and Astrophysics*

Electron Ion Collider  
The Next QCD Frontier

**Electron Ion Collider:  
The Next QCD Frontier**

Understanding the glue  
that binds us all

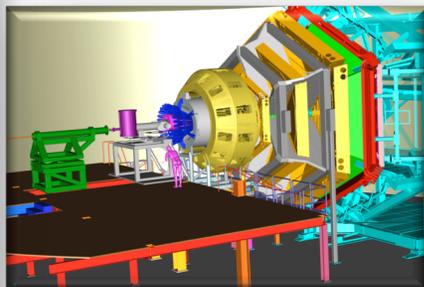
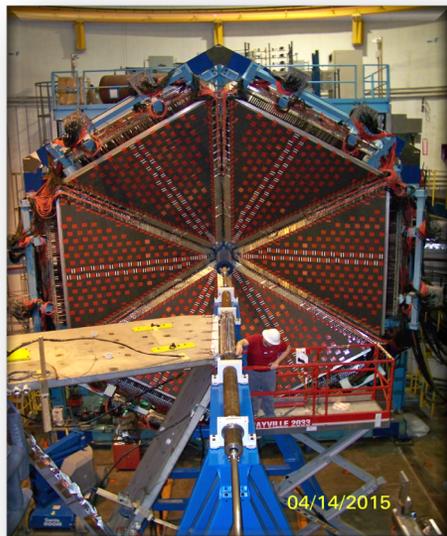
SECOND EDITION

**Role of Gluons in Nucleon and  
Nuclear Structure**



# 12 GeV Scientific Capabilities

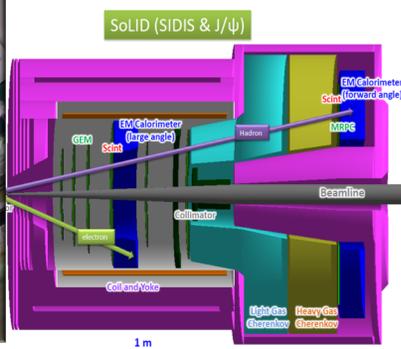
**Hall B** – understanding **nucleon structure** via generalized parton distributions



**Hall D** – exploring origin of **confinement** by studying exotic mesons



**Hall A** – form factors, future new experiments (e.g., **SoLID** and MOLLER)



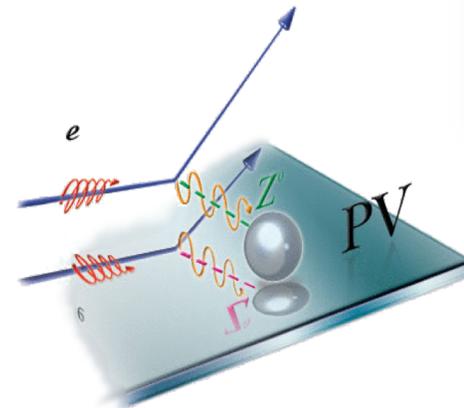
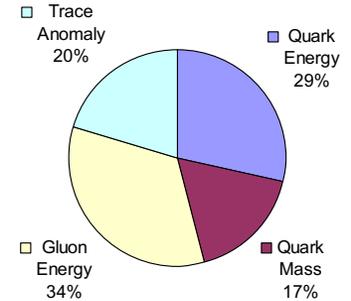
**Hall C** – precision determination of **valence quark** properties in nucleons/nuclei



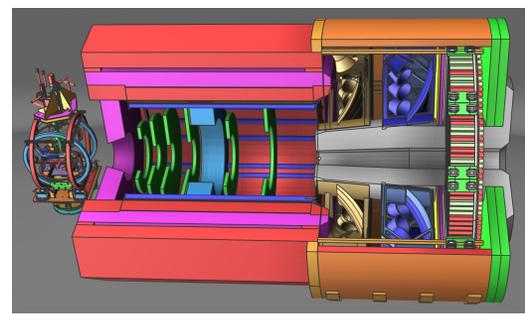


# Jefferson Lab @ 12 GeV Science Questions

- What's the origin of the proton mass?  
How can measurements help?
- Where is the missing spin in the nucleon?  
Role of orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- Can we discover evidence for physics beyond the standard model of particle physics?



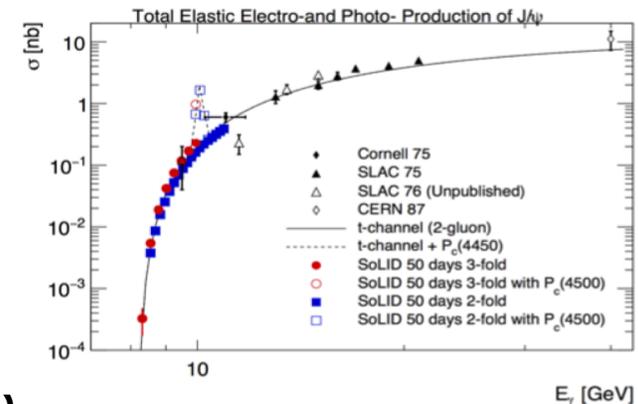
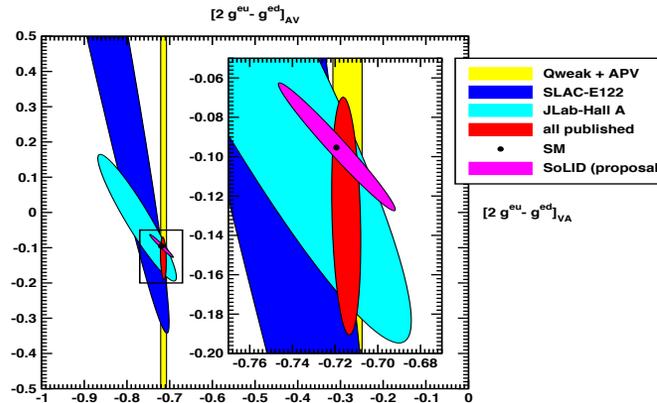
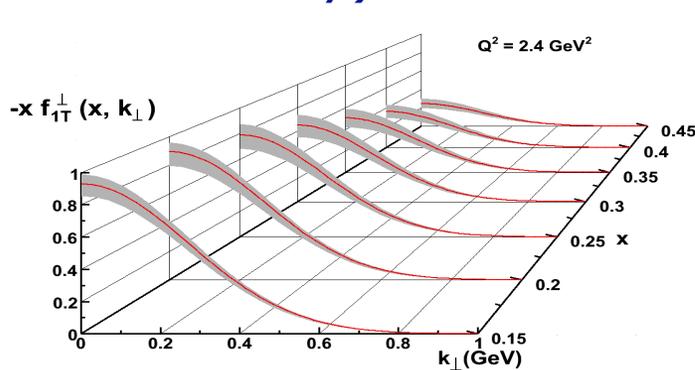
# Solenoidal Large Intensity Device (SoLID)



- Full exploitation of JLab 12 GeV Upgrade to maximize scientific return

## A Large Acceptance Detector AND Can Handle High Luminosity ( $10^{37}$ - $10^{39}$ )

- Reach ultimate precision for tomography of the nucleon
- PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV
- Threshold J/Psi - probing strong color fields in the nucleon and the origin of its mass (trace anomaly)



- Strong collaboration (300 collaborators from 72 institutions, 13 countries)

- Significant international contributions
- Strong theoretical support

- 2015 LRP recommendation IV

- We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories –
- **SoLID – Strongly endorsed mid-scale project**

# Electron Ion Collider

Future QCD Facility:  
Study QCD Sea and Gluons

# Electron Ion Collider

## NSAC 2007 Long-Range Plan:

“An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia.”

## NSAC 2015 Long-Range Plan:

We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility construction** following the completion of FRIB.

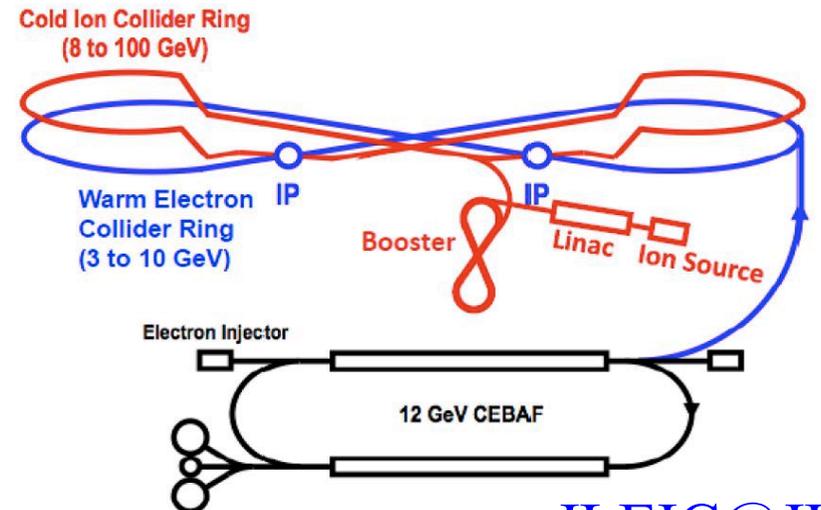
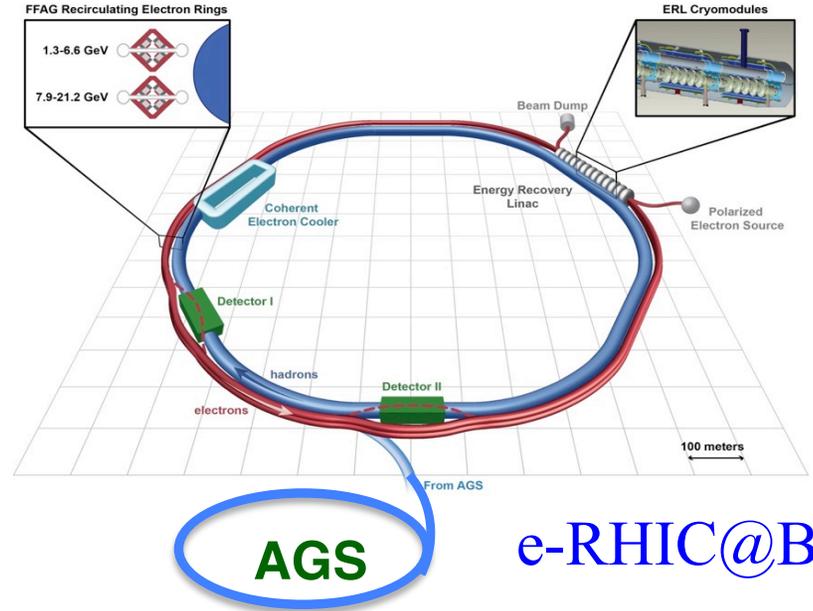
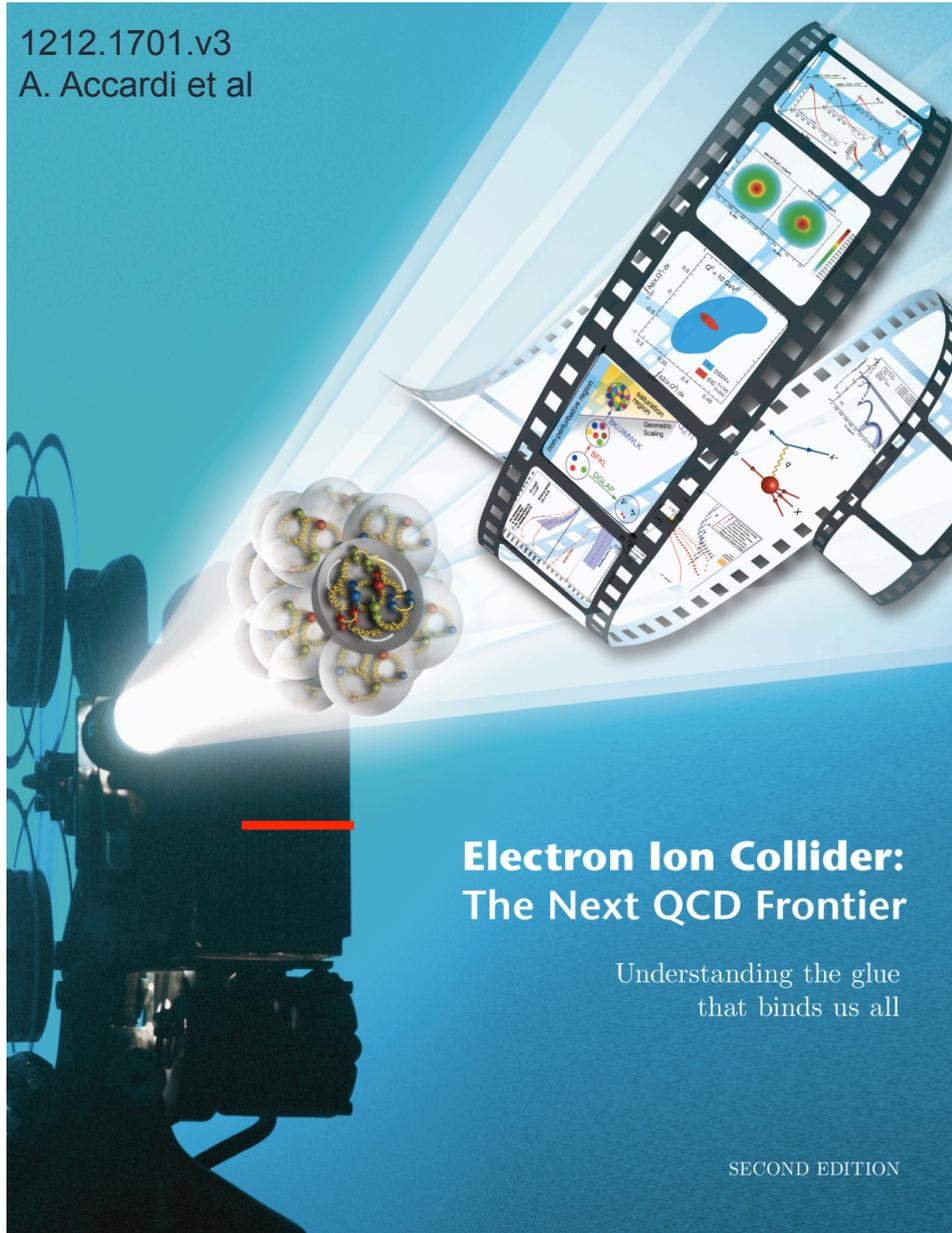
EIC Community White Paper arXiv:1212.1701v2



# The Electron Ion Collider

Two proposals for realization of the Science Case

1212.1701.v3  
A. Accardi et al



**JLEIC@JLab**

# ***Report from Review of National Academy of Sciences***

## ***Findings by The Committee on U.S.-Based Electron Ion Collider Science Assessment***

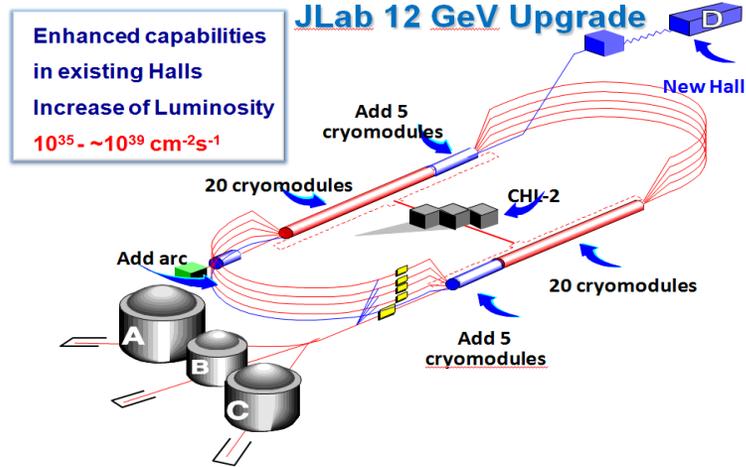
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### ***Finding 1:***

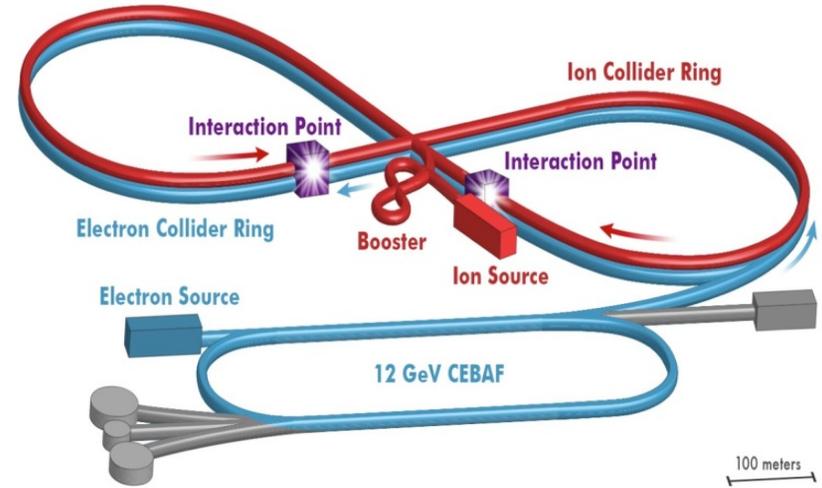
***An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:***

- ***How does the mass of the nucleon arise?***
- ***How does the spin of the nucleon arise?***
- ***What are the emergent properties of dense systems of gluons?***

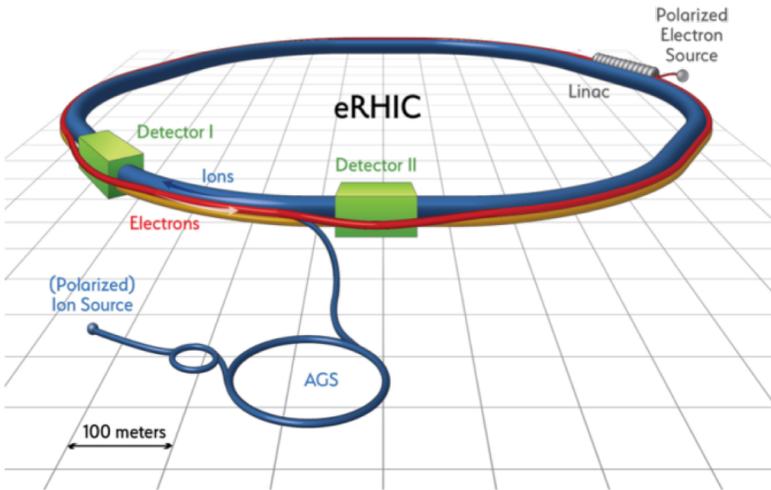
# JLab 12 and Future EIC Plan



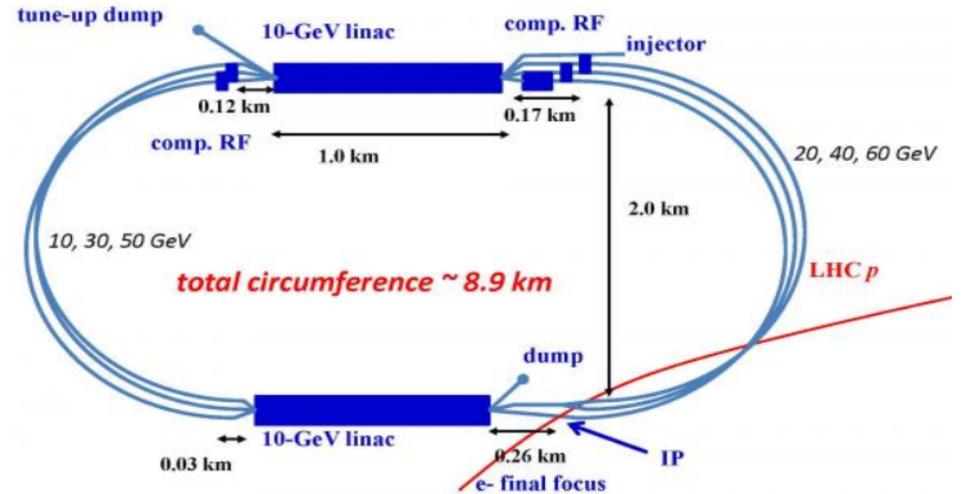
Jlab 12 upgrade (Fixed target)



JLEIC  $\sqrt{s} \sim 20$  to  $70$  GeV



eRHIC,  $\sqrt{s} \sim 140$  GeV



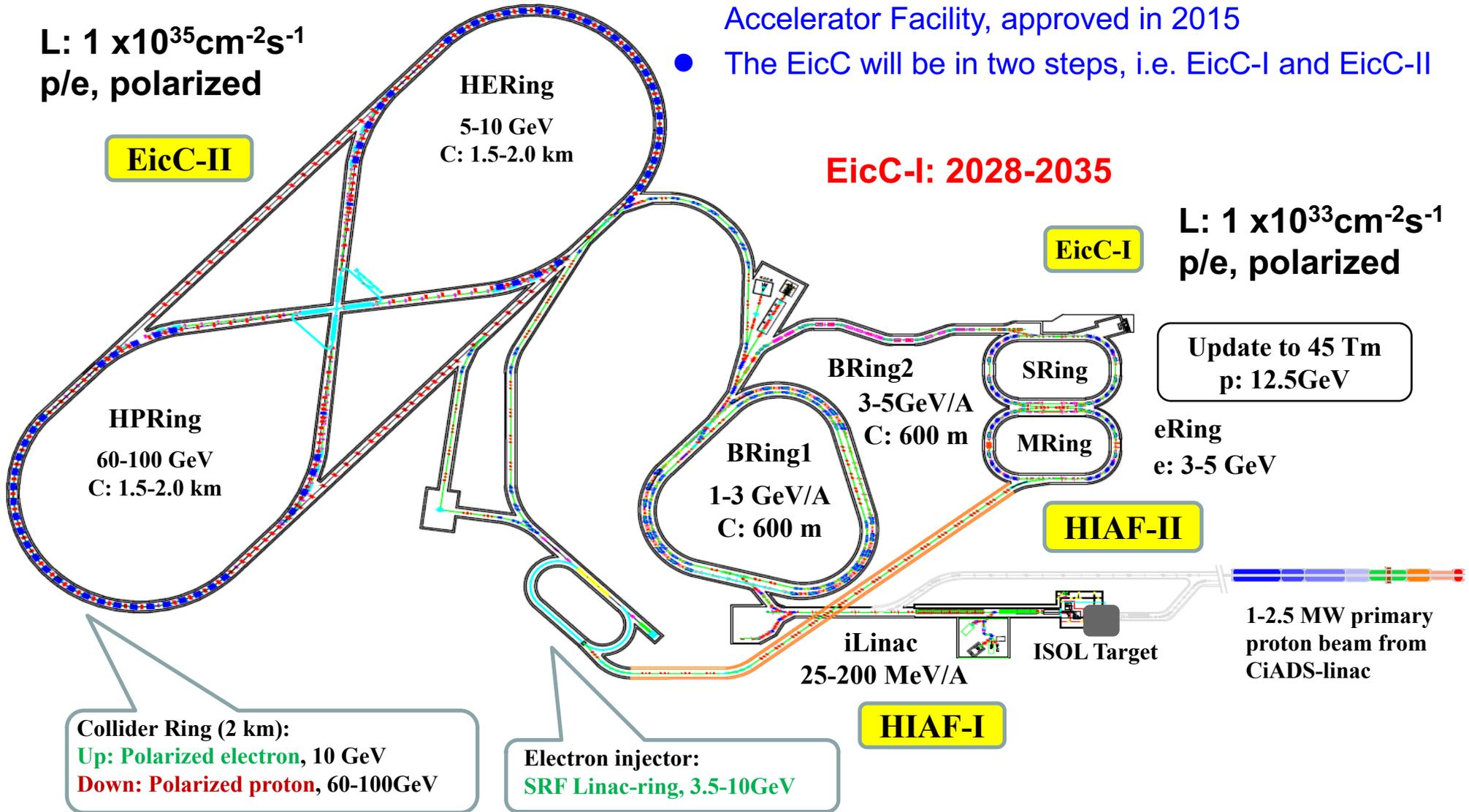
LHeC,  $\sqrt{s} : 1.3 \sim 3.5$  TeV

# EIC @ China

- Based on the HIAF (the Heavy Ion high Intensity Accelerator Facility, approved in 2015)
- The EicC will be in two steps, i.e. EicC-I and EicC-II

**L:  $1 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$**   
**p/e, polarized**

**EicC-II**



**L:  $1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$**   
**p/e, polarized**

**EicC-I: 2028-2035**

**EicC-I**

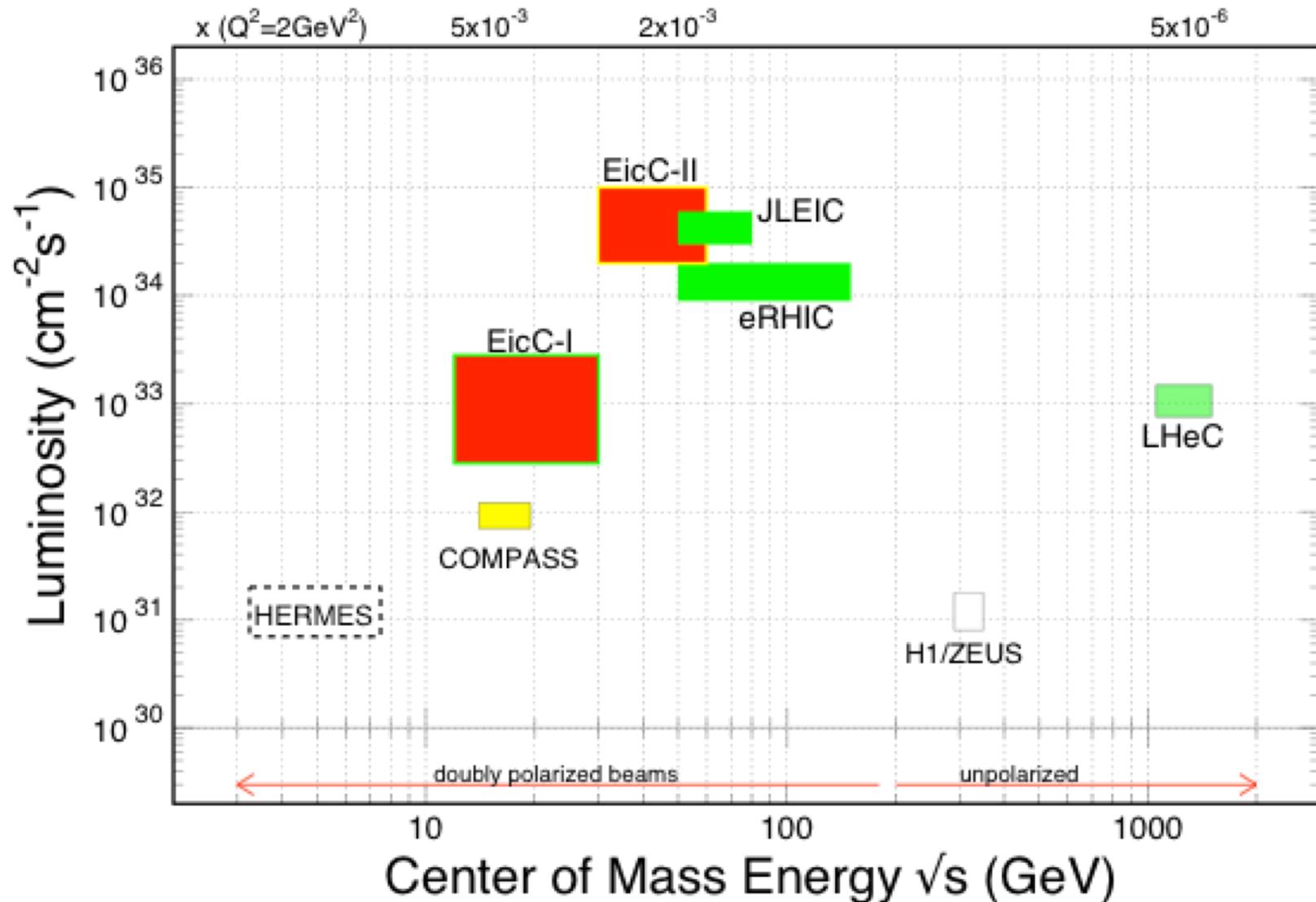
Update to 45 Tm  
 p: 12.5 GeV

eRing  
 e: 3-5 GeV

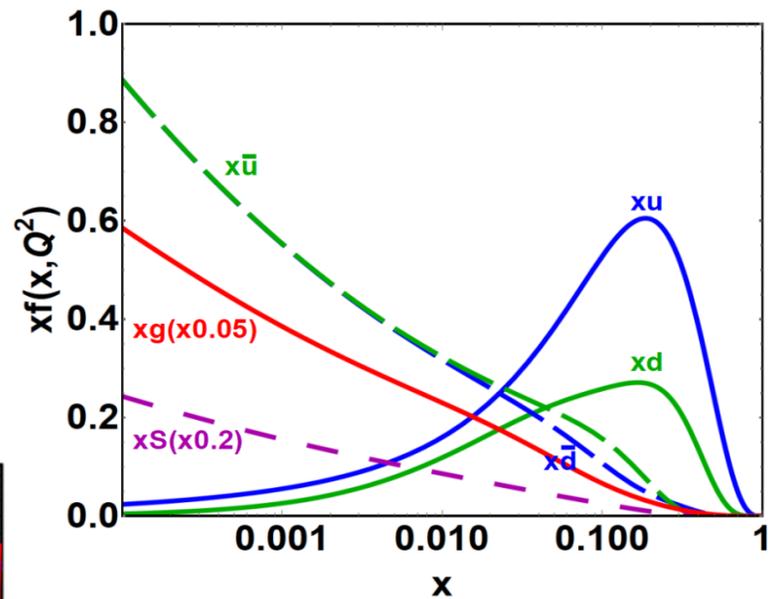
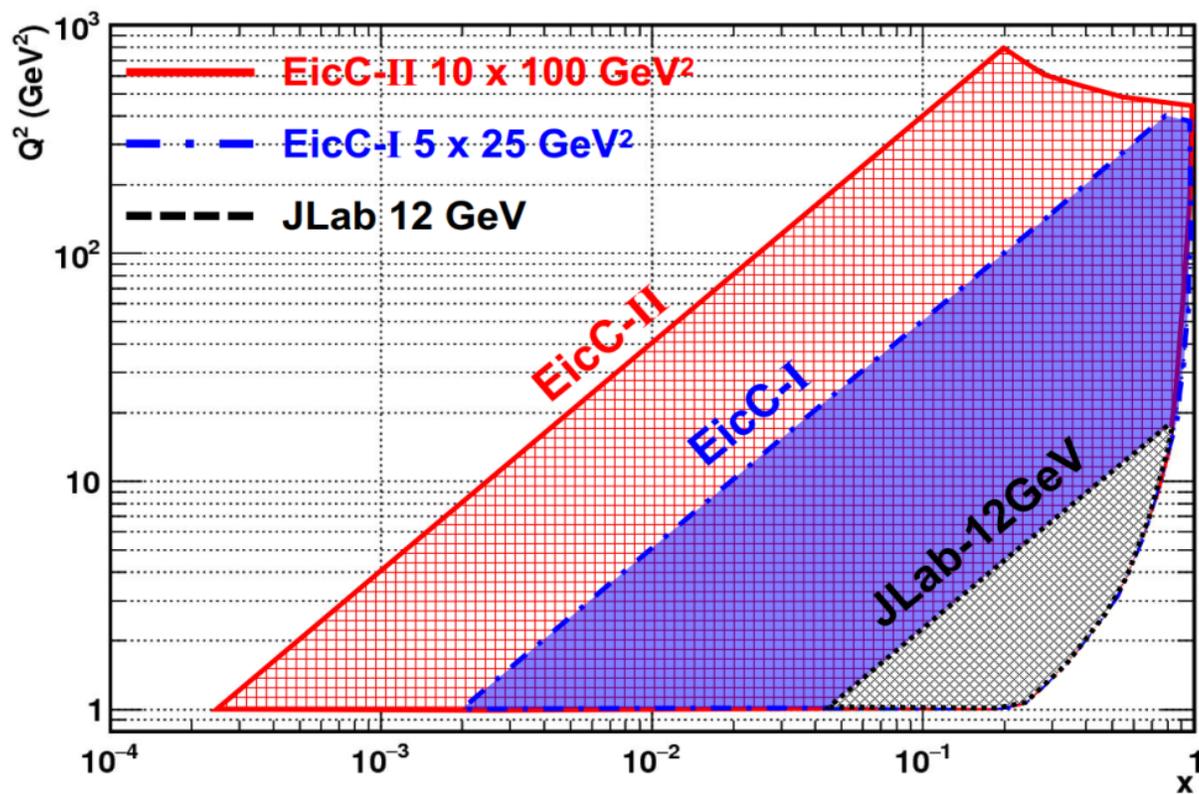
**HIAF-II**

**HIAF-I**

# Comparisons: Luminosity and Energy



# Kinematics Coverage



# Overview of EIC Experiments

A Key Question for EIC:

“How are the sea quarks and gluons, and their spins distributed in space and momentum inside the nucleon?”

- Spin and Flavor Structure of the Nucleon
- 3-d Structure in Momentum Space and Confined Motion of Partons inside the Nucleon
- 3-d Structure in Coordinator Space and Tomography of the Nucleon

Other Important Questions:

“How does the mass of the nucleon arise?”

“Where does the saturation of gluon densities set in?”

How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?”

Opportunity for Low Energy Search of Physics Beyond SM

- Parity Violating e-N

# Summary

- Understand strong interaction/nucleon structure: A challenge
- Review of History in Nucleon Structure Study
- Electron Scattering: A clean tool to study nucleon structure and QCD
- JLab facility and 12 GeV upgrade  
valence quark structure
- Future Electron-Ion Collider: new QCD frontier  
understand sea quarks and gluons  
Report from NAS review of EIC in US recently released  
  
EicC: precision study of sea quarks and high  $Q^2$  valence region

# Nucleon 3-D Structure

## *II: Nucleon Structure Study: From 1-D to 3-D*

- Electron Scattering
- Elastic Scattering: From Factors
  - Surprise:  $G_E^p$  @ high  $Q^2$ : proton shape, 2- $\gamma$  exchange
  - Proton radius puzzle
- Deep-Inelastic Scattering (DIS):
  - Unpolarized Structure Functions  $\rightarrow$  Parton Distribution Functions
  - Polarized Structure Functions  $\rightarrow$  Spin Distributions
  - “Spin Crisis/Puzzle”, Spin Decompositions
  - Orbital Angular Momentum  $\rightarrow$  Transverse Structure
- Needs to Study 3-D Structure

# Nucleon Form Factors

**Charge and Magnetization Distributions**  
**Transverse Density**

# Elastic Scattering on a Proton

From relativistic quantum mechanics one can derive the the formula electron-proton scattering where one has assumed the exchange of a single virtual photon.

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot \frac{E'}{E} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \frac{\theta}{2} \right]$$

where  $G_E$  and  $G_M$  form factors take into account the finite size of the proton.

$$G_E = G_E(Q^2), G_M = G_M(Q^2); G_E(0)=1, G_M(0) = \mu_p$$

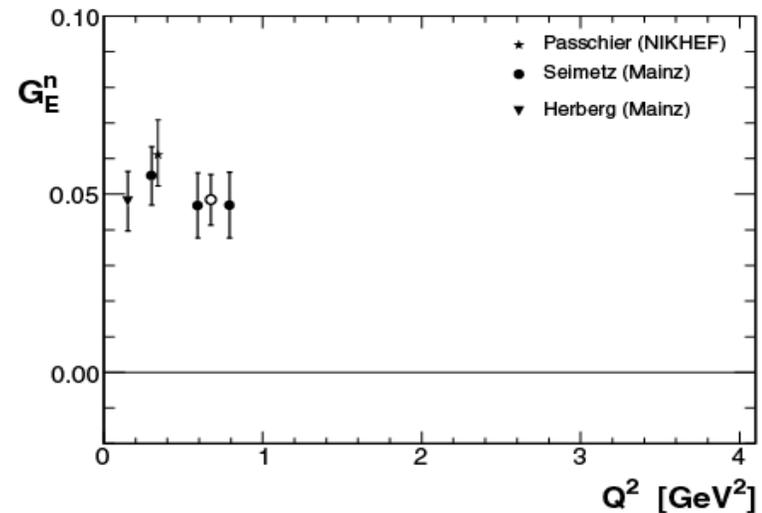
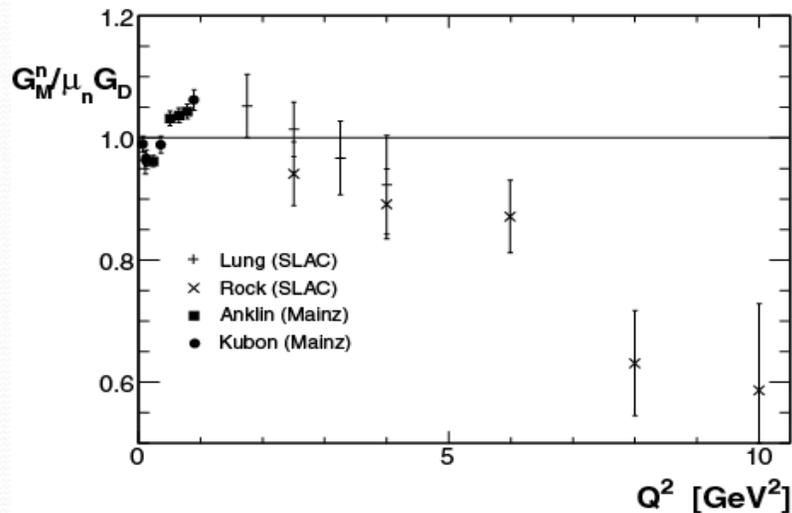
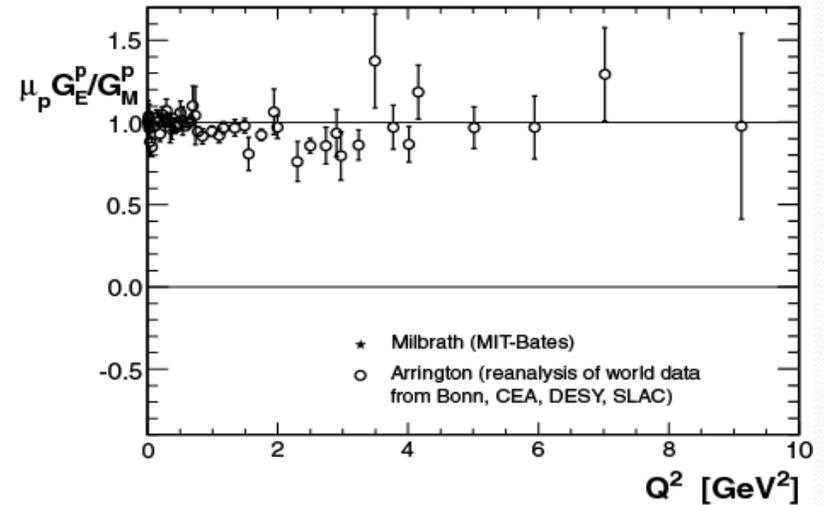
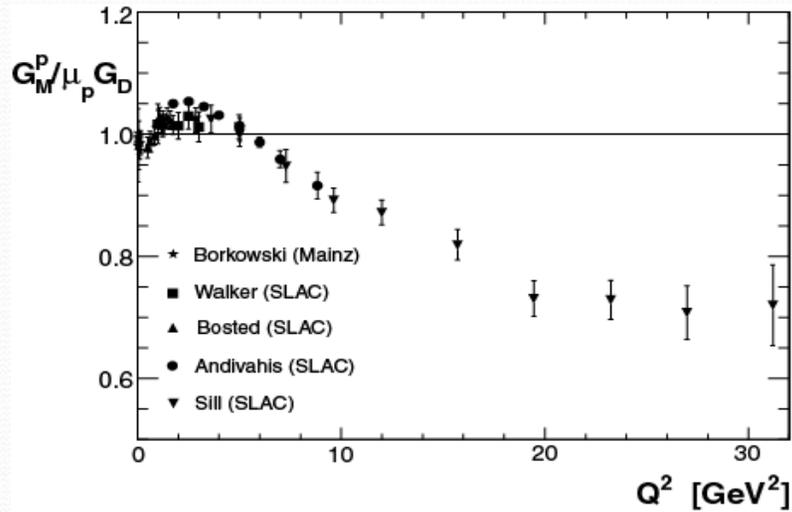
$$Q^2 = 4 E E' \sin^2(\theta/2) \text{ and } \tau = Q^2 / 4m_p^2$$

Elastic cross sections at small angles and small  $Q^2$ 's are dominated by  $G_E$  ( Prad Hall B )

Elastic cross Sections at small angles and small  $Q^2$ 's are dominated by  $G_M$  ( GMP Hall A )

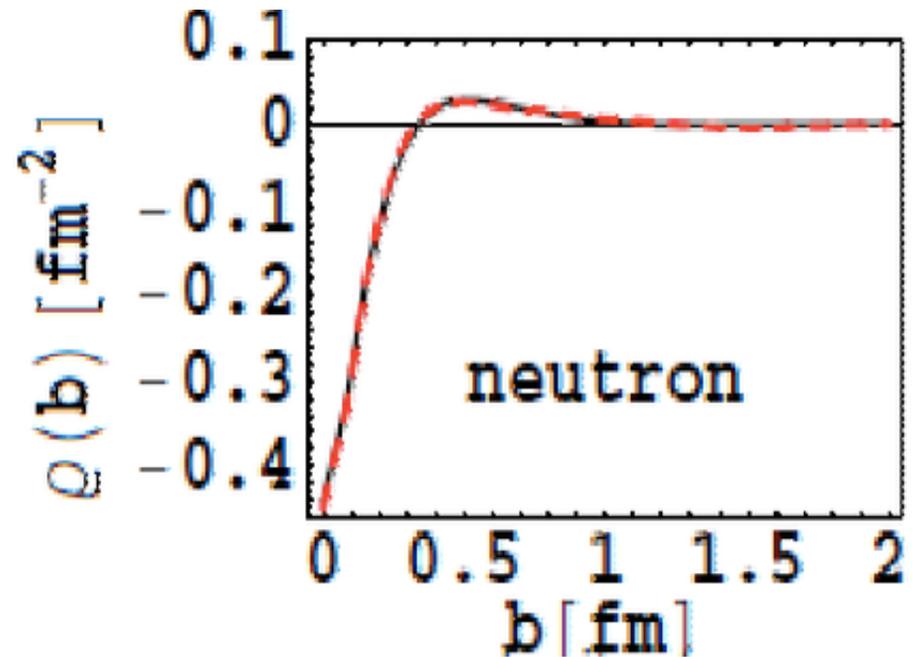
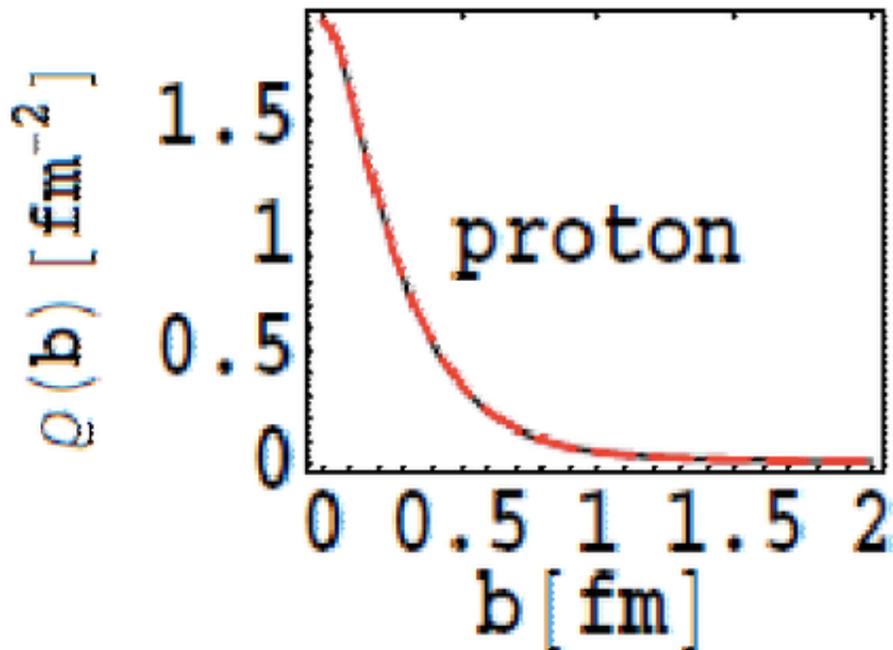
For moderate  $Q^2$ 's one can separate  $G_E$  and  $G_M$  with Rosenbluth or asymmetry measurements.

# Before JLab and Recent non-JLab Data



# Form Factors $\rightarrow$ Charge/Current Distributions (non-relativistic)

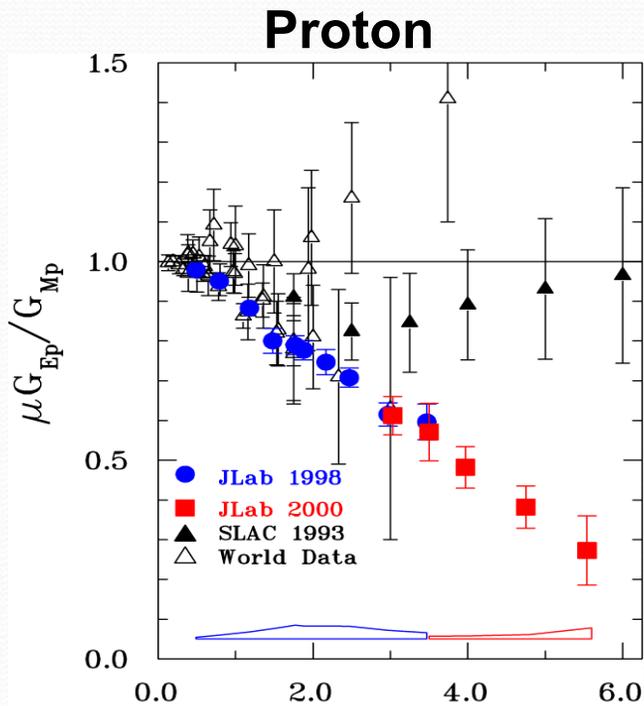
Elastic electric form factor  $\rightarrow$  Charge distributions



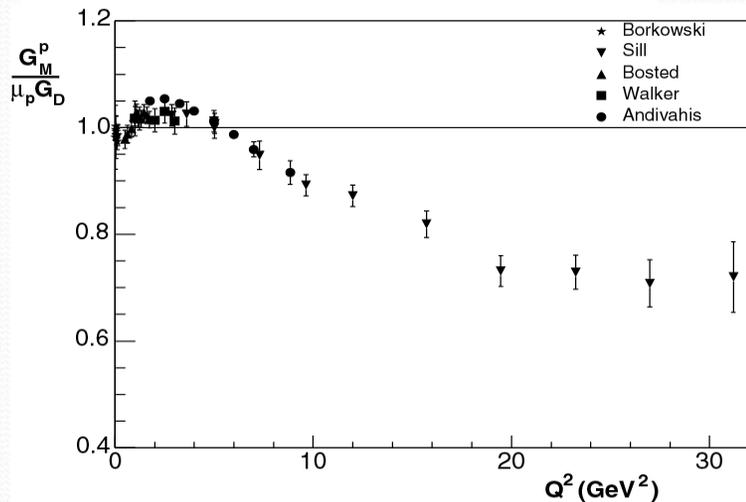
# JLab Data on EM Form Factors

## Testing Ground for Theories of Nucleon Structure

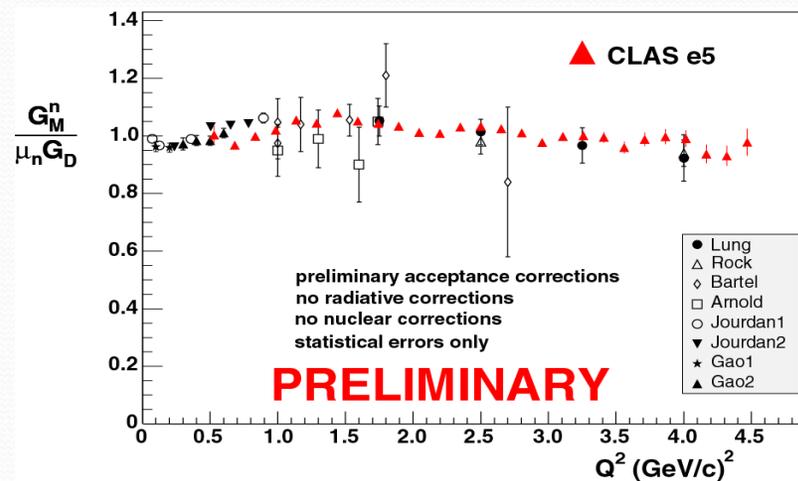
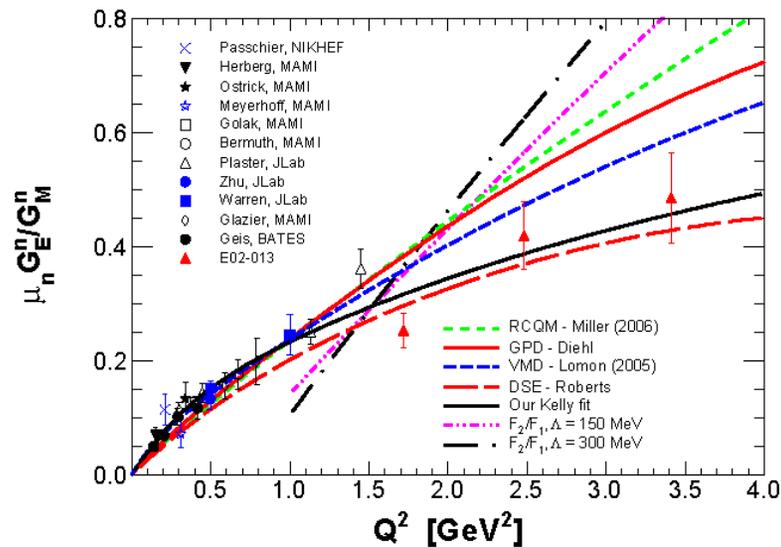
Electric



Magnetic



### Neutron



# $G_E^p$ : JLab Polarization-Transfer Data

Using Focal Plane Polarimeter in Hall A

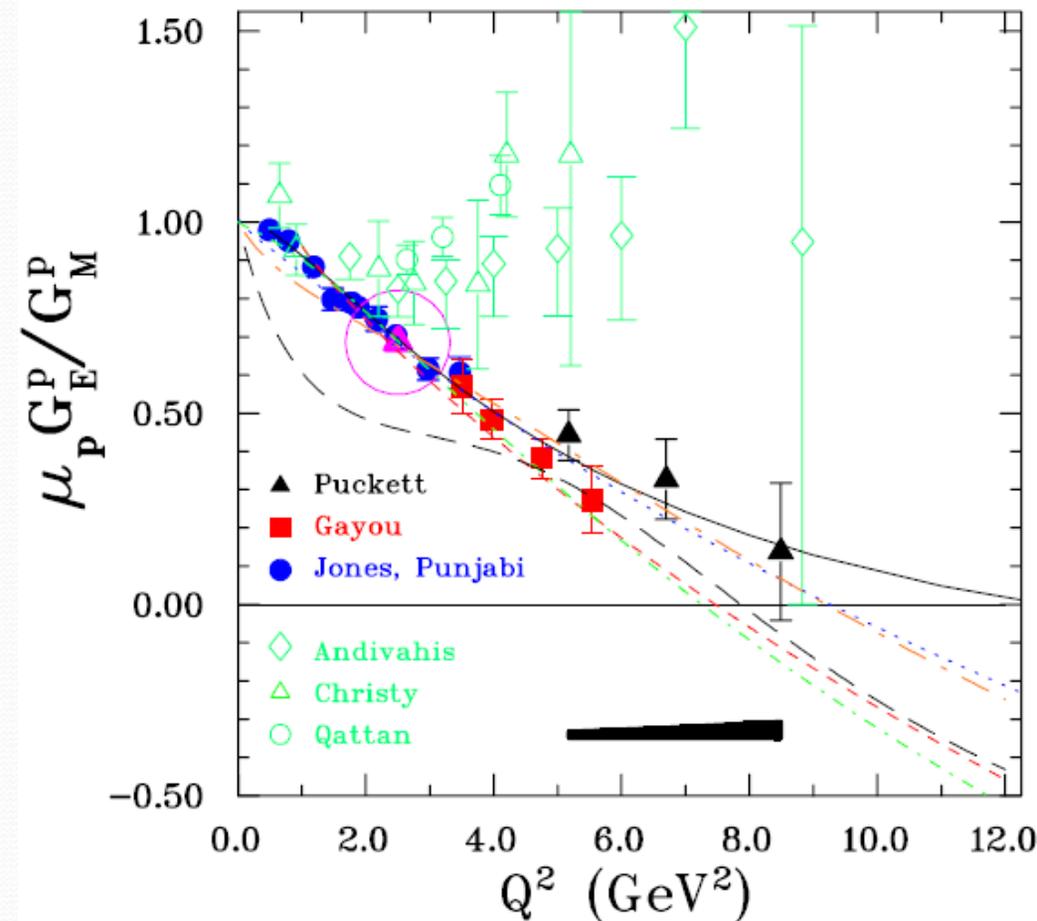
- E93-027 PRL 84, 1398 (2000)
- E99-007 PRL 88, 092301 (2002)
- E04-108, [arXiv:1005.3419v2](https://arxiv.org/abs/1005.3419v2) (2010)

Clear discrepancy between polarization transfer and Rosenbluth data

- Investigate possible theoretical sources for discrepancy  
→ likely two-photon contributions

Information on the shape of the proton and the orbital angular momentum.

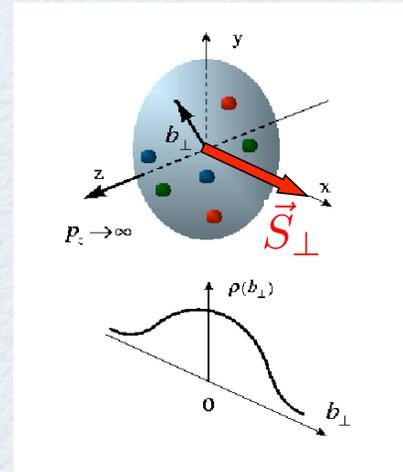
Transverse density .



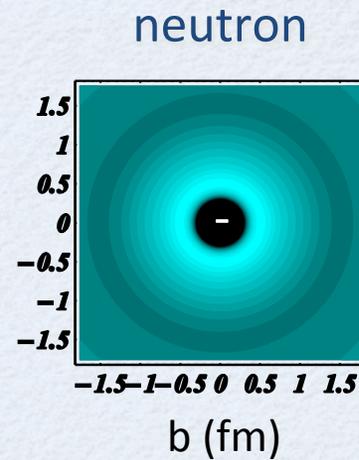
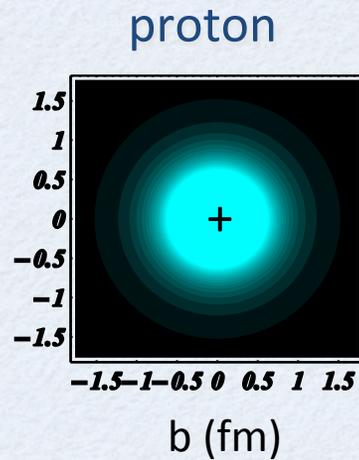
# Form factors: 2D light-front densities of hadrons

$$\rho^N(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(bQ) F_2(Q^2)$$

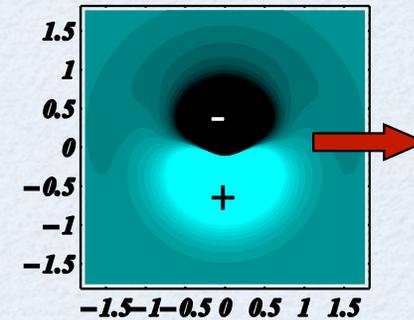
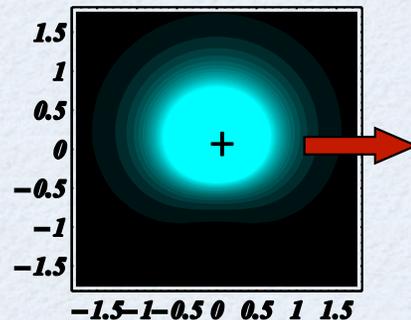
→ unpolarized Dirac FF  $F_1$   
 → transverse polarization Pauli FF  $F_2$



unpolarized charge density



density for transverse polarization



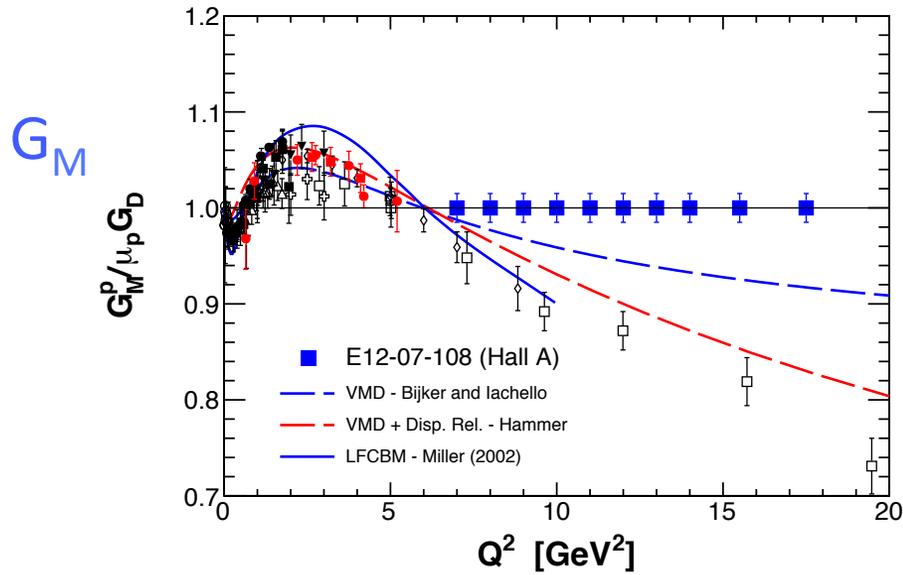
Burkardt (2000, 2003)

Miller (2007)

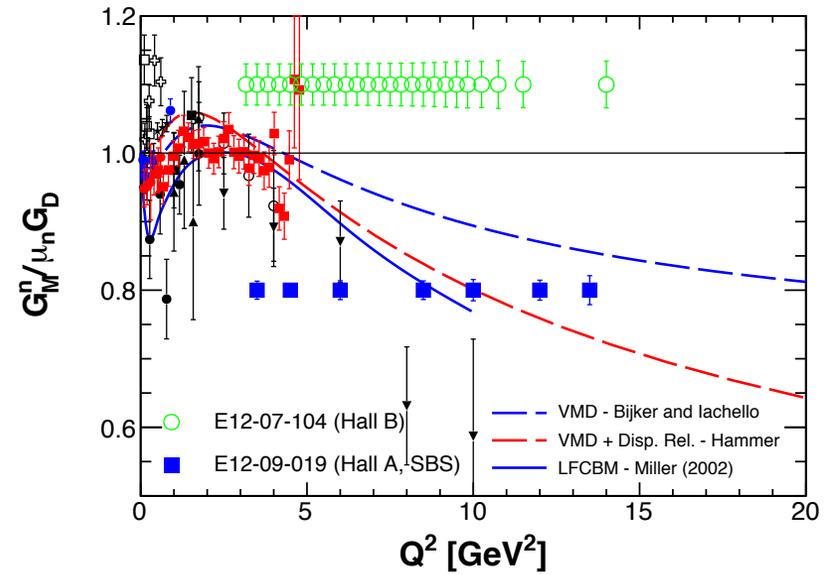
Carlson, Vdh (2008)

# Planned JLab Measurements of Form Factors

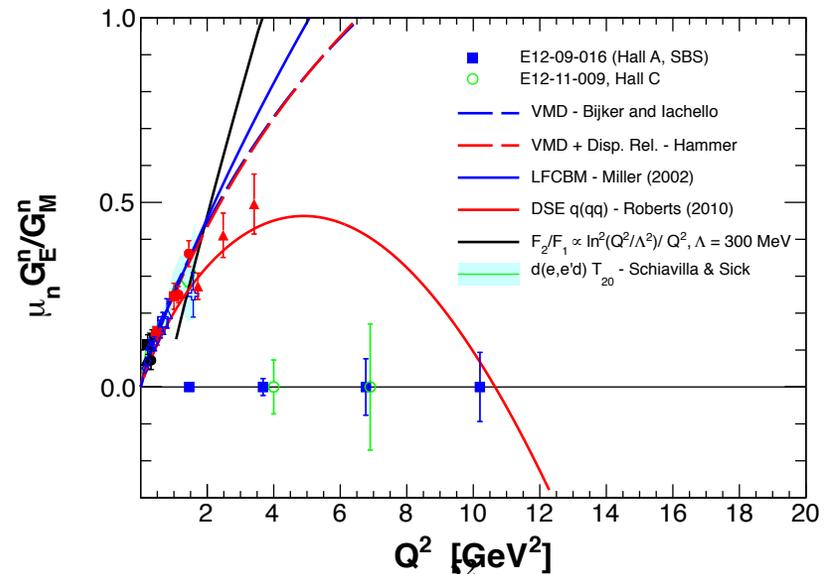
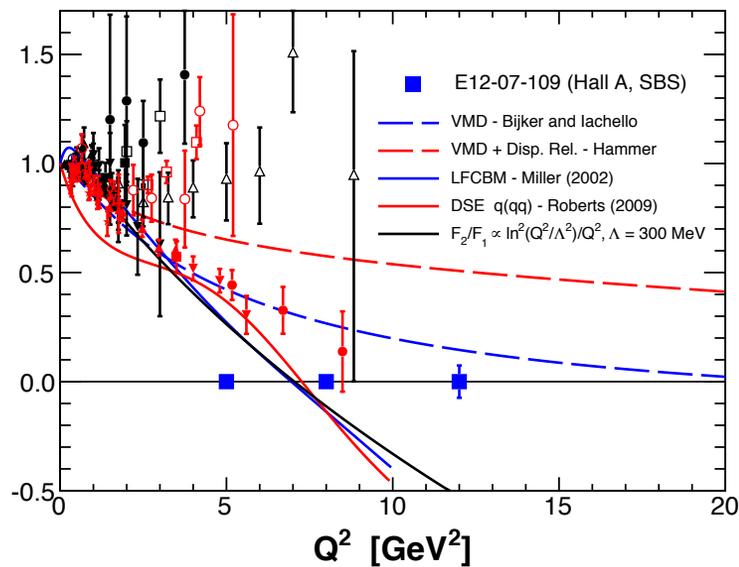
Proton



Neutron



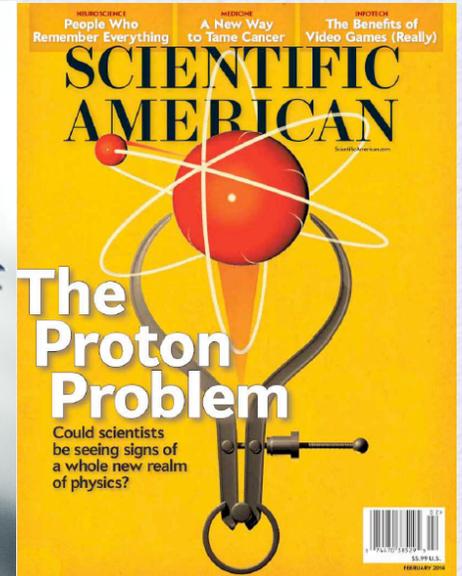
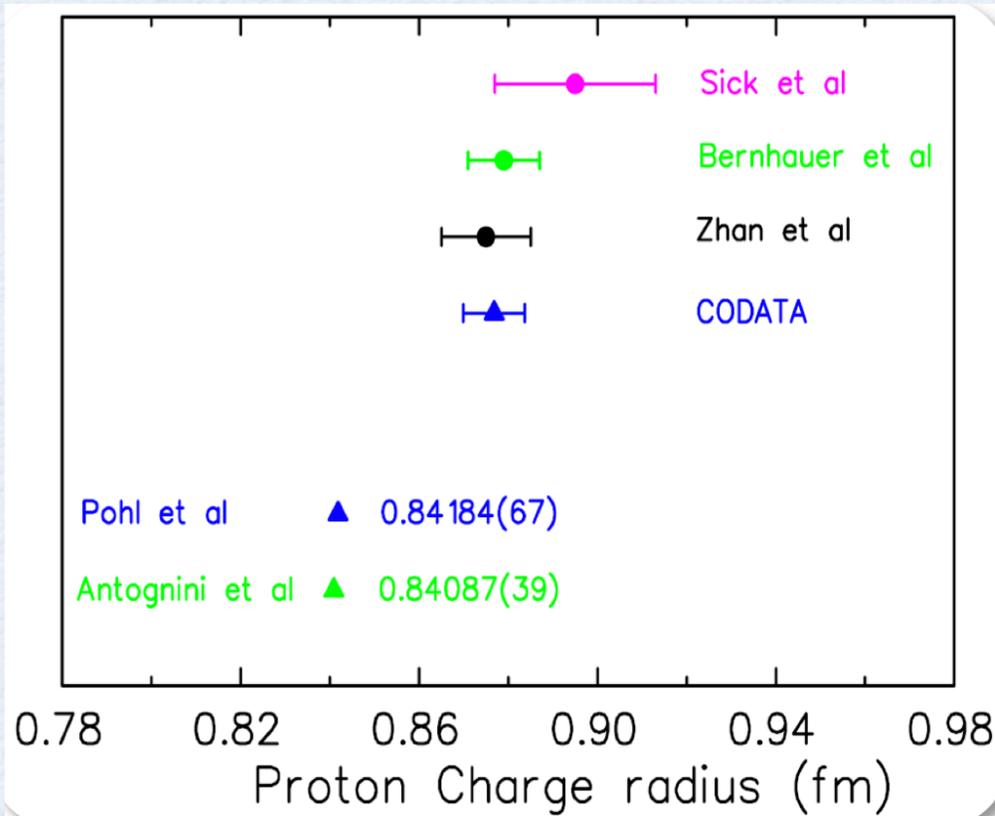
$G_E$



# Proton Radius Puzzle

**Electron probe vs. muon probe**

# Proton radius puzzle



**$\mu\text{H}$  data:**

$$R_E = 0.8409 \pm 0.0004 \text{ fm}$$

Pohl et al. (2010)

Antognini et al. (2013)



**$7 \sigma$  difference !?**

**$e\text{p}$  data:**

$$R_E = 0.8775 \pm 0.0051 \text{ fm}$$



# Proton radius puzzle: what's next ?

- ➔  $\mu\text{H}$  Lamb shift: muonic D, muonic  $^3\text{He}$ ,  $^4\text{He}$  have been performed
- ➔ electronic H Lamb shift: higher accuracy measurements underway
- ➔ electron scattering analysis: **Lorenz et al.**
  - radius extraction fits (use fits with correct analytical behavior:  $2\pi$  cut)
  - radiative corrections, two-photon exchange corrections

new fit  $R_E = 0.904(15)$  fm ( $4\sigma$  from  $\mu\text{H}$ ) **Lee, Arrington, Hill (2015)**

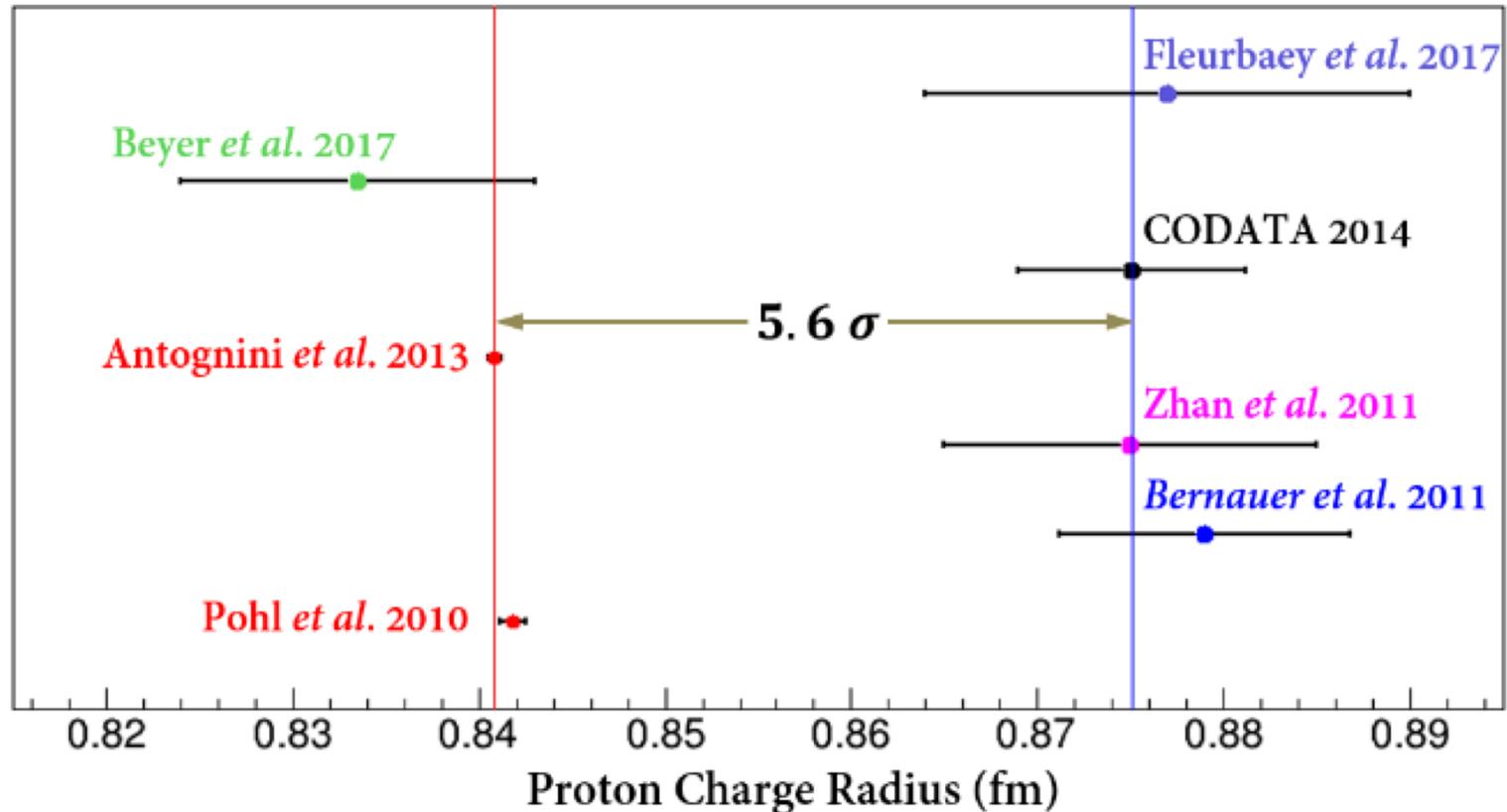
➔ electron scattering experiments:  
new  $G_{Ep}$  experiments down to  $Q^2 \approx 2 \times 10^{-4}$   $\text{GeV}^2$

- **MAMI/A1**: Initial State Radiation (2013/4)
- **JLab/Hall B**: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)  
see talk: H. Gao
- **MESA**: low-energy, high resolution spectrometers (2019)

➔ muon scattering experiments: **MUSE@PSI** (2017/8)

➔  $e^-e^+$  versus  $\mu^- \mu^+$  photoproduction: lepton universality test

# Proton Radius Puzzle



- CODATA recommended value
- Recent experimental results
  - Muonic hydrogen spectroscopy (Antognini, Pohl)
  - Ordinary hydrogen spectroscopy (Beyer, Fleurbaey)
  - Elastic ep-scattering measurements (Bernauer, Zhan)
  - **Latest from York University on hydrogen spectroscopy (this week!)**

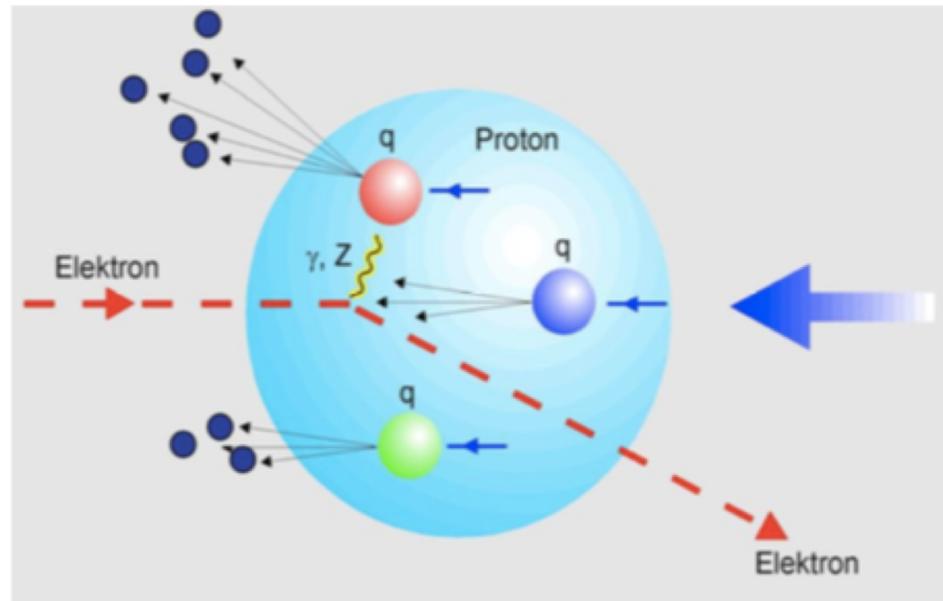
# Deep-Inelastic Scattering Unpolarized Structure Functions

Parton Distribution Functions

# How to “see” substructure of a nucleon?

## □ Modern Rutherford experiment – Deep Inelastic Scattering:

SLAC 1968:  $e(p) + h(P) \rightarrow e'(p') + X$



✧ Localized probe:

$$Q^2 = -(p - p')^2 \gg 1 \text{ fm}^{-2}$$

➔  $\frac{1}{Q} \ll 1 \text{ fm}$

✧ Two variables:

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N \nu}$$

$$\nu = E - E'$$

➔ Discovery of spin 1/2 quarks, and partonic structure!



What holds the quarks together?

➔ The birth of QCD (1973)

– Quark Model + Yang-Mill gauge theory



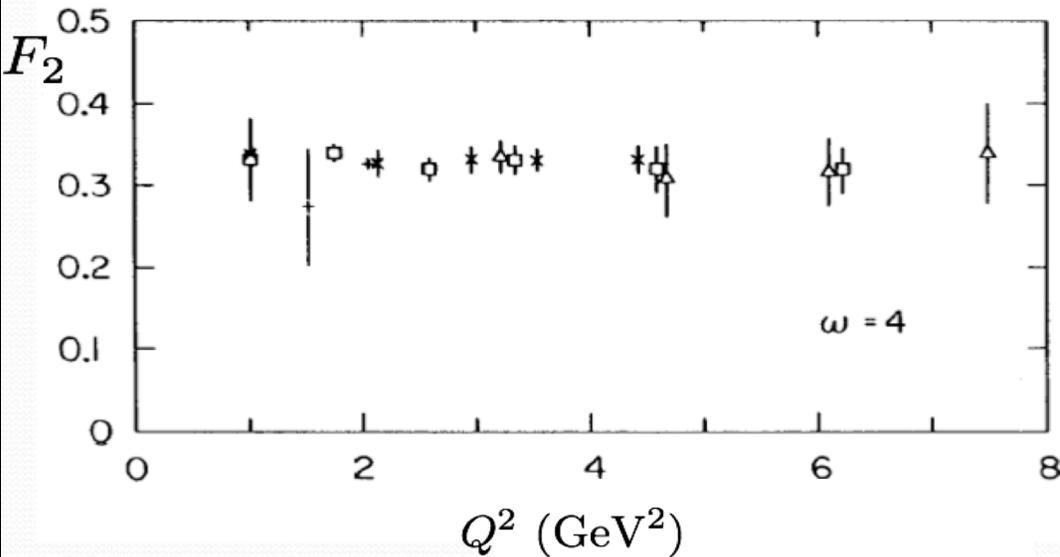
Nobel Prize, 1990

# Deep-Inelastic Electron Scattering

## Discovery of Quarks (Partons)

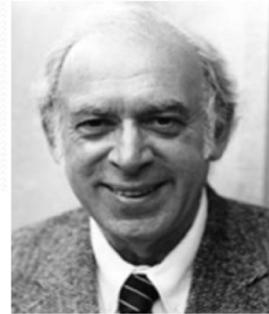
**Bjorken scaling:**

+ 6°    □ 18°  
 × 10°    △ 26°



**Point particles cannot be further resolved; their measurement does not depend on wavelength, hence  $Q^2$ ,**

**Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.**



J.T. Friedman



R. Taylor

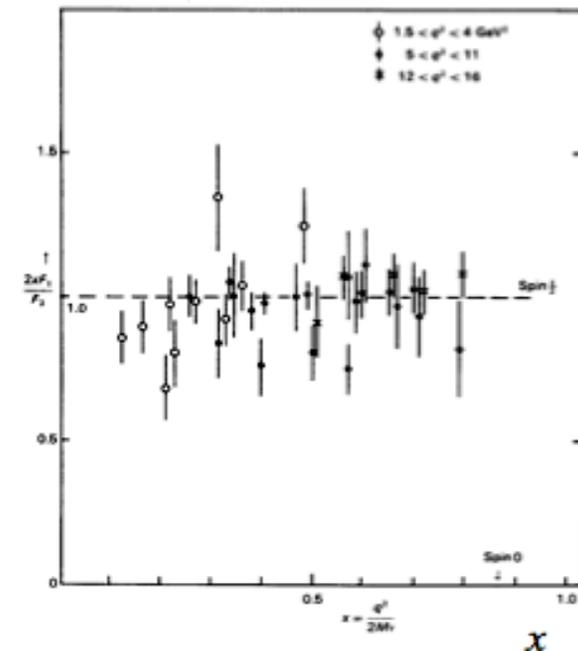


H.W. Kendall

**Nobel Prize 1990**

**Callan-Gross relation:**

$$\frac{2xF_1}{F_2}$$



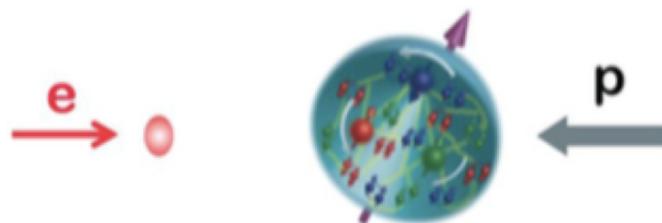
spin 1/2

spin 0

# QCD factorization

- The key and a first principle method to relate experimental data to QCD theory

- Electron-hadron:



$$\sigma_{\text{tot}}^{\text{DIS}} = \text{Hard-part Probe} \otimes \text{Parton-distribution Structure} + O\left(\frac{1}{QR}\right)$$

The diagram shows the factorization of the total DIS cross-section. On the left, a Feynman diagram labeled 'Hard-part Probe' shows an incoming electron ( $e^-$ ) with momentum  $k$  interacting with a quark ( $q$ ) inside a hadron with momentum  $xP$ . The quark then emits a photon. This is multiplied by a diagram labeled 'Parton-distribution Structure' which shows a hadron with momentum  $P$  containing a parton with momentum  $k$  and a distribution function  $J(x)$ . The result is the total cross-section plus a higher-order correction term  $O(1/QR)$ .

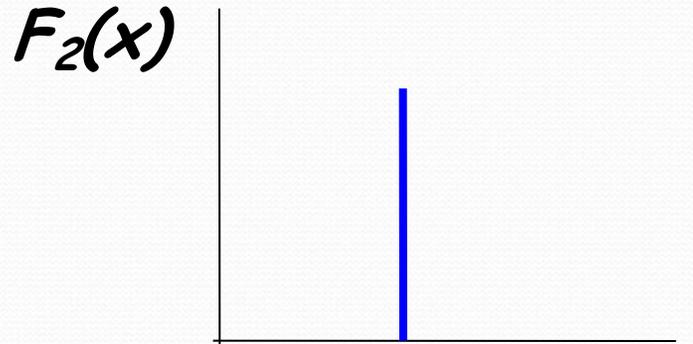
**Hard-part  
Probe**

**Parton-distribution  
Structure**

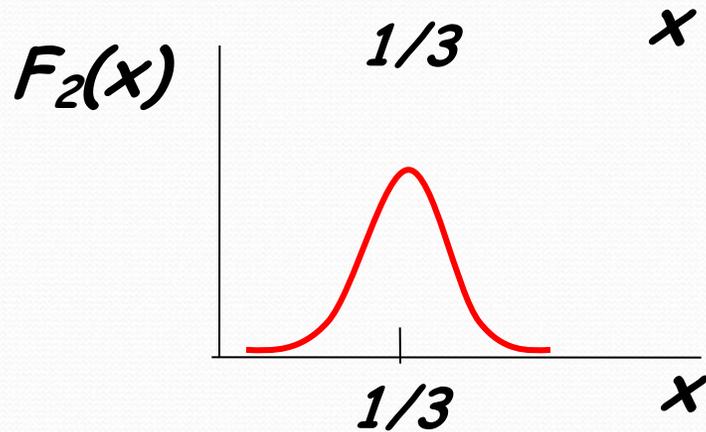
**Correction  
Approximation**

- PDFs: encoding most nonperturbative information in hadron collision

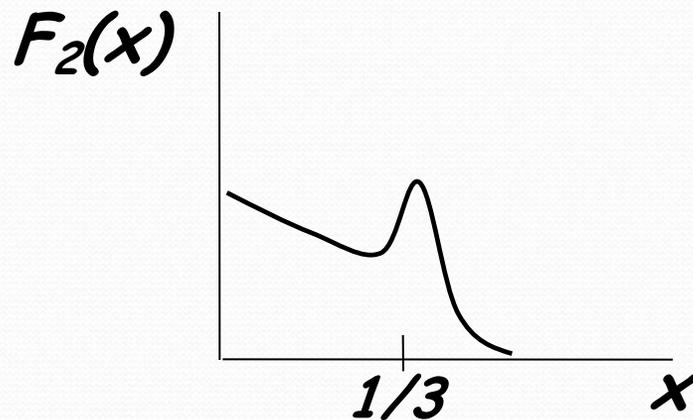
# Nucleon Structure



*Three quarks with 1/3 of total proton momentum each.*



*Three quarks with some momentum smearing.*



*The three quarks radiate gluons to lower momentum fractions  $x$ .*

# Quark-Parton Model

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 f_i(x) \quad g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$$

$$f_i(x) = q_i^\uparrow(x) + q_i^\downarrow(x)$$

$$\Delta q_i(x) = q_i^\uparrow(x) - q_i^\downarrow(x)$$

$q_i(x)$  quark momentum distributions of flavor  $i$

$\uparrow(\downarrow)$  parallel (antiparallel) to the nucleon spin

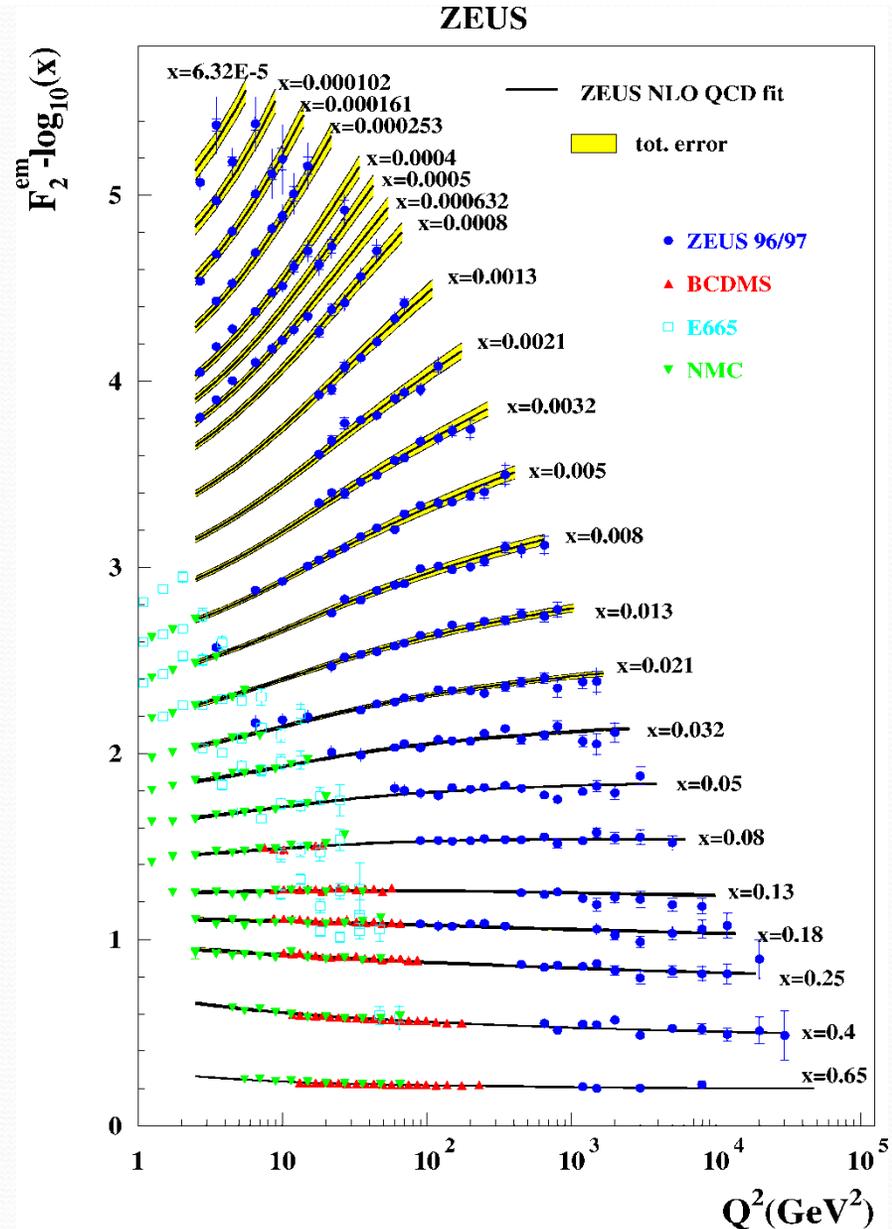
$$F_2 = 2xF_1 \quad g_2 = 0$$

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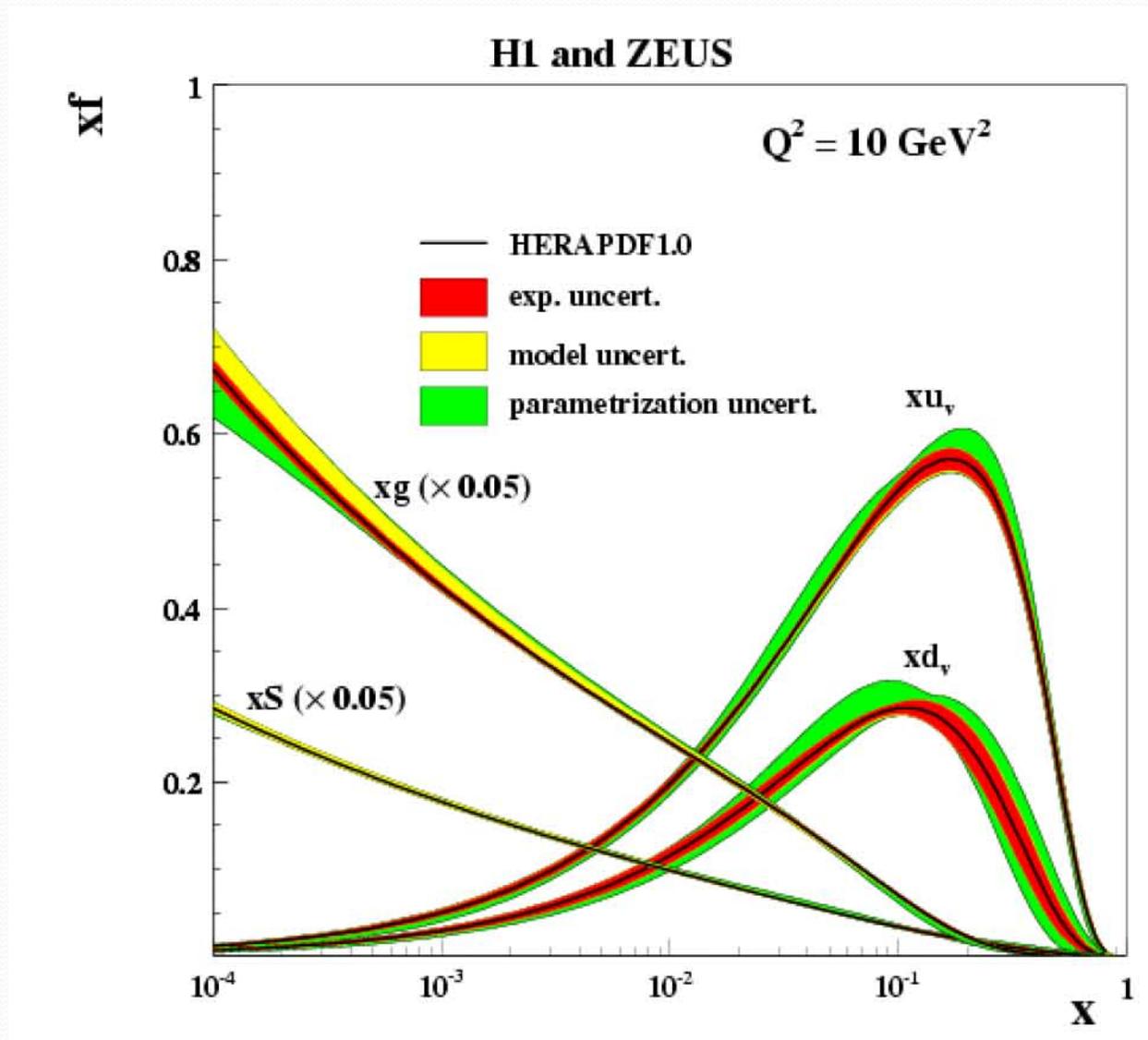
$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum \Delta q_i(x)}{\sum f_i(x)}$$

# Unpolarized Structure Function $F_2$

- Bjorken Scaling
- Scaling Violation
- Gluon radiation –
- QCD evolution
- NLO: Next-to-Leading-Order
- One of the best experimental tests of QCD



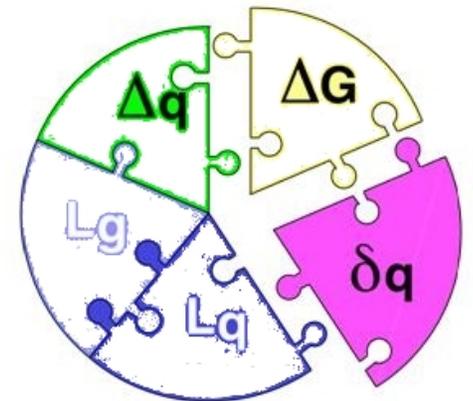
# Parton Distribution Functions (CTEQ6)



JHEP 1001: 109 (2010)

# Polarized Deep-Inelastic Scattering Polarized Structure Functions

Spin Distributions, “Spin Crisis/Puzzle”  
Orbital Angular Momentum



# Spin Milestones (I)

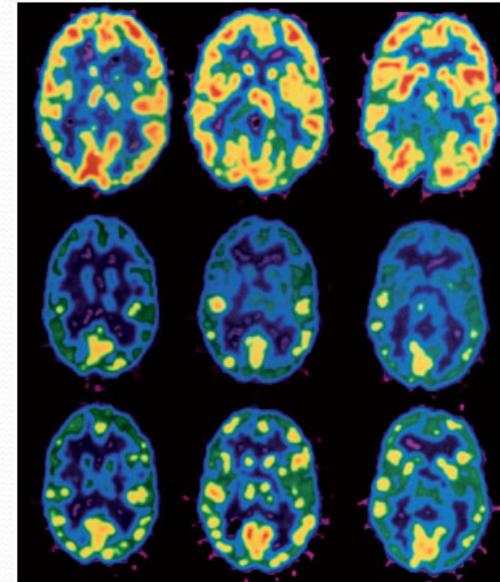
- Nature: ([www.nature.com/milestones/milespin](http://www.nature.com/milestones/milespin))
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - **1935: Proton anomalous magnetic moment**
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1950s: Development of magnetic devices (9)
  - 1950-51: 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)



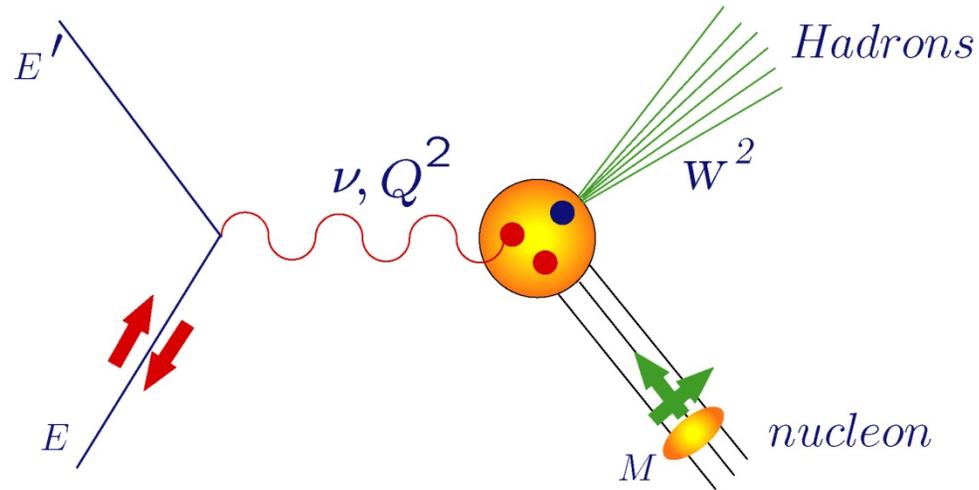
**Pauli and Bohr watch a spinning top**

# Spin Milestones (II)

- 1973: Magnetic resonance imaging(15)
- 1975-76:NMR for protein structure determination (16)
- 1978: Dilute magnetic semiconductors (17)
- 1980s: “Proton spin crisis or puzzle”
- 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)
- (Spin-polarized suprecurrents for spintronics, 1/2011)
- 2000s: “Nucleon transverse spin puzzle”?
- ? : More puzzles in nucleon spin?
- .....
- ? : Breakthroughs in nucleon spin/nucleon structure study?
- .....
- ? : Applications of nucleon spin physics?



# Polarized Deep Inelastic Electron Scattering



$$x = \frac{Q^2}{2M\nu} \quad \text{Fraction of nucleon momentum carried by the struck quark}$$

$Q^2 = 4\text{-momentum transfer of the virtual photon, } \nu = \text{energy transfer, } \theta = \text{scattering angle}$

- All information about the nucleon vertex is contained in
  - $F_2$  and  $F_1$  the unpolarized (spin averaged) structure functions,
  - and
  - $g_1$  and  $g_2$  the spin dependent structure functions

# Cross Section & Spin Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2 \frac{\theta}{2}}{Q^4} \left[ \frac{F_2}{\nu} + 2\frac{F_1}{M} \tan^2 \frac{\theta}{2} \right]$$

$$\frac{d^2\sigma}{dE' d\Omega} (\downarrow\uparrow - \uparrow\uparrow) = \frac{4\alpha^2 E'}{MQ^2 \nu E} \left[ (E + E' \cos \theta) g_1 - \frac{Q^2}{\nu} g_2 \right]$$

$$\frac{d^2\sigma}{dE' d\Omega} (\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin \theta E'^2}{MQ^2 E \nu^2} (\nu g_1 + 2E g_2)$$

# Quark-Parton Model

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 f_i(x) \quad g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$$

$$f_i(x) = q_i^\uparrow(x) + q_i^\downarrow(x)$$

$$\Delta q_i(x) = q_i^\uparrow(x) - q_i^\downarrow(x)$$

$q_i(x)$  quark momentum distributions of flavor  $i$

$\uparrow(\downarrow)$  parallel (antiparallel) to the nucleon spin

$$F_2 = 2xF_1 \quad g_2 = 0$$

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$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum \Delta q_i(x)}{\sum f_i(x)}$$

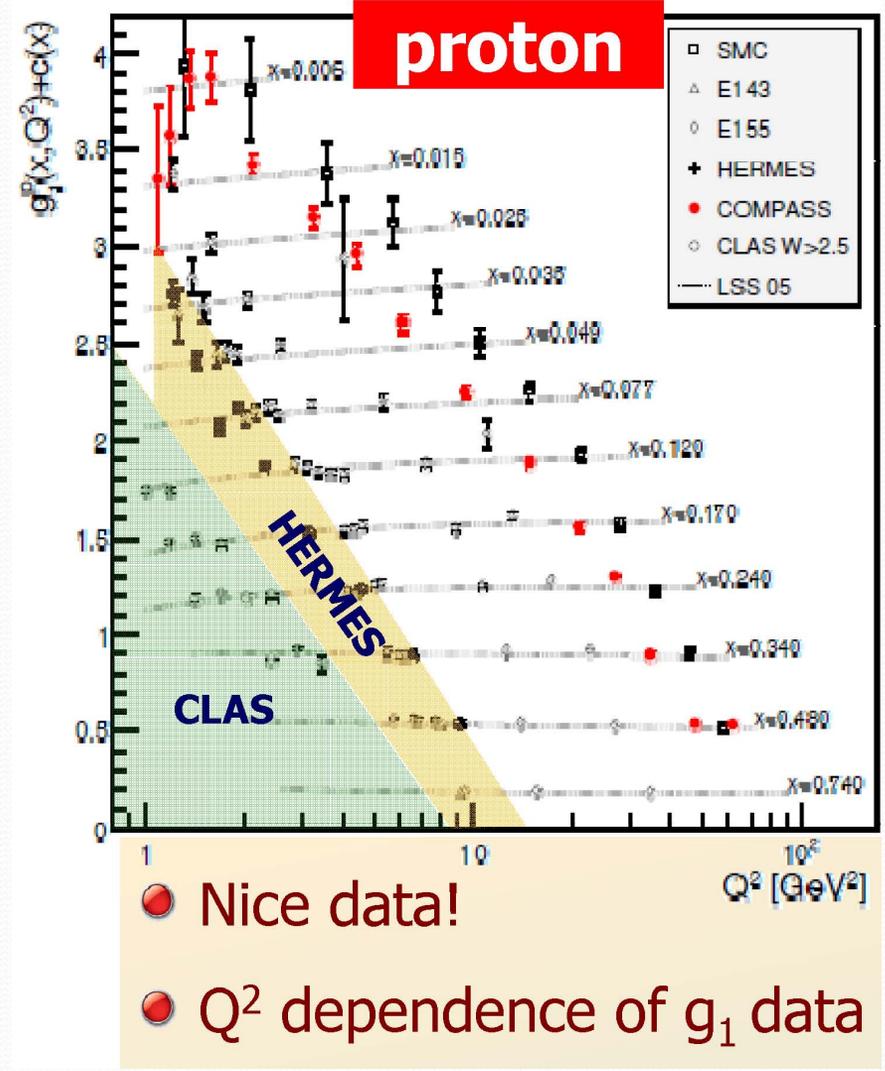
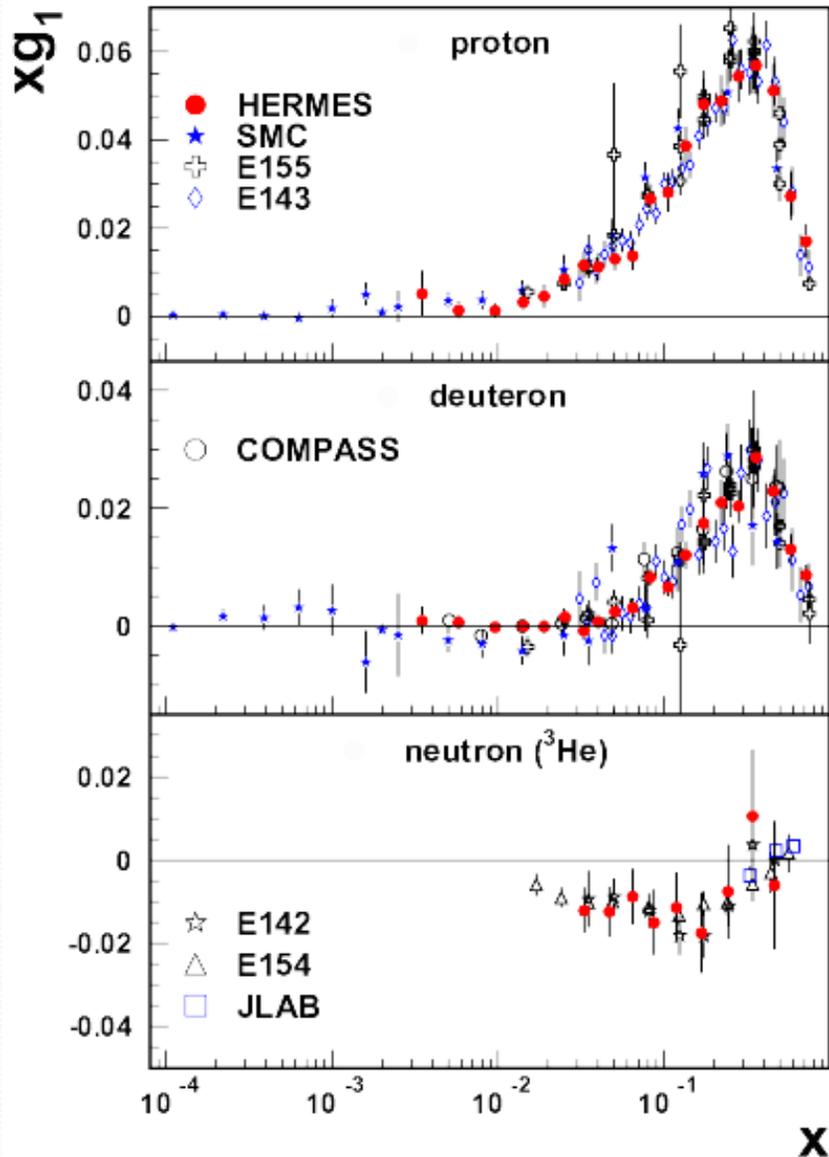
# Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC  
quark contribution to proton spin is very small  
 $\Delta\Sigma = (12+-9+-14)\%$  ! 'spin crisis'
- 1990s: SLAC, SMC (CERN), HERMES (DESY)  
 $\Delta\Sigma = 20-30\%$ , the rest: gluon and quark orbital angular momentum  
 $(\frac{1}{2})\Delta\Sigma + L_q + \Delta G + L_G = 1/2$   
gauge invariant  $(\frac{1}{2})\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$   
Bjorken Sum Rule verified to <10% level
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, ... :  
 $\Delta\Sigma \sim 30\%$ ;  $\Delta G$  contributes, orbital angular momentum significant  
Needs 3-d structure information to complete the proton spin puzzle

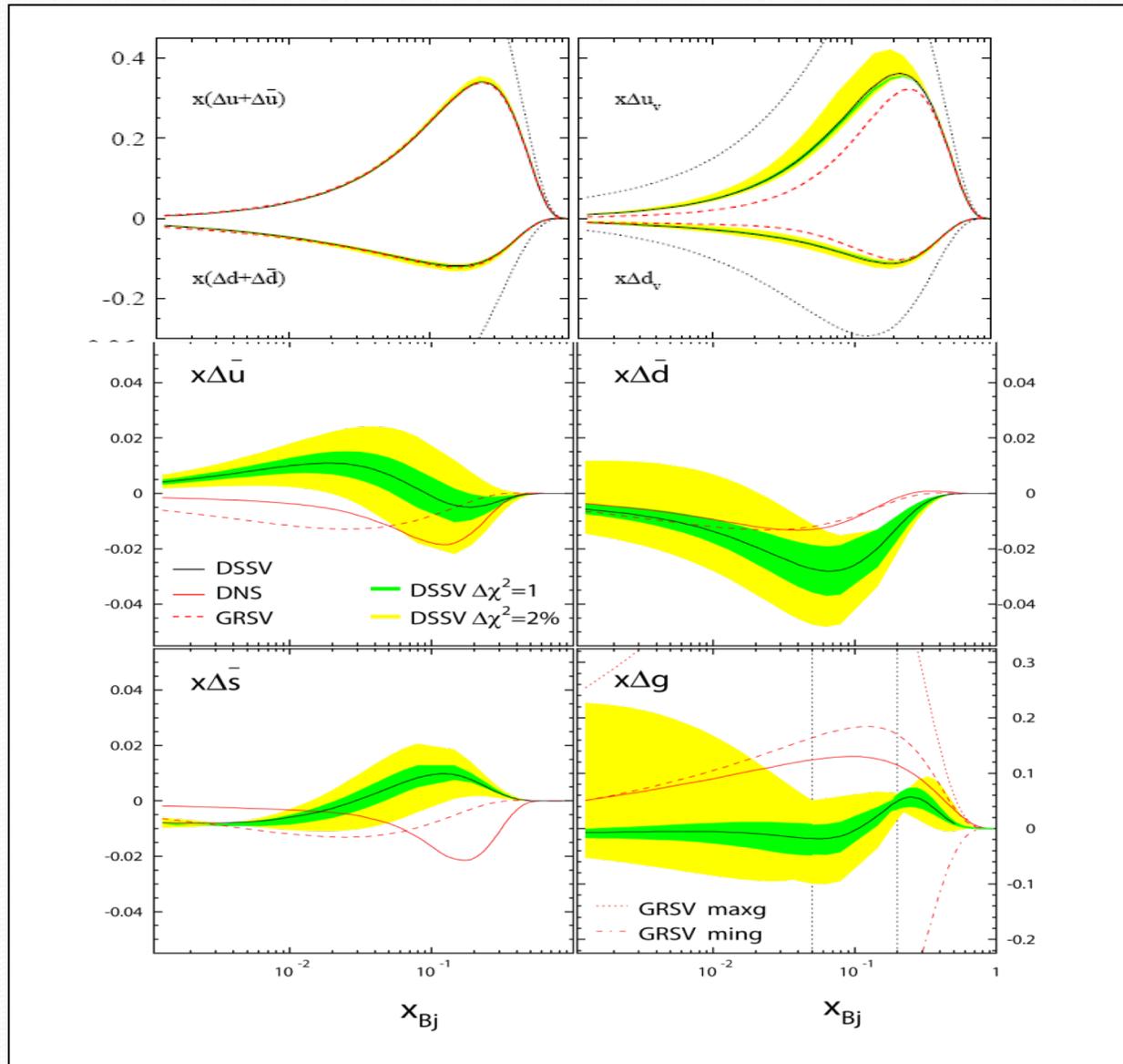
**Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;**

**J. P. Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893**

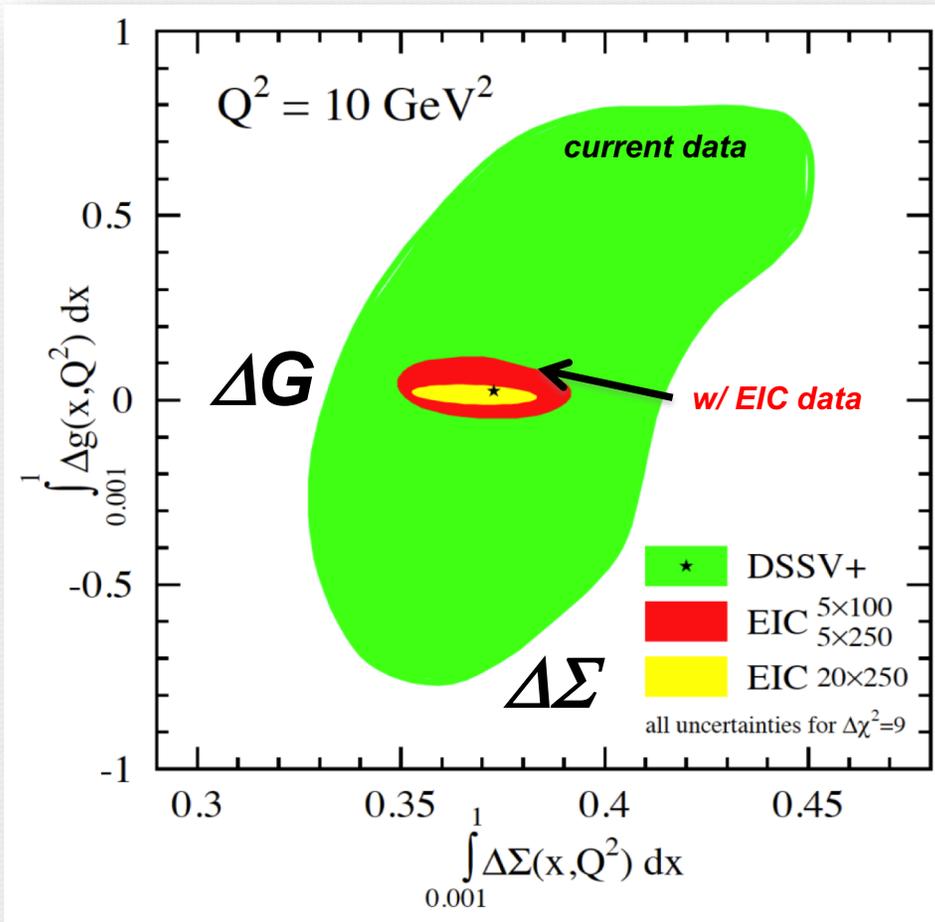
# Polarized Structure functions



# Polarized Parton Distributions



# ***EIC: Are the Gluons Polarized?***



## ***A Polarized EIC:***

- ***Tremendous improvement on  $\Delta G$***
- ***Also improvement in  $\Delta \Sigma$***
- ***Spin Flavor decomposition of the Light Quark Sea***

# Summary

- Electron Scattering to study Nucleon Structure
- Elastic: Form Factors
  - charge/current distributions → transverse density
  - $G_E^p$  @ large  $Q^2$  surprise, proton radius puzzle
- Deep-Inelastic Scattering
  - Precision unpolarized structure functions in large kinematic coverage
  - Parton Distributions, best knowledge on nucleon structure
  - best test of QCD
- Spin Structure Study Full of Surprises and Puzzles
  - Quark spin only contributes 20-30%, Gluon spin contribution is significant
  - Orbital Angular Momentum is important
  - Needs 3-D structure information