Physics with an Electron-Ion Collider

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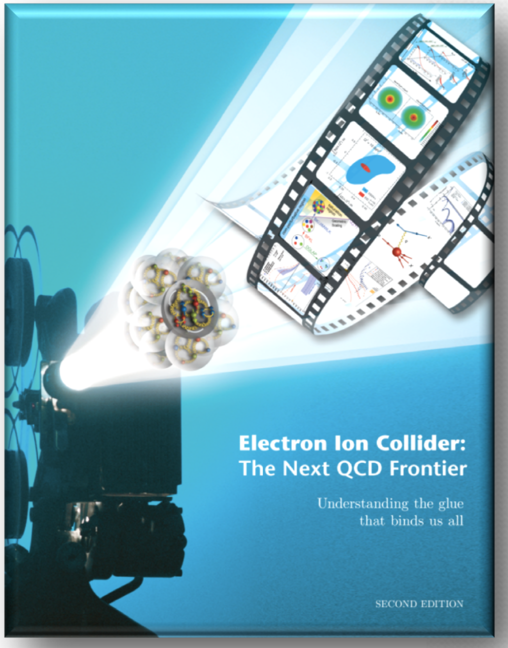
Pre-Workshop Lectures, Hadron-China2018, July 25, 2018

- *I: Introduction, Overview,*
- *II: Form Factors*
- *III: 1-d Structure : Parton Distribution Functions*
- *IV: 3-d Structure: TMDs and GPDs*

Not covered:

- *Spin Structure (Xiaochao Zheng's lecture)*
- *Parity Violation (Xiaochao Zheng's lecture)*
- *Hadron Spectroscopy*
- *Quark Gluon Structure of Nuclei*



Physics with an Electron-Ion Collider

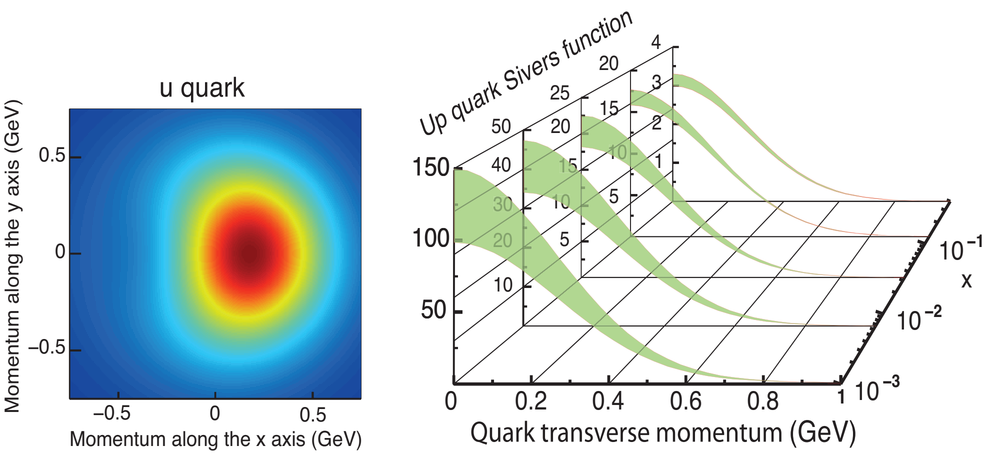
I: Introduction and Overview

- Introduction and History
- Electron (Lepton) As A Clean Probe
- Facilities:

  Fixed Target: SLAC, HERMES, COMPASS, Jefferson Lab, …

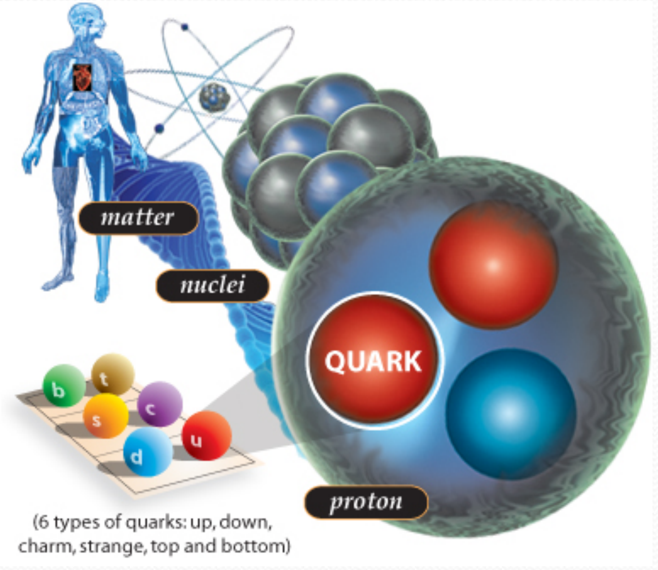
  Electron-Ion Collider : HERA, Future EIC: JLEIC, e-RHIC, EicC, LHeC
- EIC Experiments:

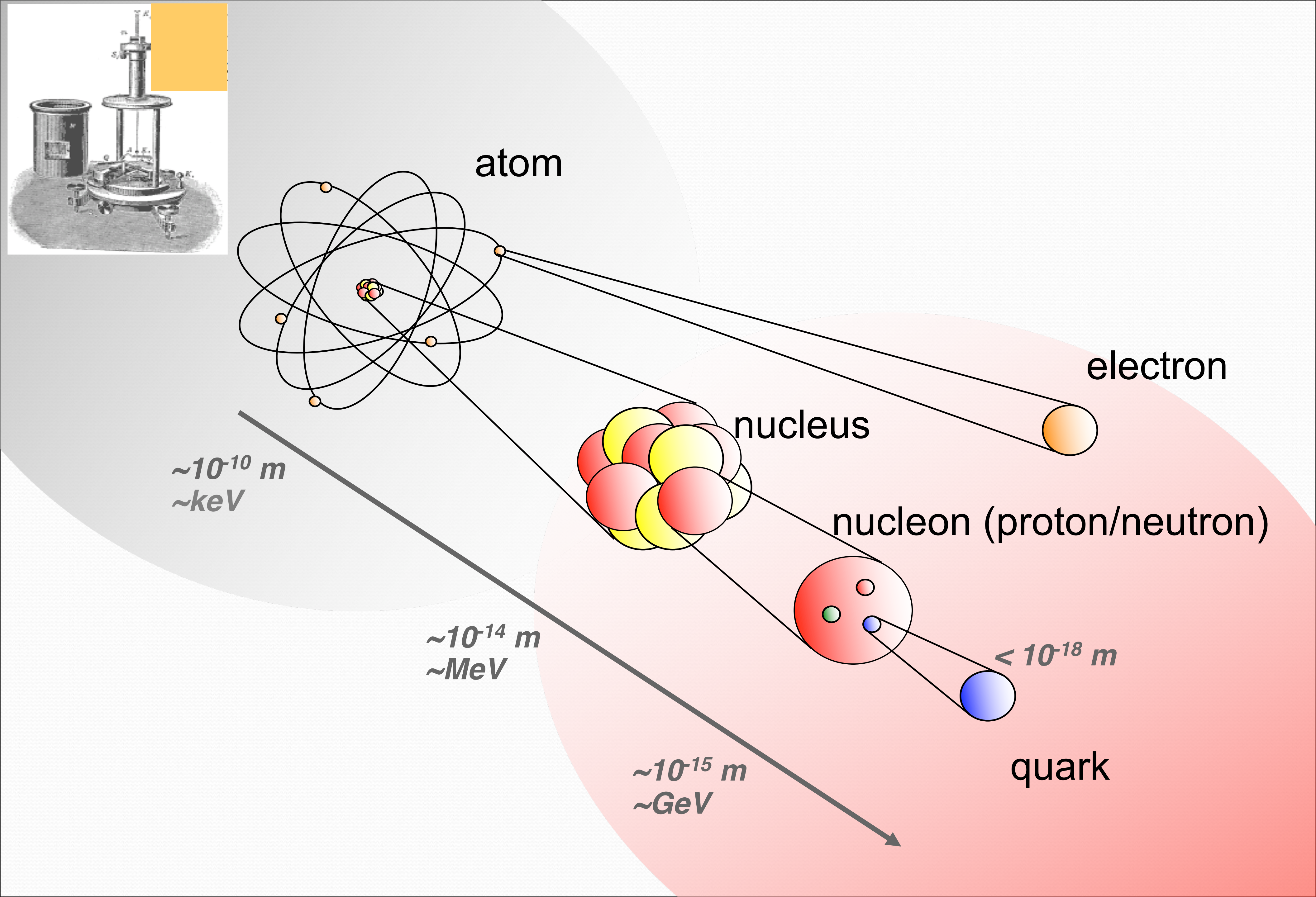
  Focus on e-N



Introduction: What and Why

Nucleon Structure and Strong Interaction (QCD)

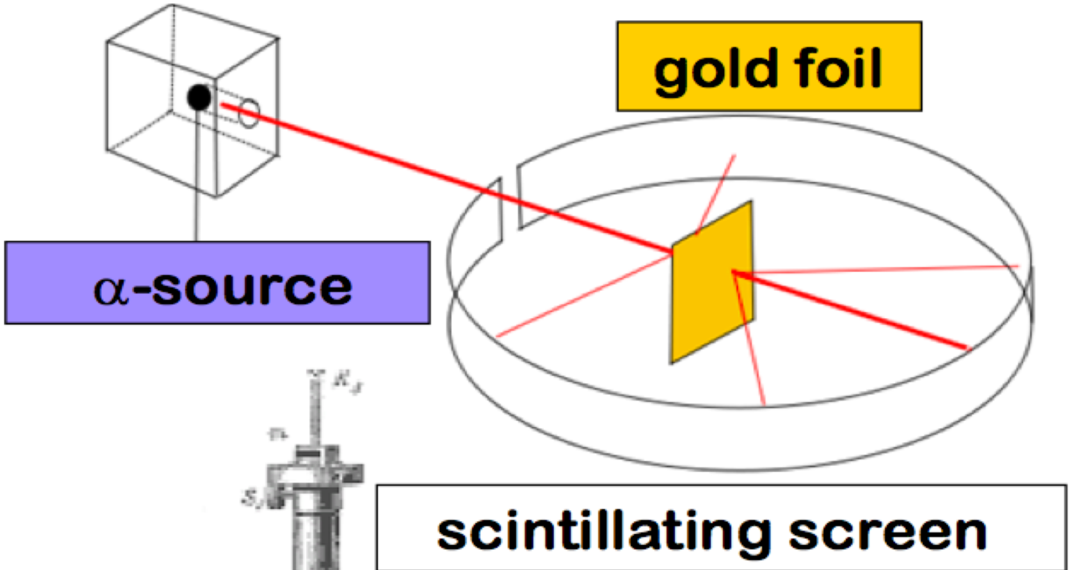


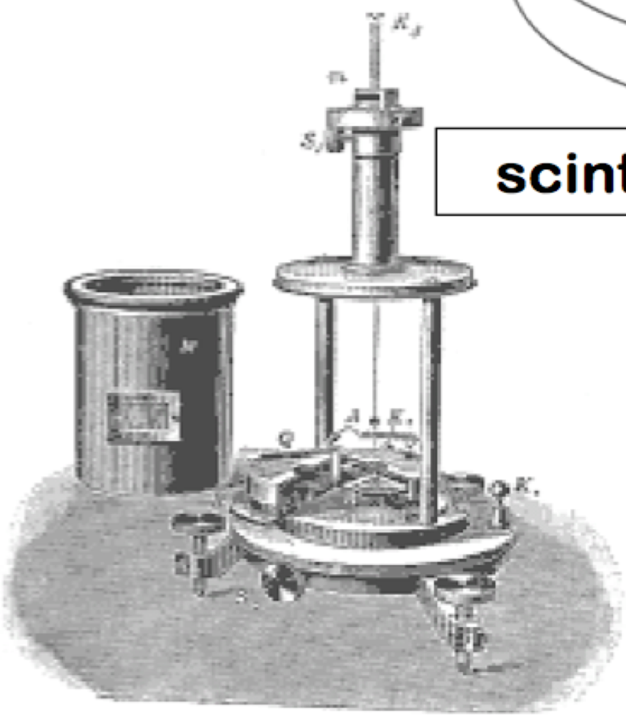

atom
electron
nucleus
nucleon (proton/neutron)
$< 10^{-18}$ m
quark
$\sim 10^{-10}$ m
~keV
$\sim 10^{-14}$ m
~MeV
$\sim 10^{-15}$ m
~GeV

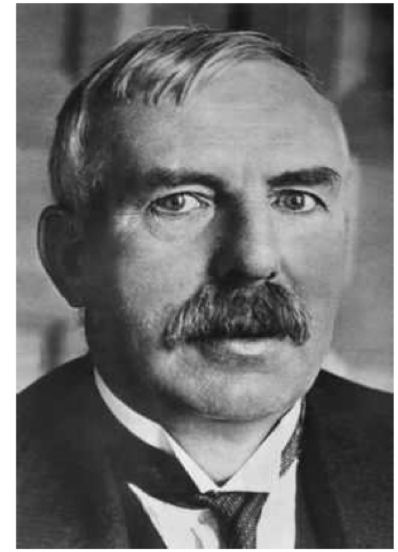
Rutherford Scattering

Discovery of Nucleus

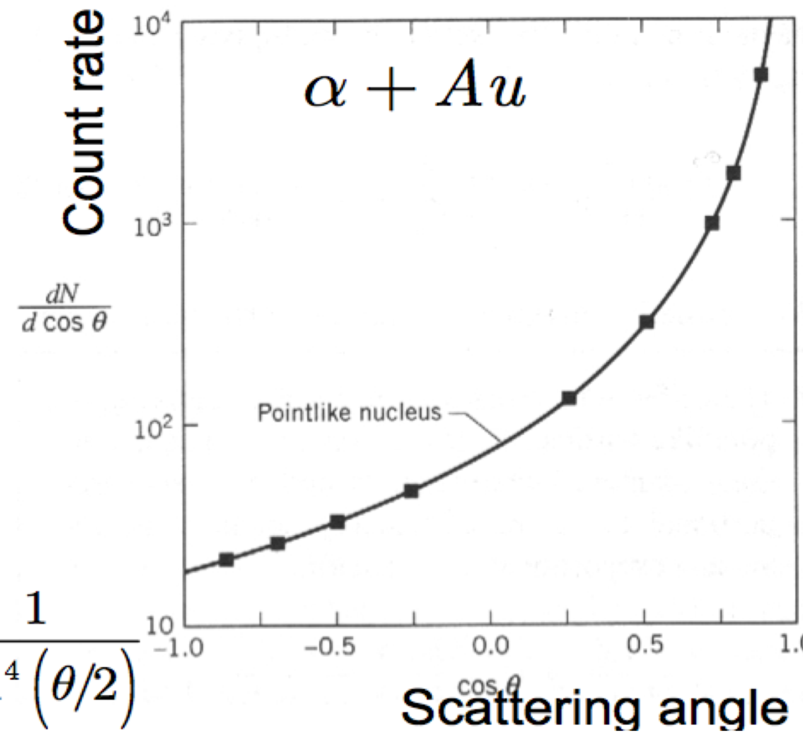
~5 MeV







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; $r_{\text{nucleus}} \sim 10^{-4}\, r_{\text{atom}} \sim 10^{-14}$ m

Discovery of (Electron) Spin

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

Pieter Zeeman
Nobel Prize 1902

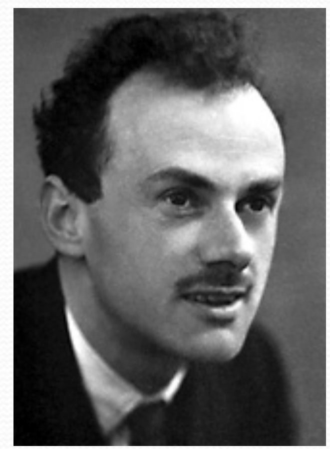
- 1922 Stern-Gerlach experiment
  silver beam split
  in inhomogeneous field
  Bohr magneton: $\mu_e = e\hbar/2m_e c$

Postcard from Gerlach to Bohr

- 1925 spinning electron
  Uhlenbeck and Goudsmit, Pauli
  spin: internal property, $S_e = 1/2$

Wolfgang Pauli
for “Pauli Principle”
Nobel Prize 1945

- 1928 Dirac equation
  relativistic effect: spin ←→ magnetic moment



Paul Dirac
Nobel Prize 1933

Anomalous Magnetic Moment (of Proton)

- 1933 Otto Stern

  Magnetic moment of the proton

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

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

  anomalous magnetic moment (a.m.m) κ_p= 1.5 +- 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: κ_p=1.792847386 +- 0.000000063

  and κ_n=-1.91304275 +- 0.00000045

Neutron, Mesons and Quark Model

- 1932: Discovery of the neutron by Chadwick

  proton, neutron: basic building blocks for nuclei
- 1935: Yukawa "strong" force → π meson
- 1937: Discovery of "meson"
- 1946: Powell, "π and μ mesons"

  μ mesons → muon

  Zoo of hadrons
- 1964 Gell-Mann

  Classify strong interacting particles (hadrons)

  with a simple quark model

James Chadwick
Nobel Prize 1935

Hideki Yukawa
Nobel Prize 1949

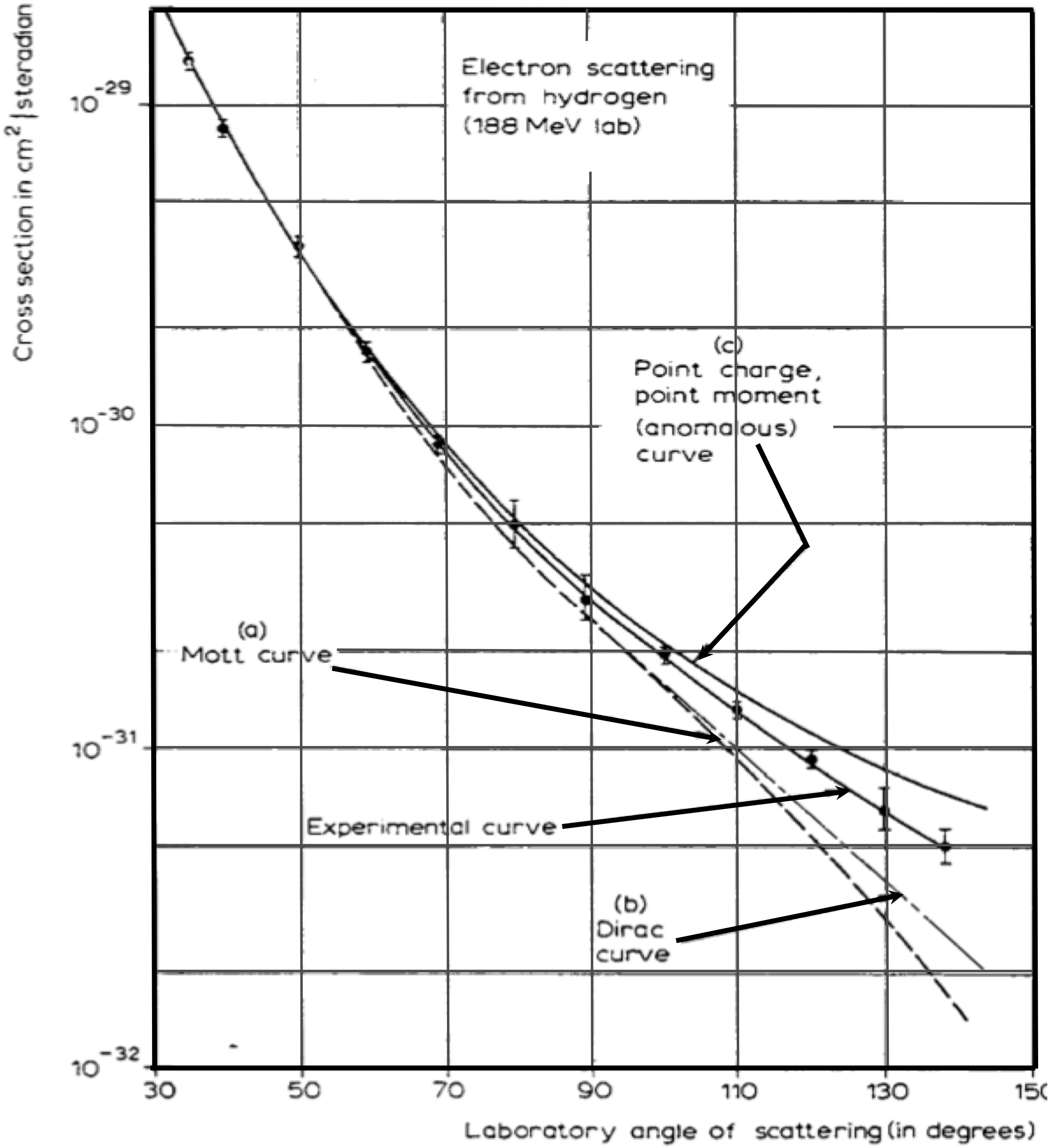
Cecil Frank Powell
Nobel Prize 195

Murray Gell-Mann
Nobel Prize 1969

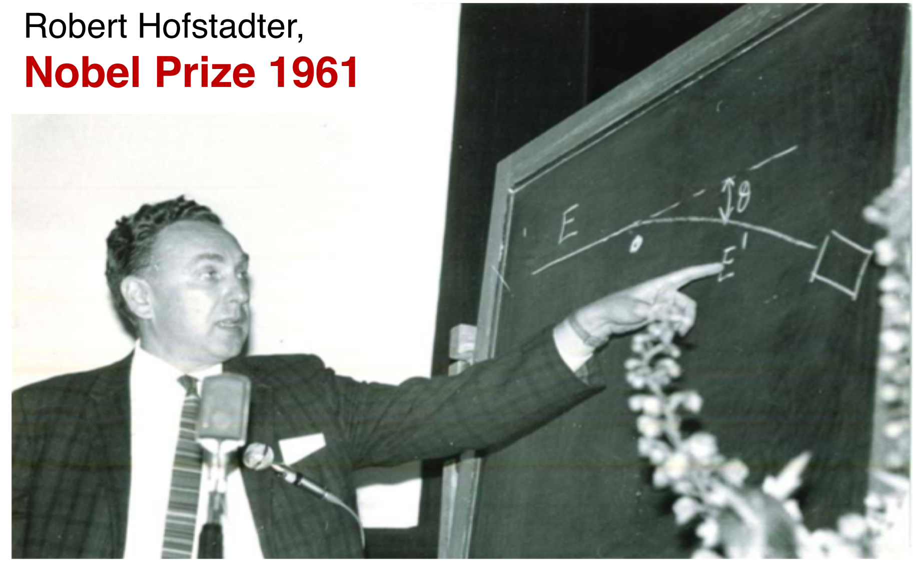
Elastic Electron Scattering

~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,

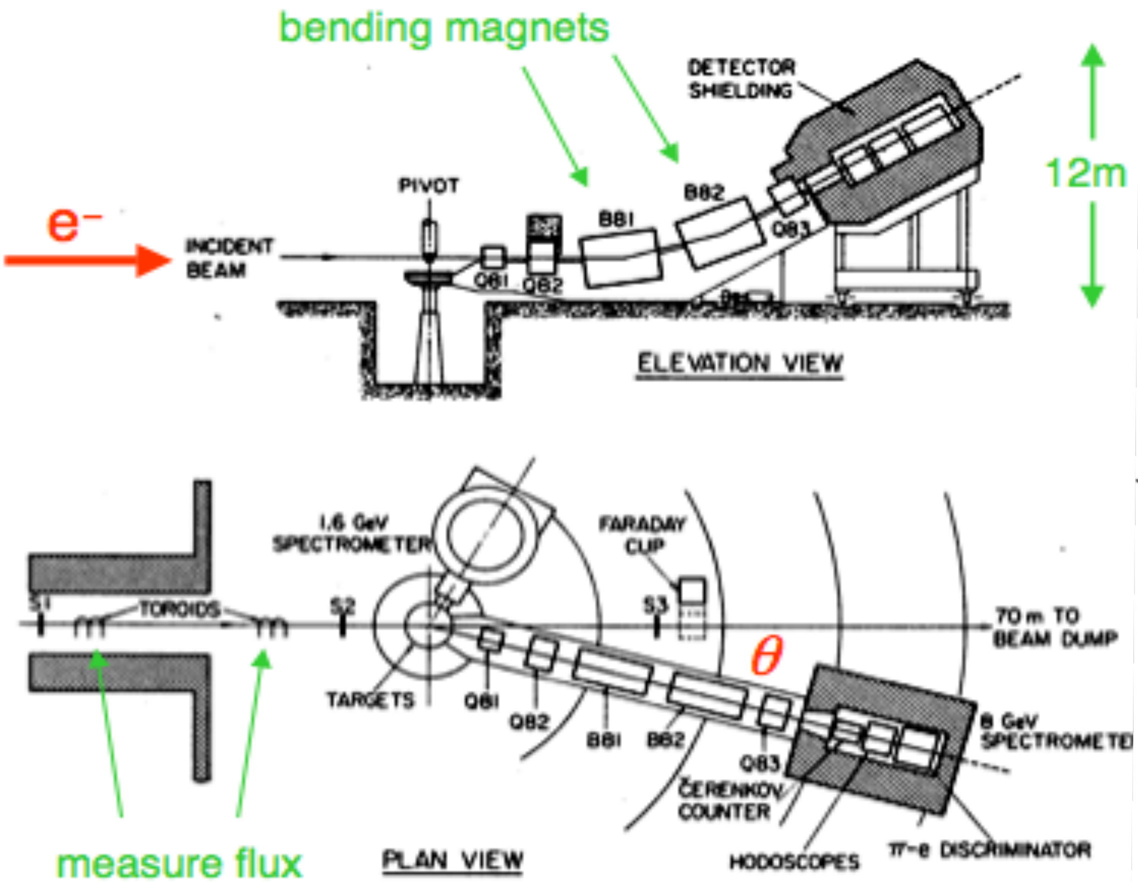
$$g_p \neq 2, \quad g_p \simeq 5.6$$

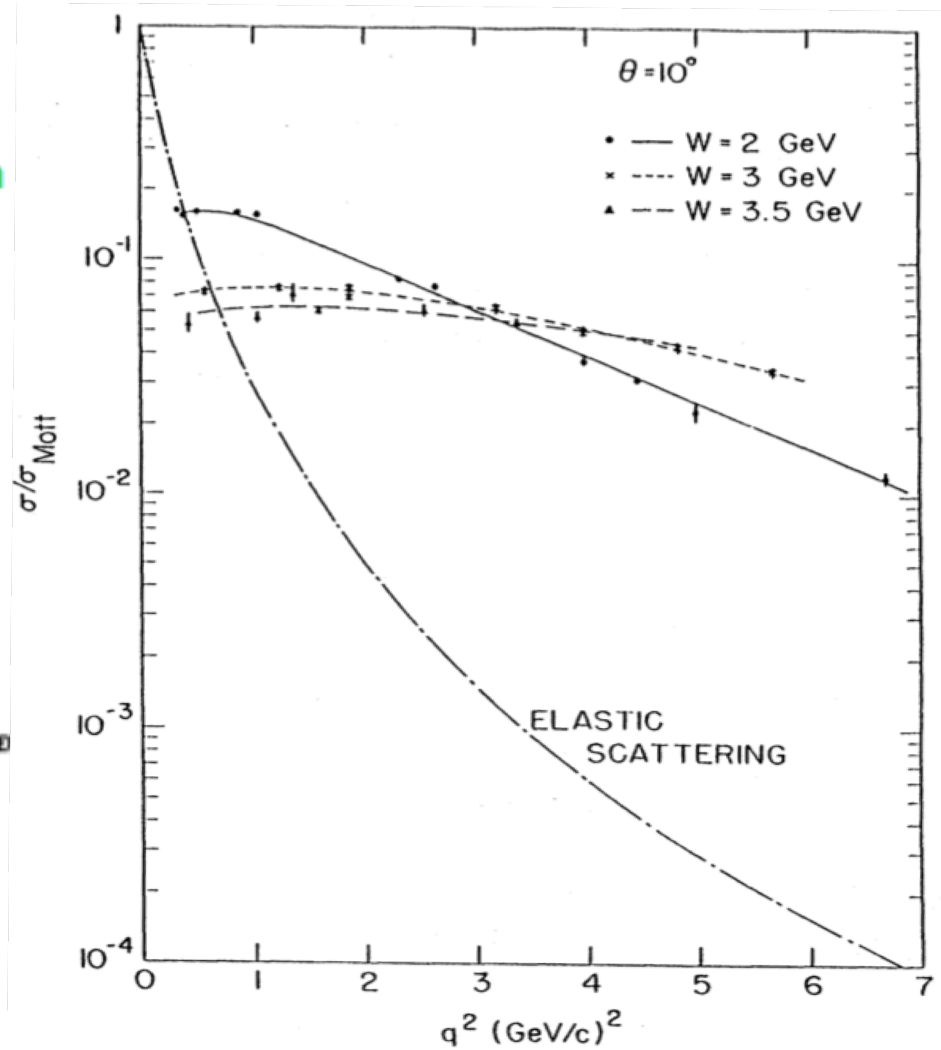
and, hence, internal (spin) structure.

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)

~10 GeV



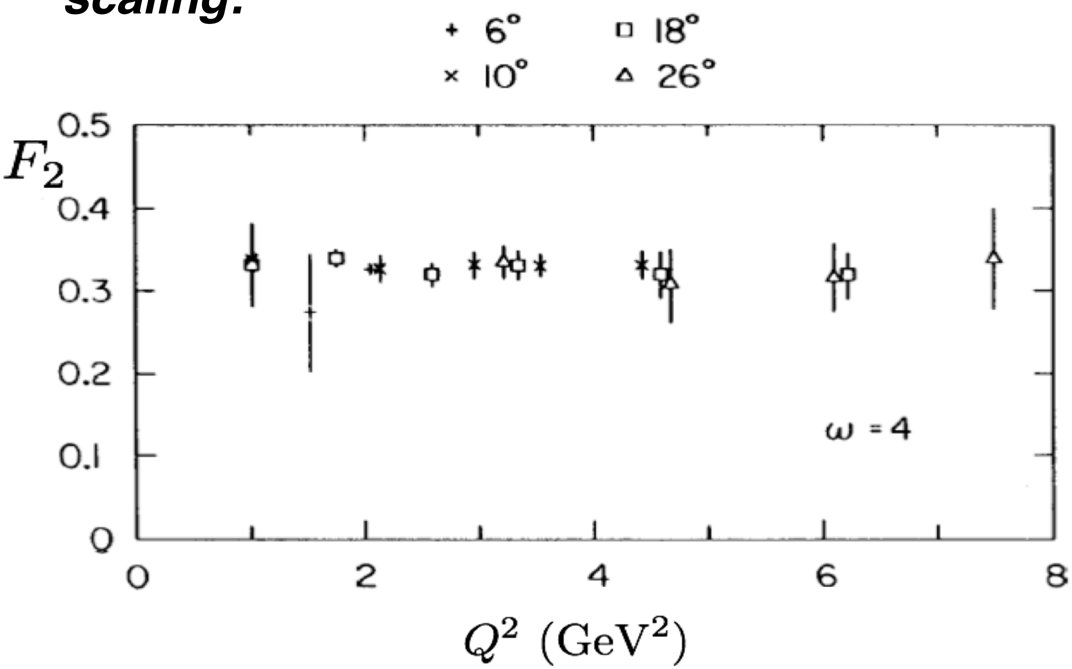


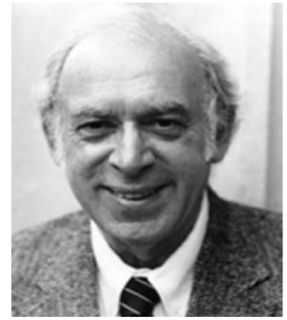
e.g. J.T.Friedman and H.W. Kendall, Ann.Rev.Nucl.Sci. 22 (1972) 203

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)

Bjorken scaling:





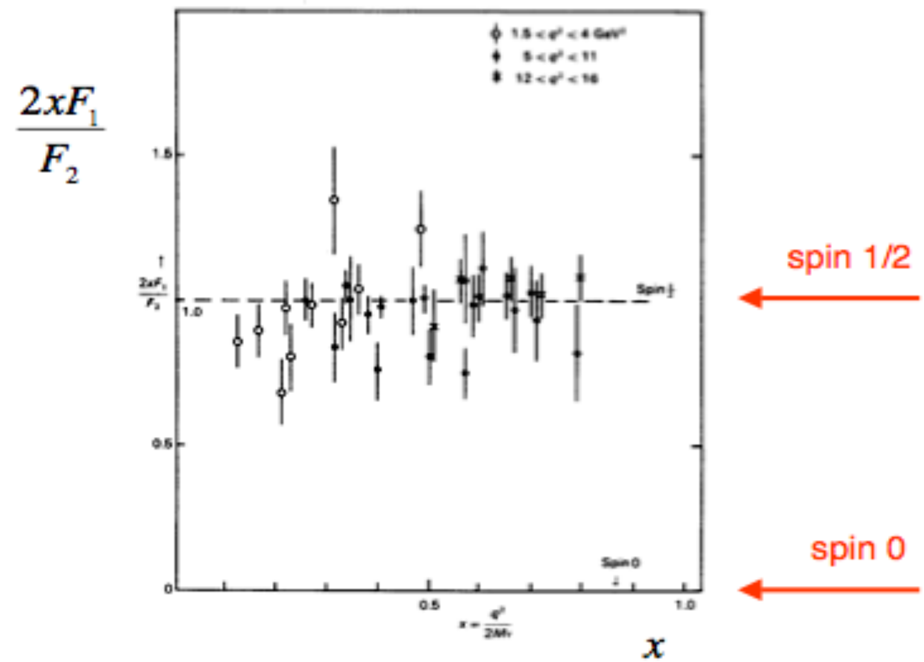
J.T. Friedman

R. Taylor

H.W. Kendall

Nobel Prize 1990

Callan-Gross relation:



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.

Birth of QCD

- Problems with simple quark model:

1. pion mass is light (~140 MeV) compared with
   nucleon (1 GeV) and ρ meson (770 MeV)
   → spontaneous breaking of chiral symmetries
   quark mass ~ 300 MeV ?
2. Pauli principle → new degree of freedom: color
   no free quarks observed !

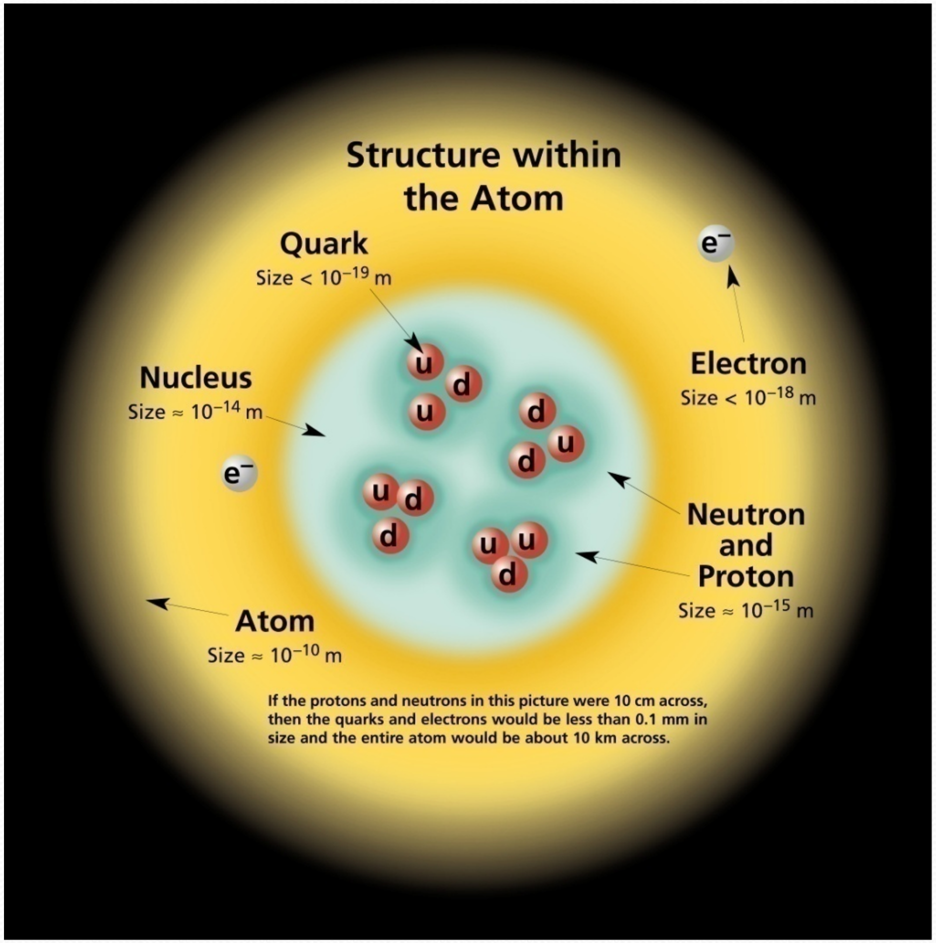
- 1972-73 Gell-Mann, Fritzsch, Leutwyler,
  Gross, Politzer, Wilczek
  SU(3) color gauge field → QCD

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



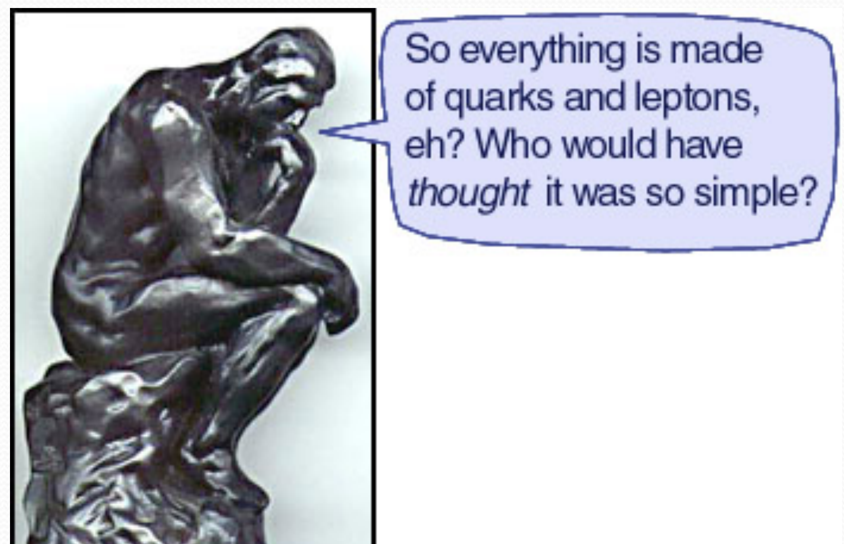
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

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

Quarks spin = 1/2

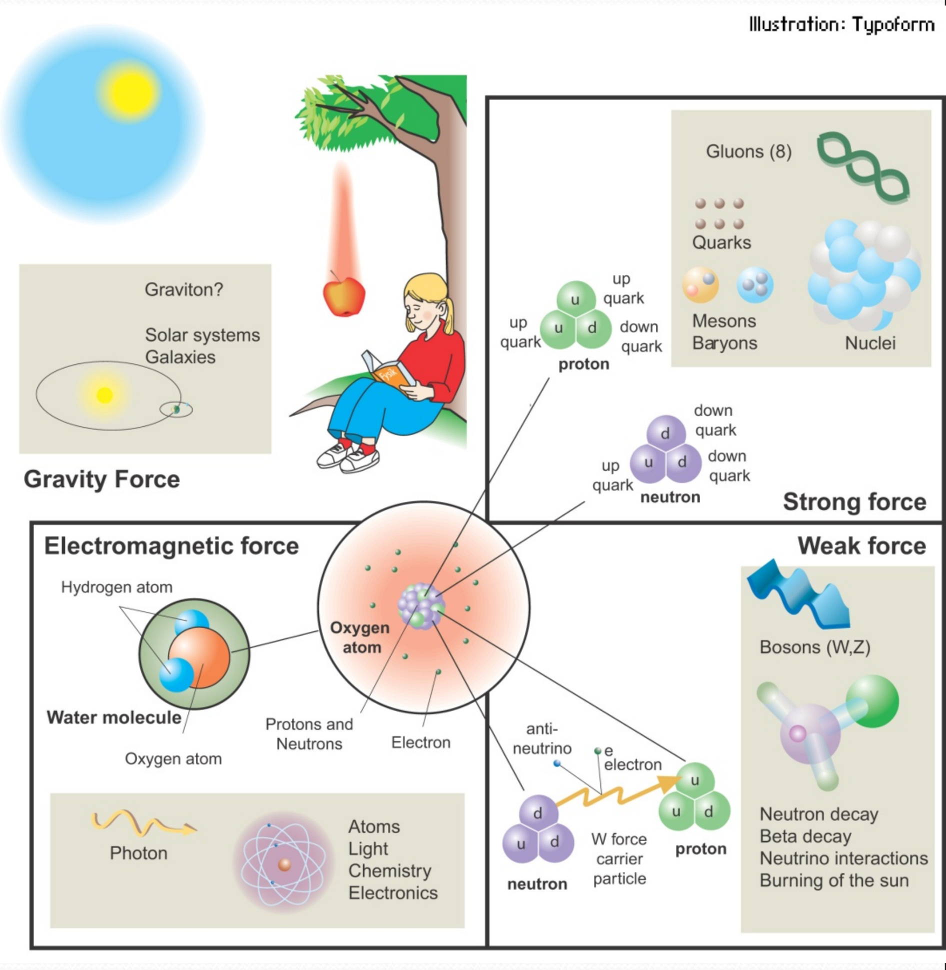
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3



What Holds the World Together?

Four Known Interactions

- Gravitational Interaction (graviton?)
  long range, always attractive
  strength, extremely weak, $\sim 10^{-40}$
- Electromagnetic Interaction (γ)
  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

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t top	175	2/3
b bottom	4.3	–1/3

BOSONS

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

Unified Electroweak spin = 1

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

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: 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)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

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

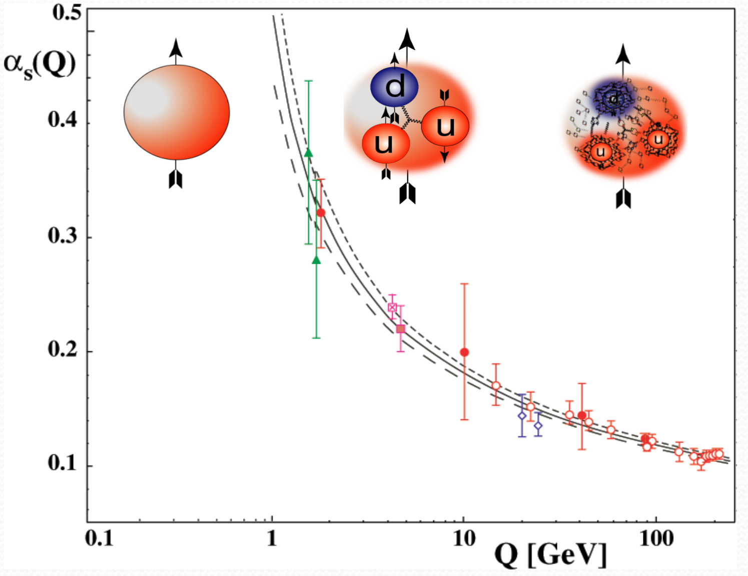
- Beyond Standard Model

  Energy frontier: LHC search Beyond SM

  Precision tests of Standard Model at low energy

  Precision information of nucleon structure needed

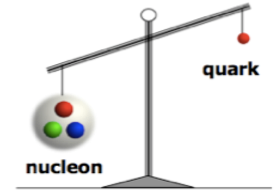
running coupling "constant"



Nucleon Structure: A Universe Inside

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

➢ **Proton mass "puzzle":**



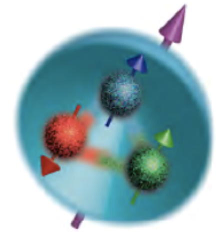
Quarks carry $\sim 1\%$? of proton's mass

m_q ~ 10 MeV

m_N ~ 1000 MeV

How does glue dynamics generate the energy for nucleon mass?

➢ **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)**

Color Confinement Asymptotic freedom

Q (GeV)

200 MeV (1 fm) 2 GeV (1/10)

Probing 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 <-> Confinement**
  - **Responsible for ~99% of the nucleon mass**
  - **Higgs mechanism is (almost) irrelevant to light quarks**

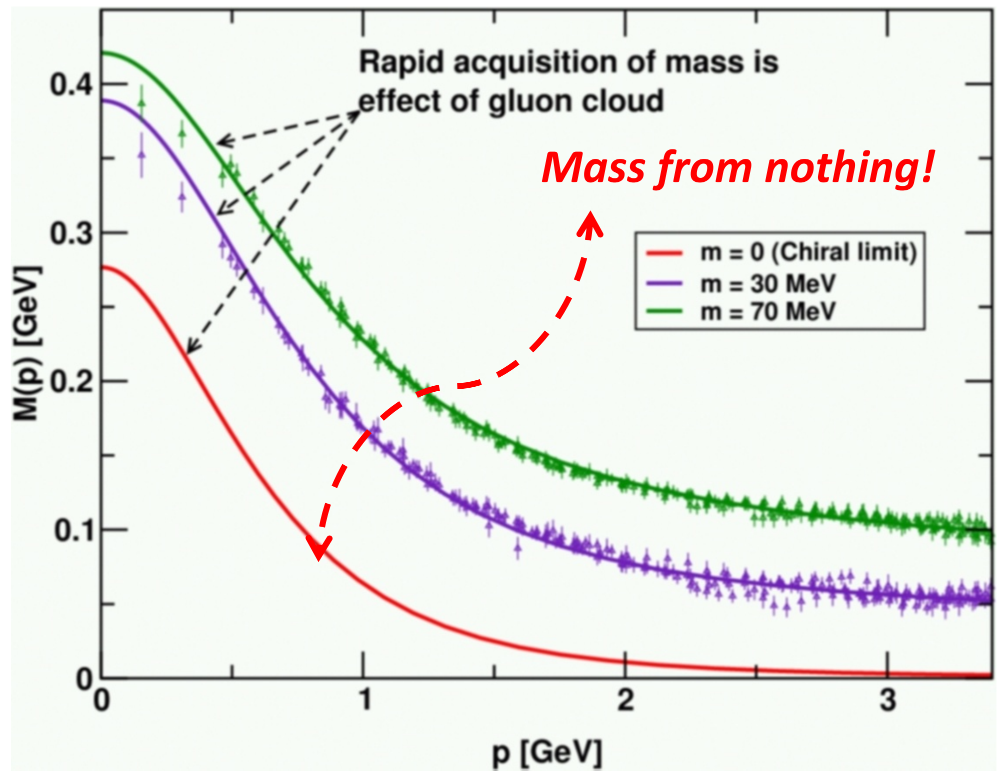
- **Recent development in theory**
  - **Lattice QCD**
  - **Bound State QCD: Dyson-Schwinger**
  - **Ads/CFT: Holographic QCD**
  - **QCD Dynamics**
  - **……**

- **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, ……

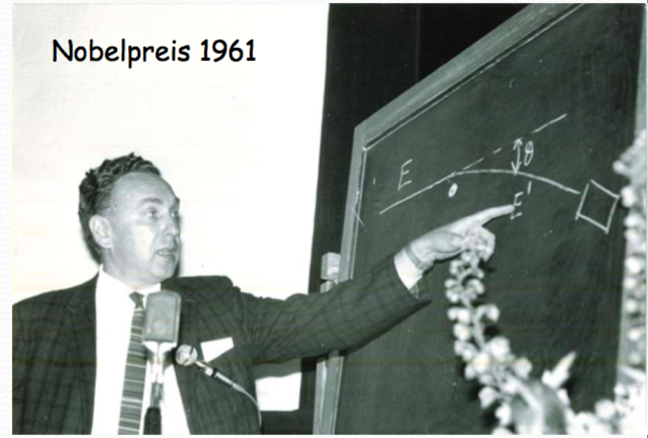


How: Electron Scattering and e-p/e-A colliding

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



Robert Hofstadter,
Nobel Prize 1961

- Elastic Electron Scattering: Form Factors
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions

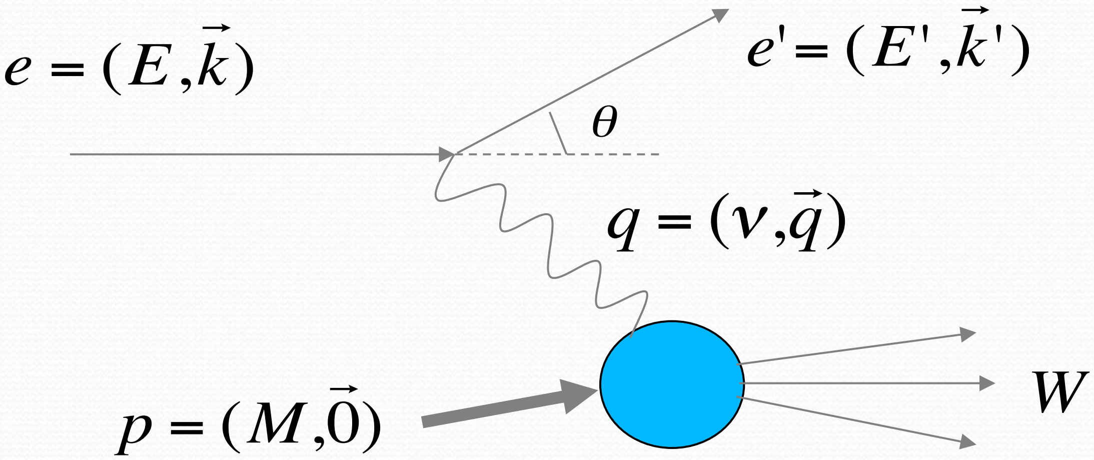
- Resonance Excitations

  → 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

J.T. Friedman ***R. Taylor*** ***H.W. Kendall***
Nobel Prize 1990

Inclusive Electron Scattering



4-momentum transfer squared

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

Invariant mass squared

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

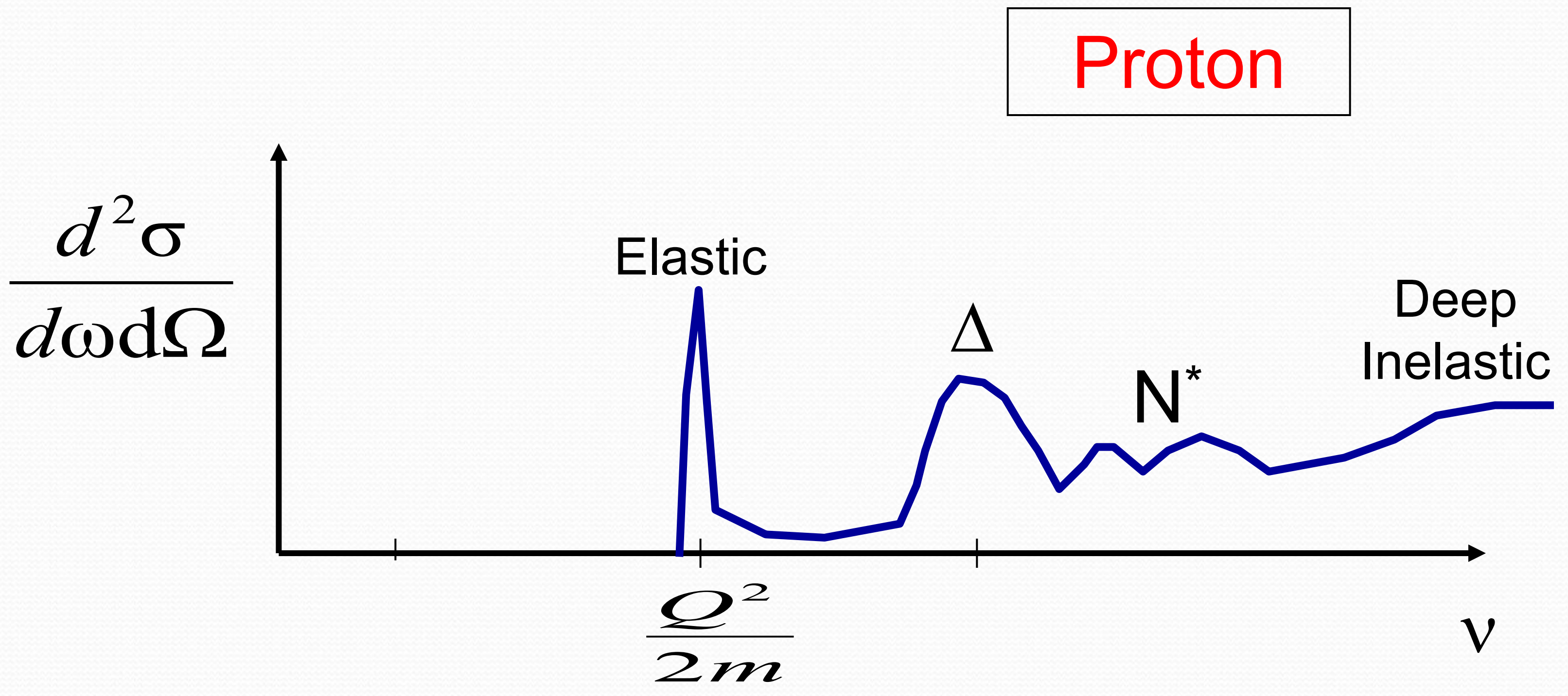
Unpolarized:

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

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

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: Fix target, 20/50 GeV (polarized) electron beam,, polarized p, d and ^{3}He
- CERN: EMC/NMC/SMC/COMPASS
  Fixed target, ~200 GeV polarized μ 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}He
- JLab: fixed target, 6/12 GeV polarized e beam, polarized p,d,3He
  highest luminosity 10^{39}.
- Low energy facilities: Mainz, MIT-Bates, Saclay, NIKHEF, …
- Future EIC: e-RHIC, JLEIC, EIC@HIAF, LHeC, …

Jefferson Lab at a Glance

CEBAF

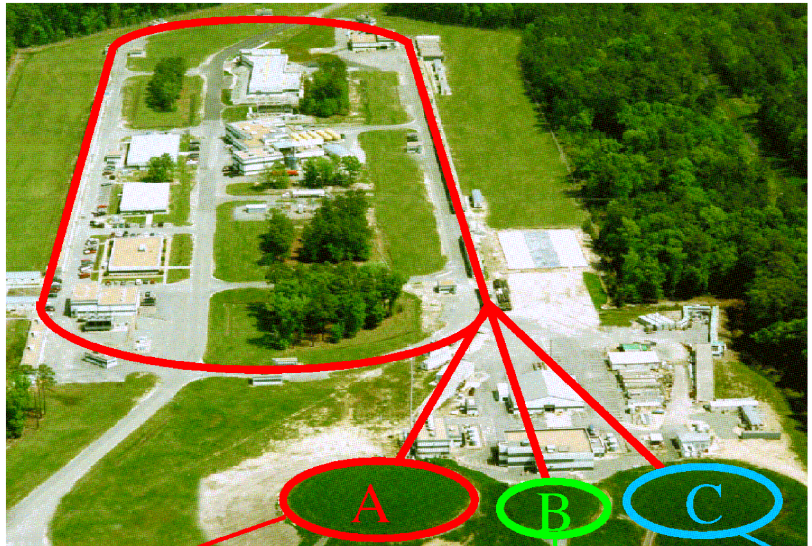
- **High-intensity** electron accelerator based on **CW SRF** technology
- I_{max} = 200 μA
- Pol_{max} = 90%
- E_{max} = 6 GeV: 1995-2012
- **Energy Upgrading to 12 GeV (2012-2017)**
- **12 GeV data taking started**

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

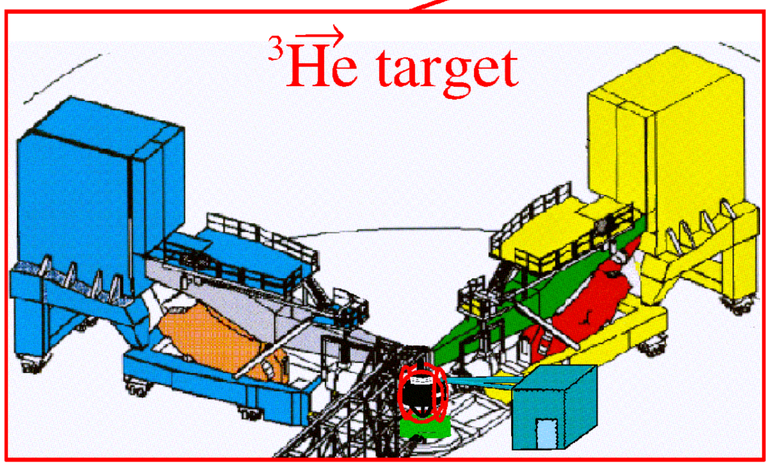
Thomas Jefferson National Accelerator Facility

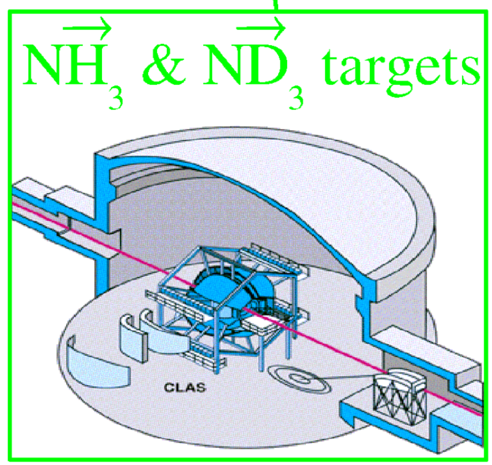
Newport News, Virginia, USA

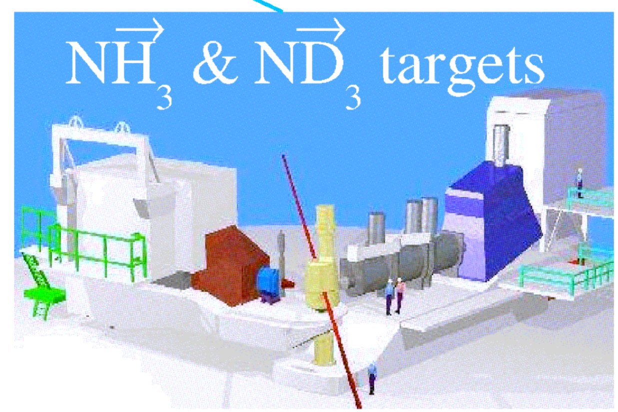
6 GeV polarized
CW electron beam
Pol=85%, 200μA
Luminosity ~ 10^{39}



Upgrading to 12 GeV
nearly complete

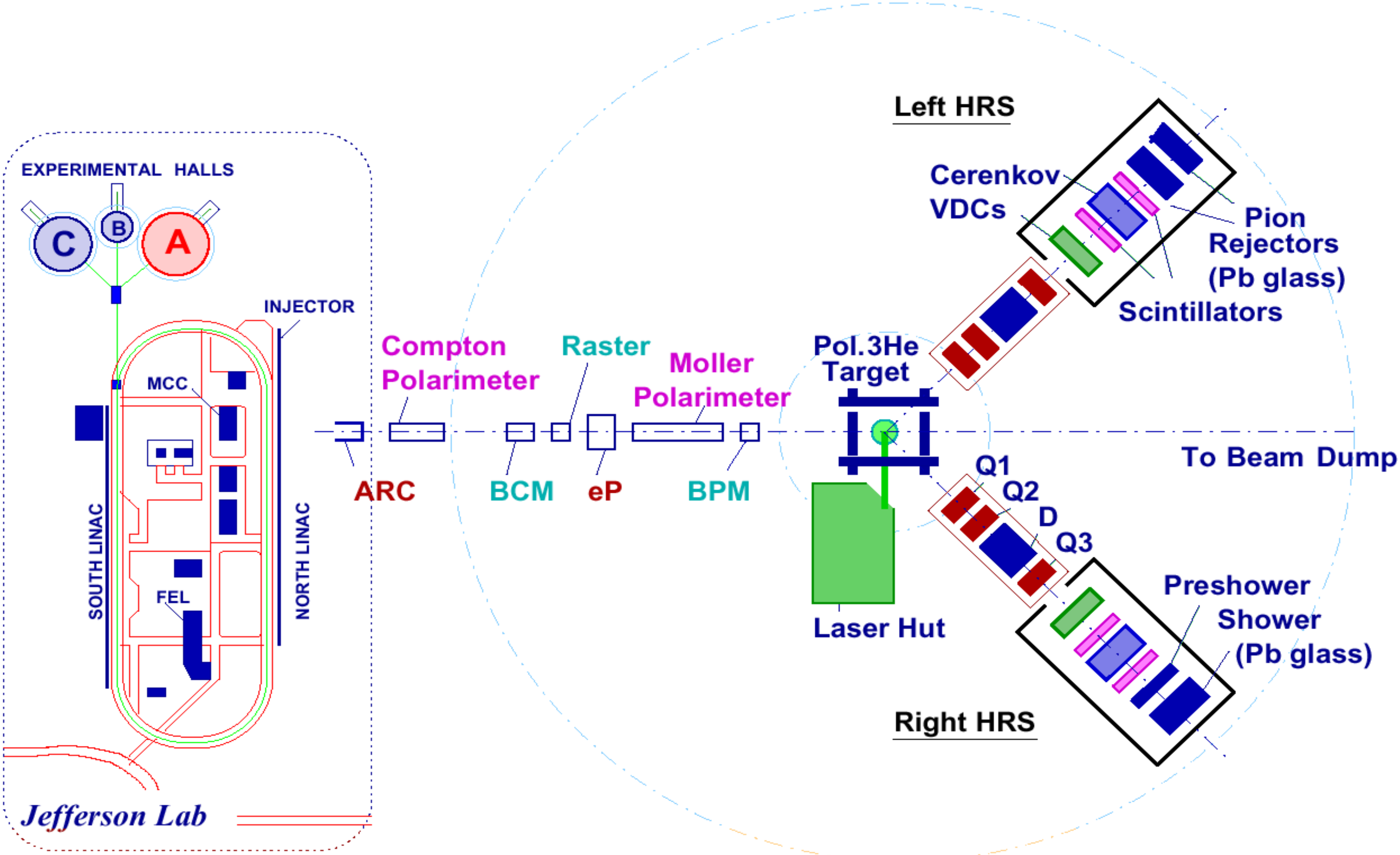






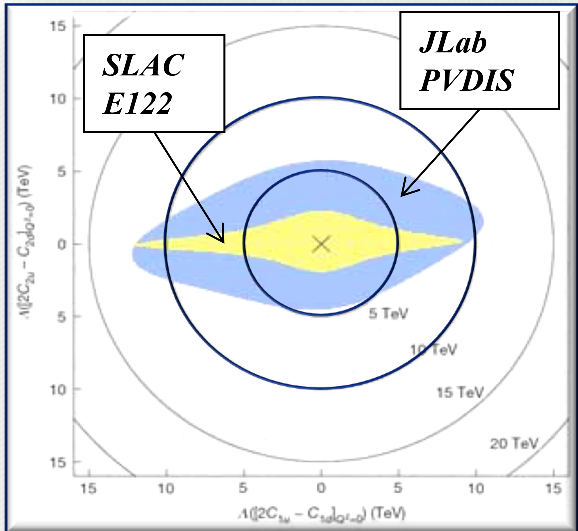
HallA: two HRS' **Hall B:CLAS** **Hall C: HMS+SOS**

Jefferson Lab Hall A Experimental Setup for inclusive polarized n (^3He) Experiments

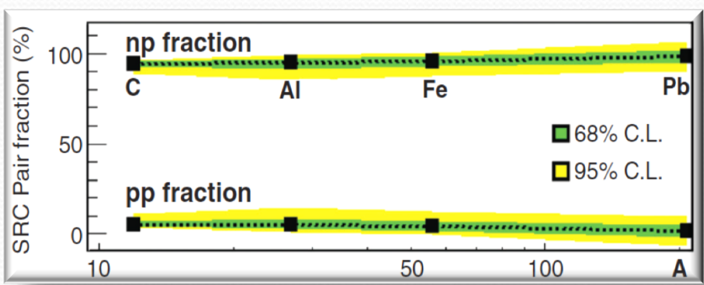


JLab 2014

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



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



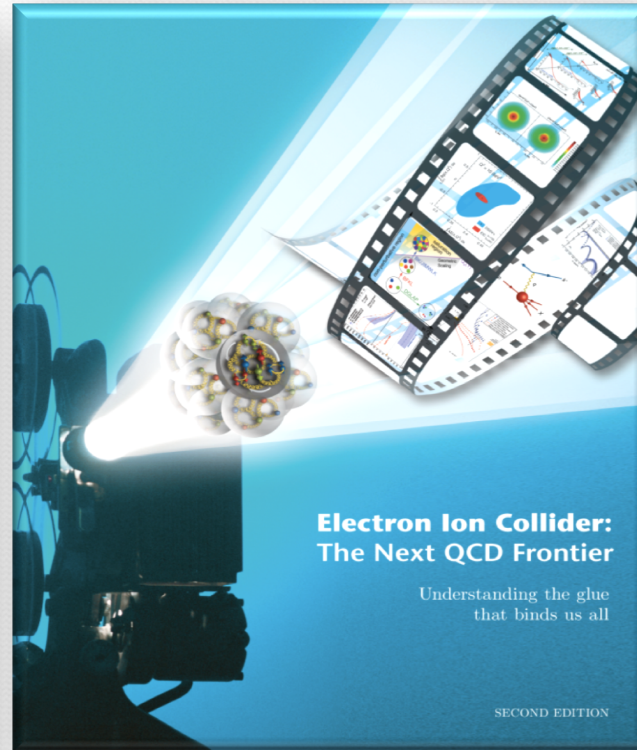
Near-Future

Decade of Experiments Approved
Eager to Start 12 GeV Science!

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

Future

Electron Ion Collider
The Next QCD Frontier

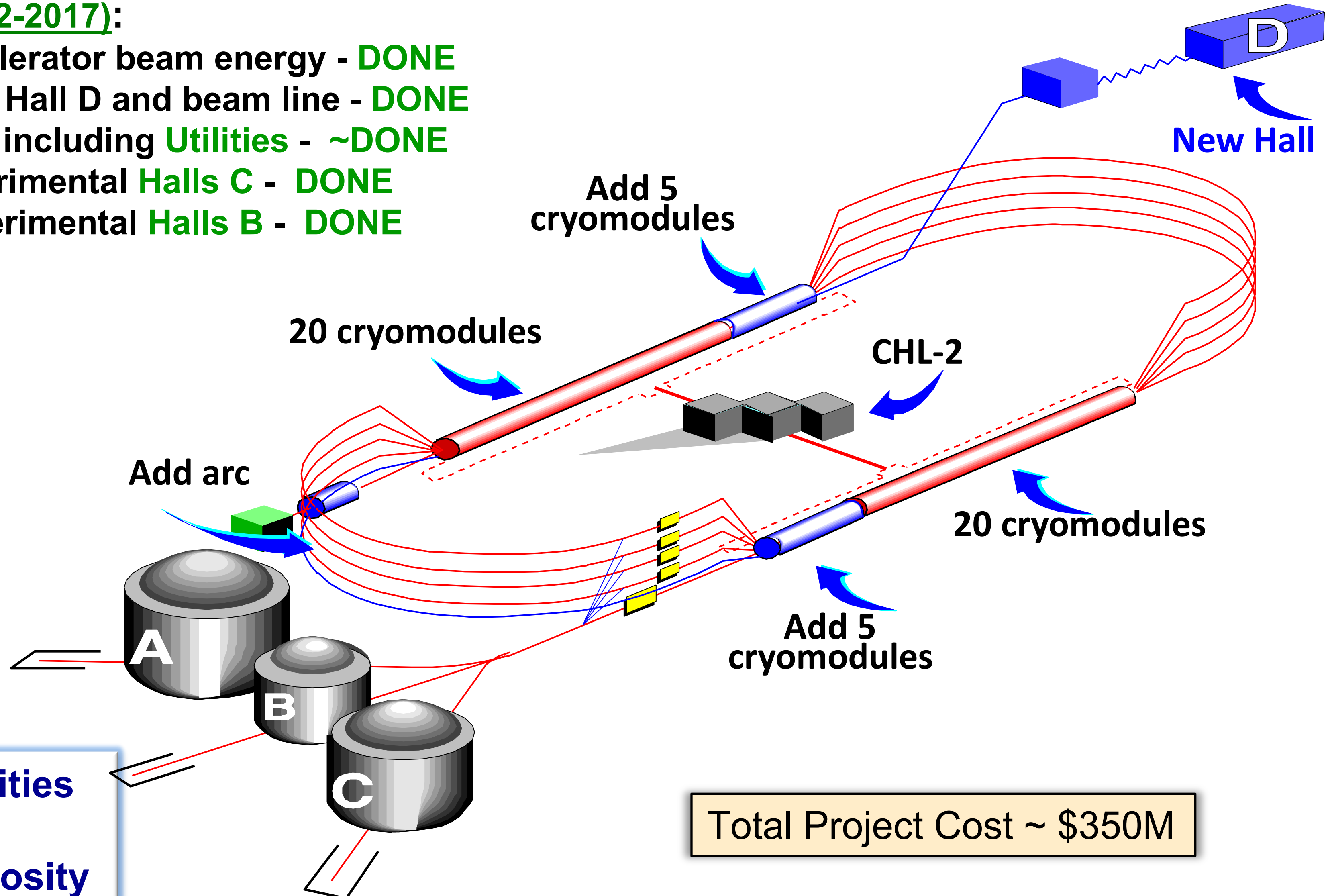


Role of Gluons in Nucleon and Nuclear Structure

12 GeV Upgrade Project

Project Scope (2012-2017):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - DONE

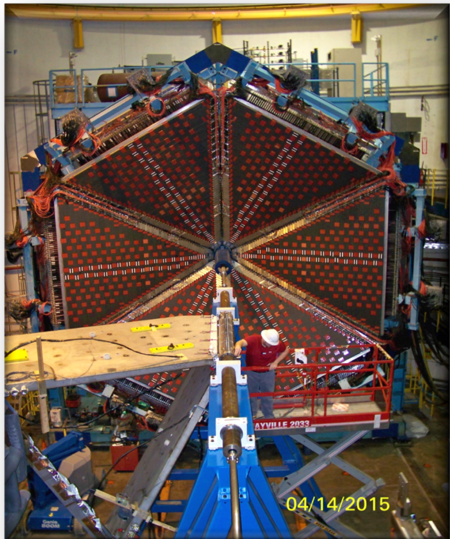


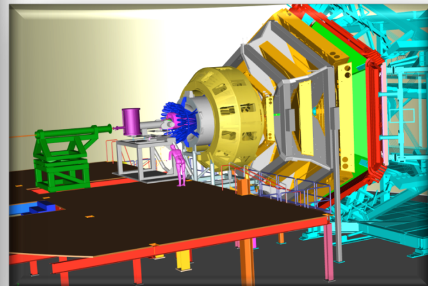
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

Total Project Cost ~ $350M

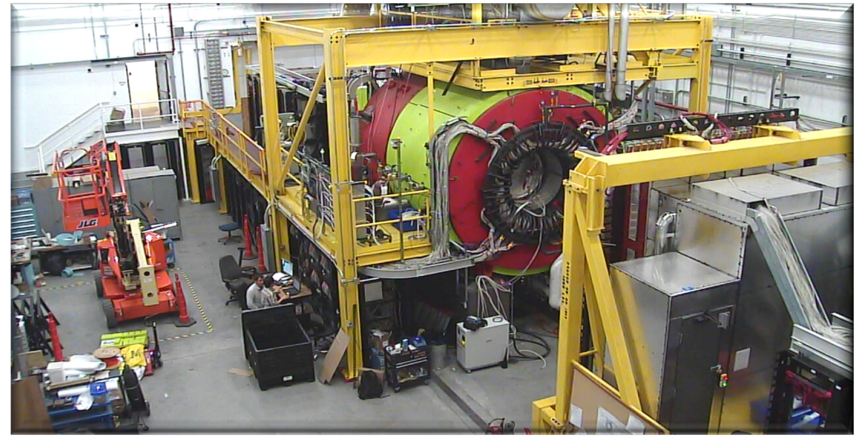
12 GeV Scientific Capabilities

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

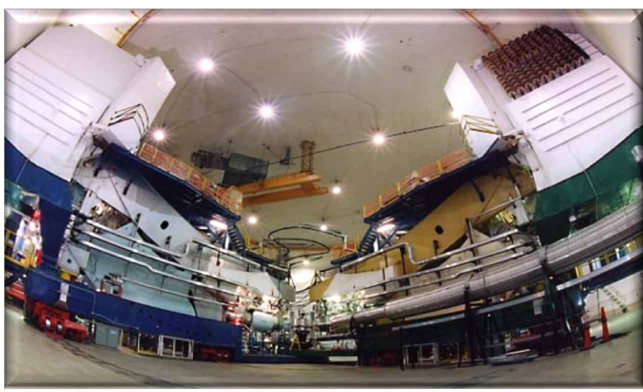


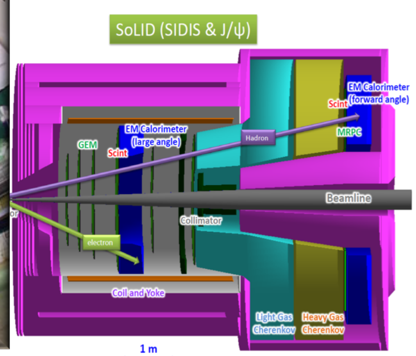


Hall D* – exploring origin of *confinement* by studying *exotic mesons



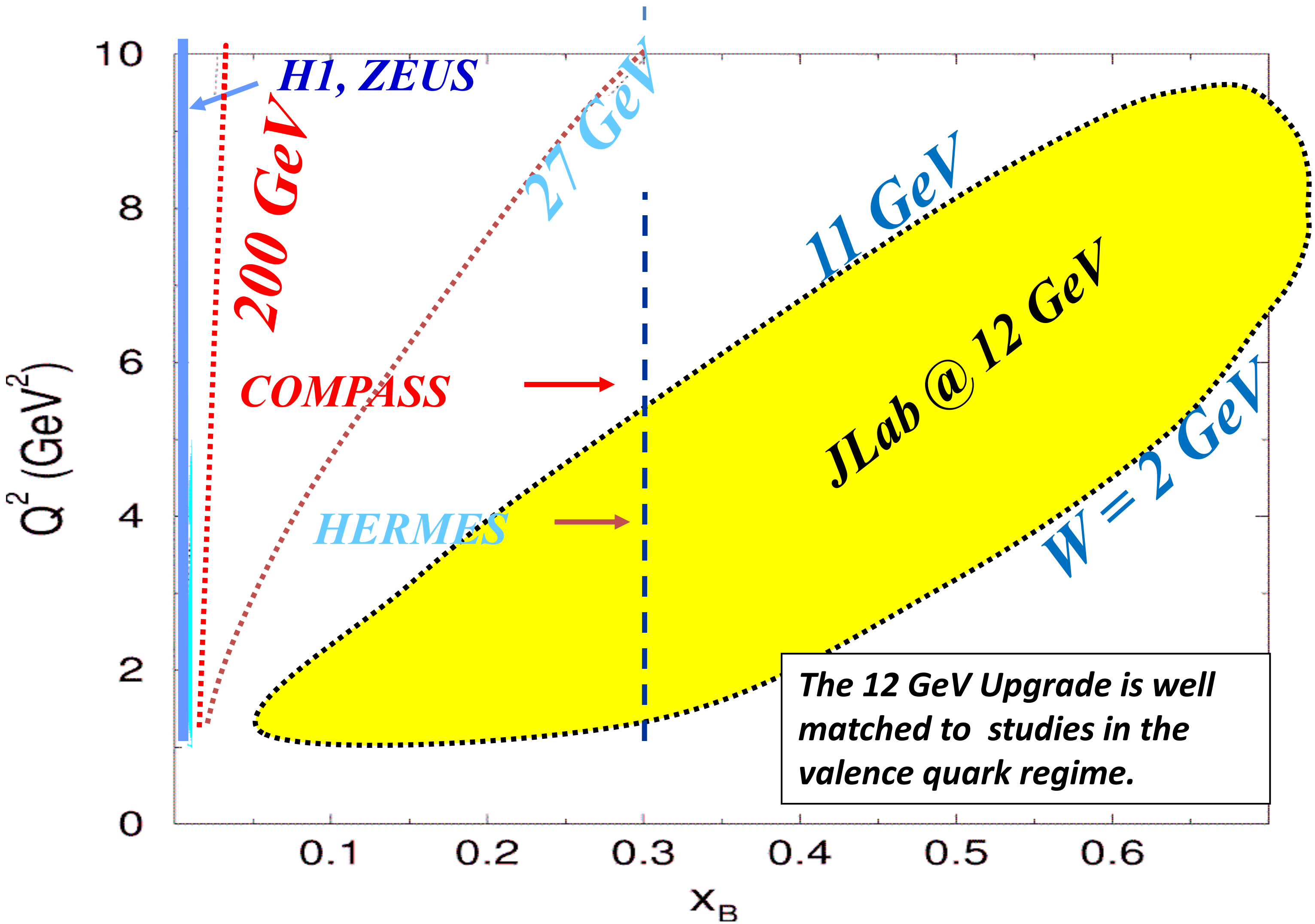
***Hall A* – form factors, future new experiments (e.g., SoLID and MOLLER)**





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

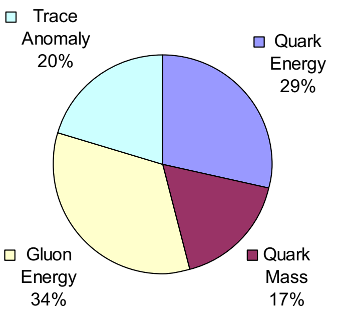
Kinematics Coverage of the 12 GeV Upgrade



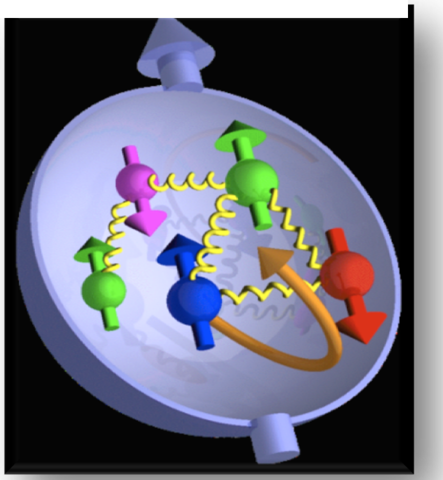
The 12 GeV Upgrade is well matched to studies in the valence quark regime.

Jefferson Lab @ 12 GeV Science Questions

- What's the origin of the proton mass?
 How can measurements help?

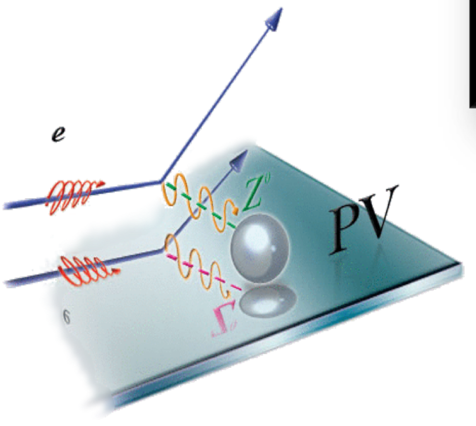


- Where is the missing spin in the nucleon?
Role of orbital angular momentum?

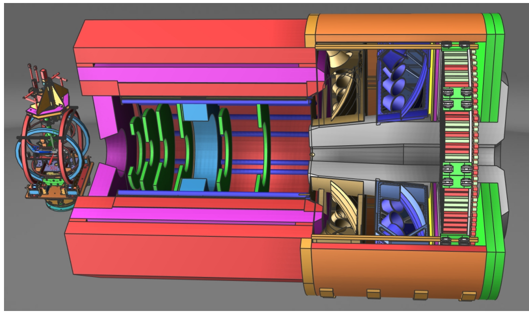


- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?

- Can we discover evidence for physics
beyond the standard model
of particle physics?



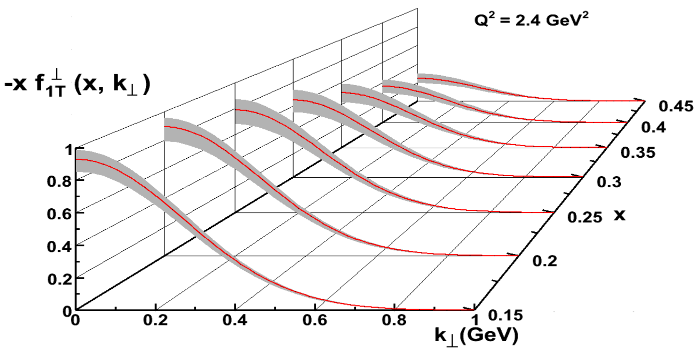
Solenoidal Large Intensity Device (SoLID)

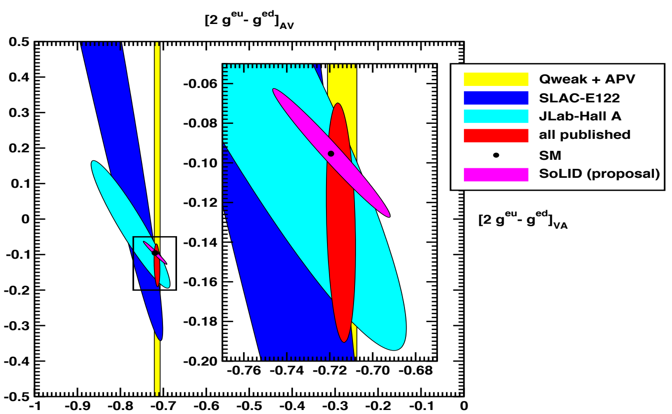


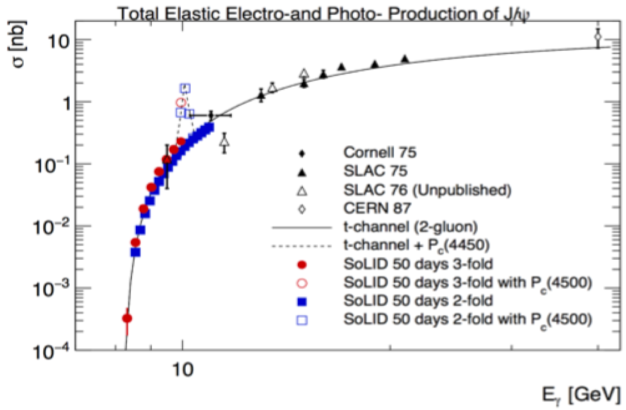
- *Full exploitation of JLab 12 GeV Upgrade to maximize scientific return*

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."

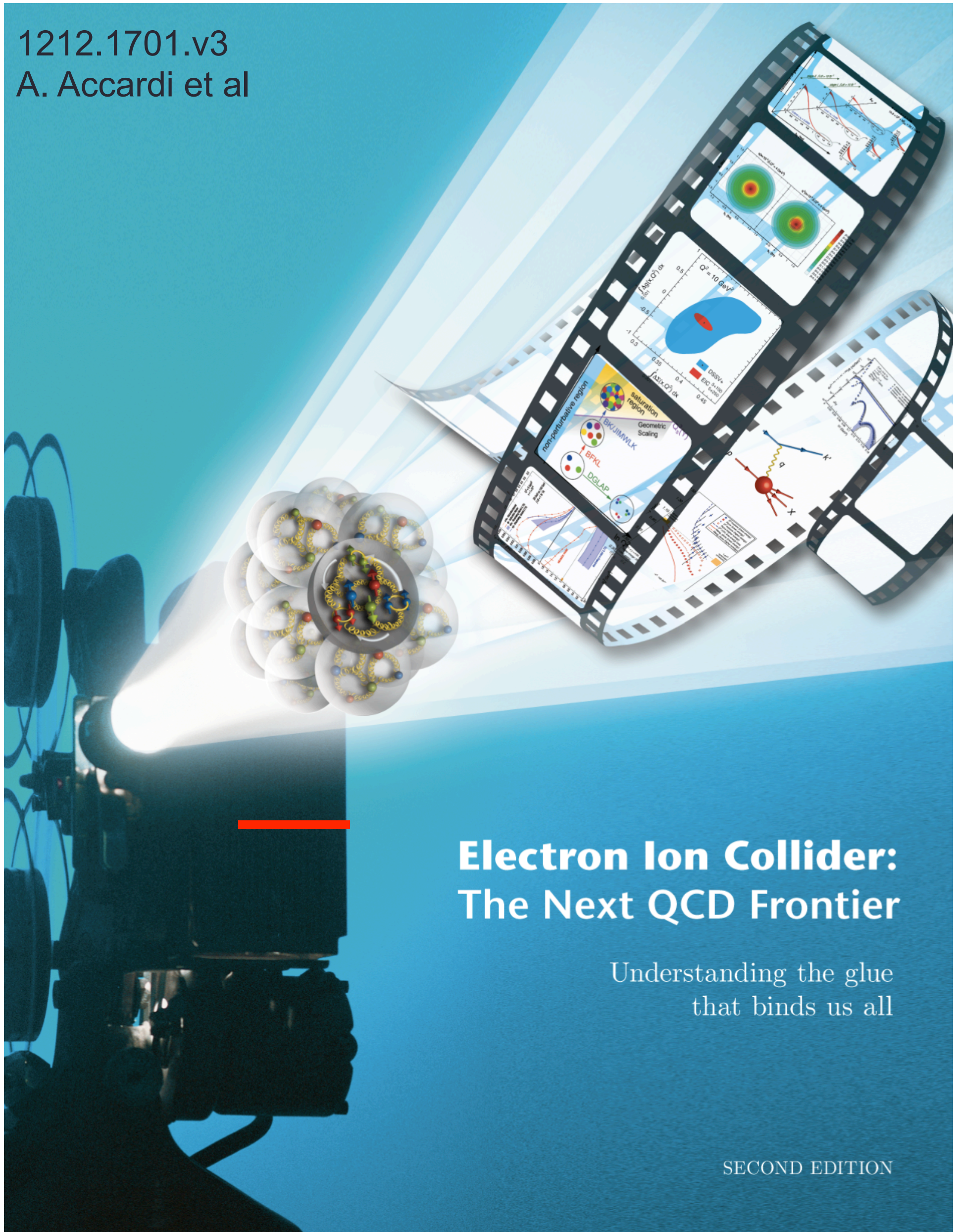
NSAC 2015 Long-Range Plan:

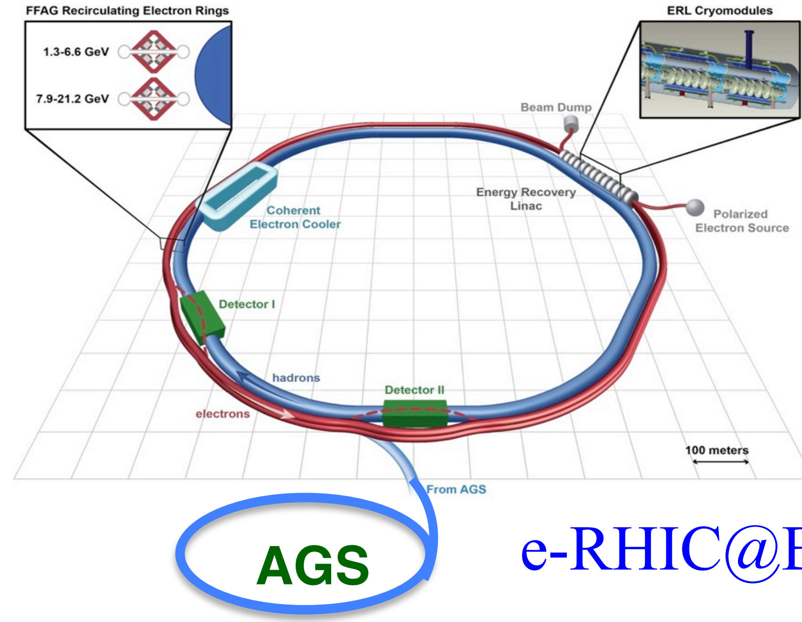
We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility construction** following the completion of FRIB.

EIC Community White Paper arXiv:1212.1701v2

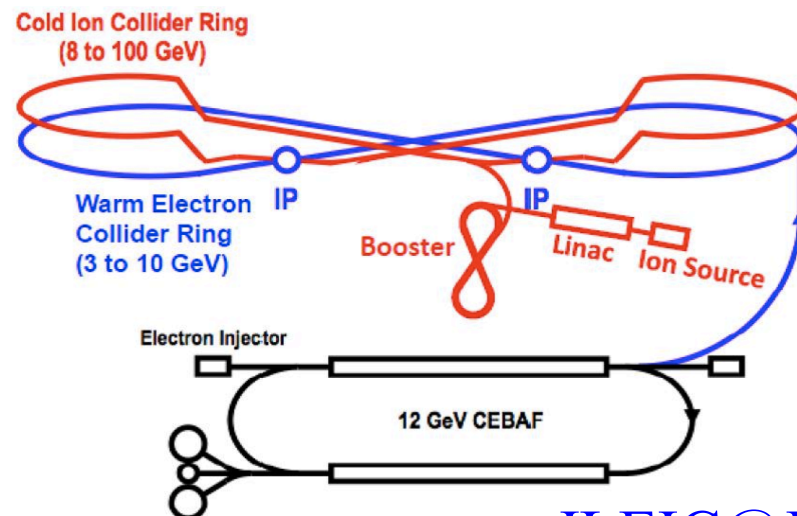
The Electron Ion Collider

Two proposals for realization of the Science Case



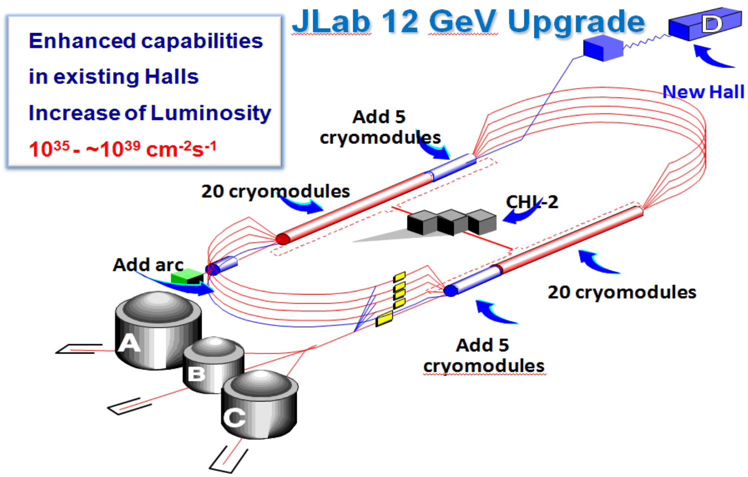


e-RHIC@BNL

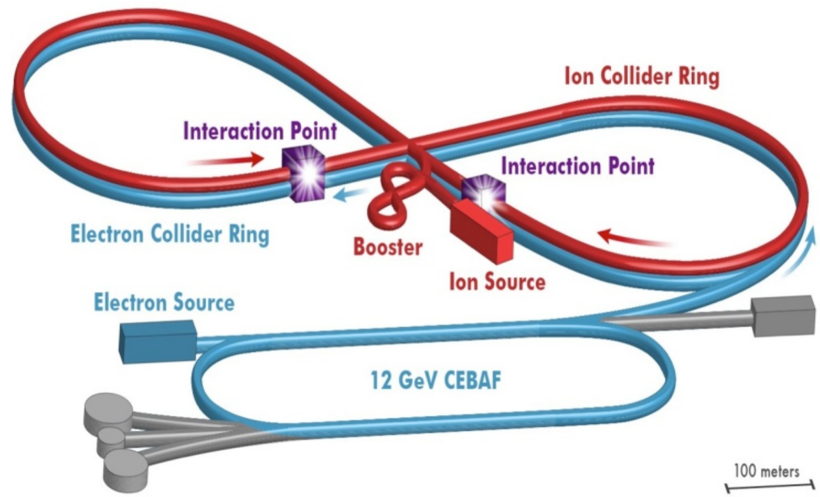


JLEIC@JLab

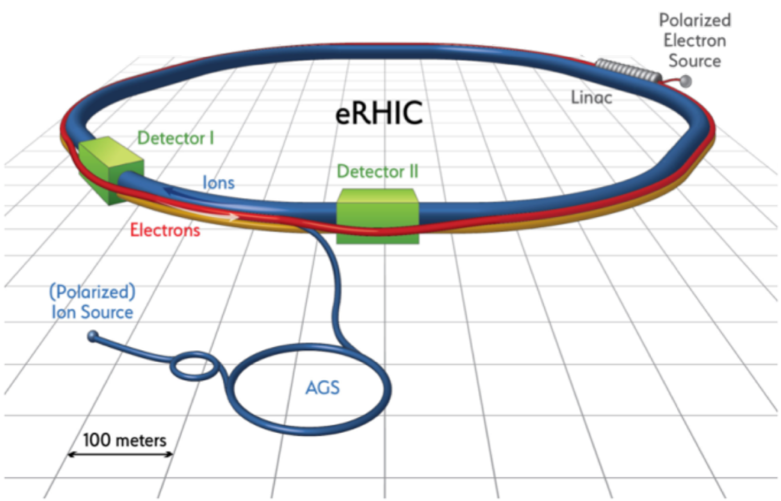
JLab 12 and Future EIC Plan



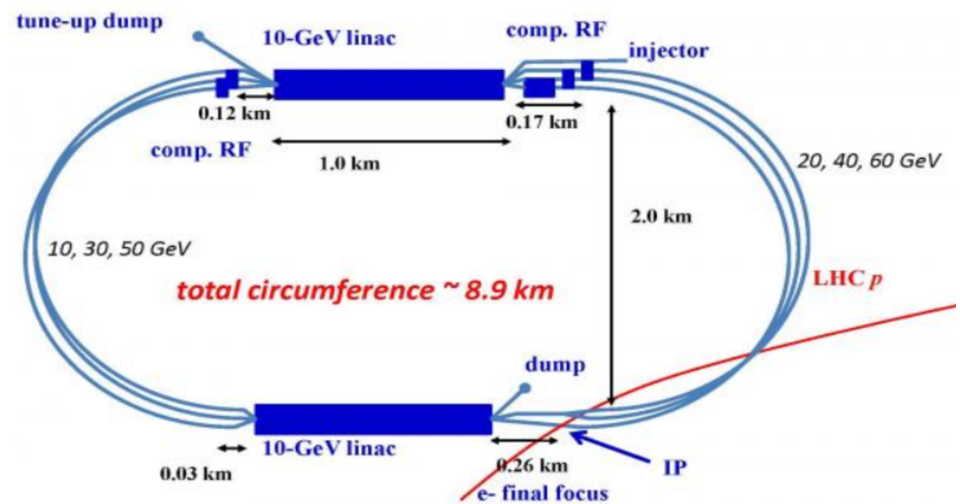
Jlab 12 upgrade (Fixed target)



JLEIC √s ~ 20 to 70 GeV



eRHIC, √s ~ 140 GeV

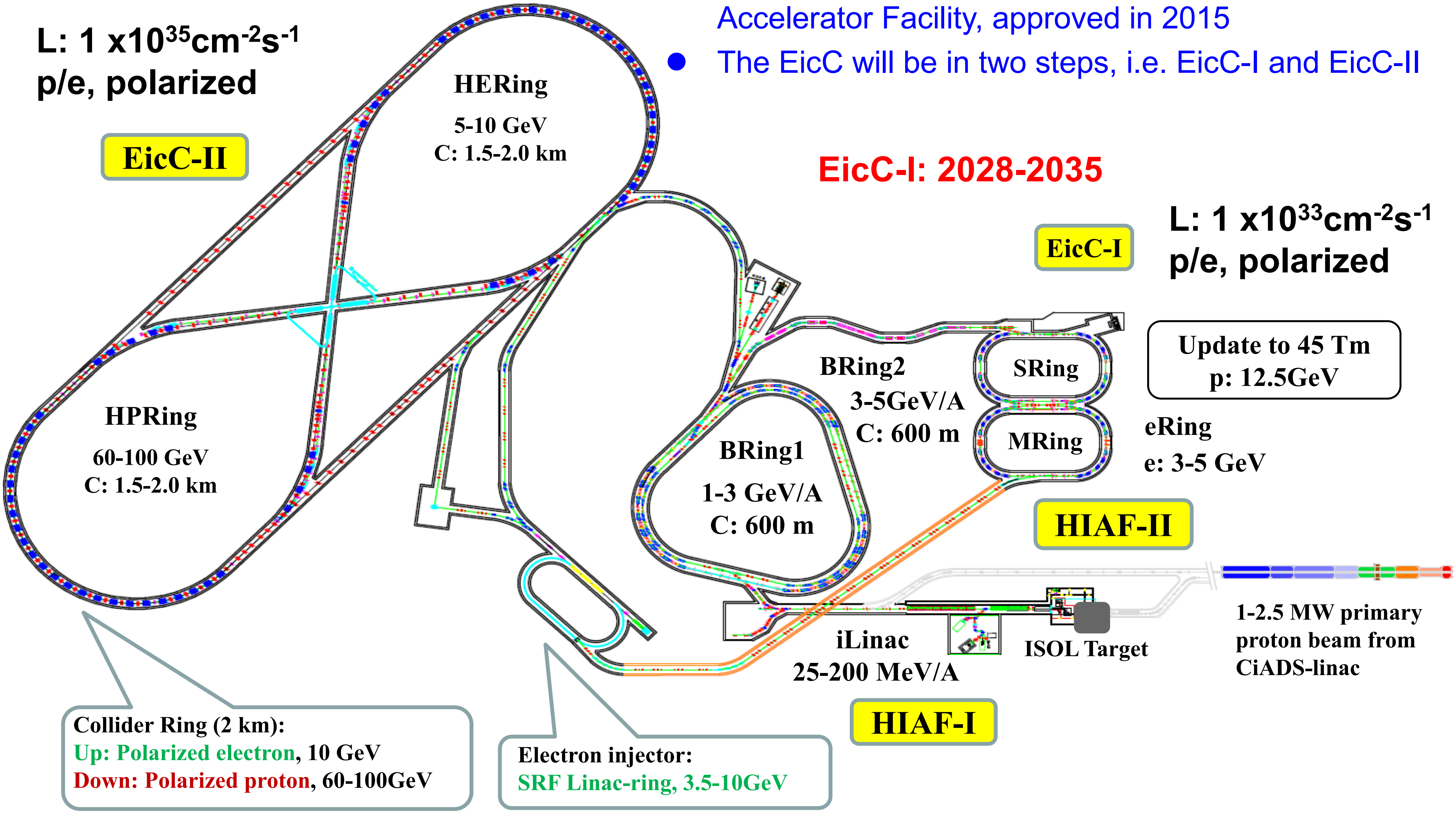


LHeC, √s : 1.3~3.5 TeV

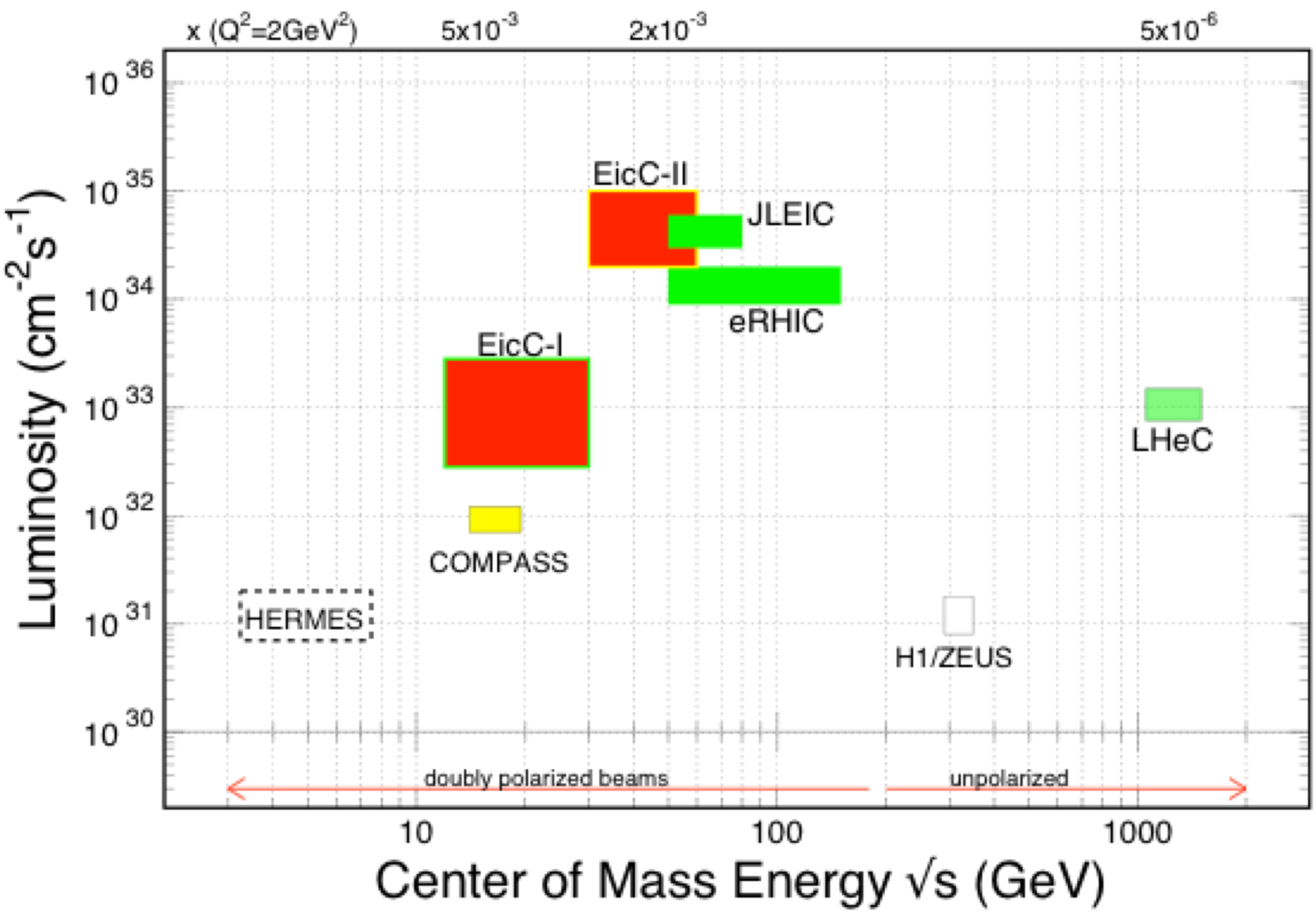
EIC @ China

Xurong Chen

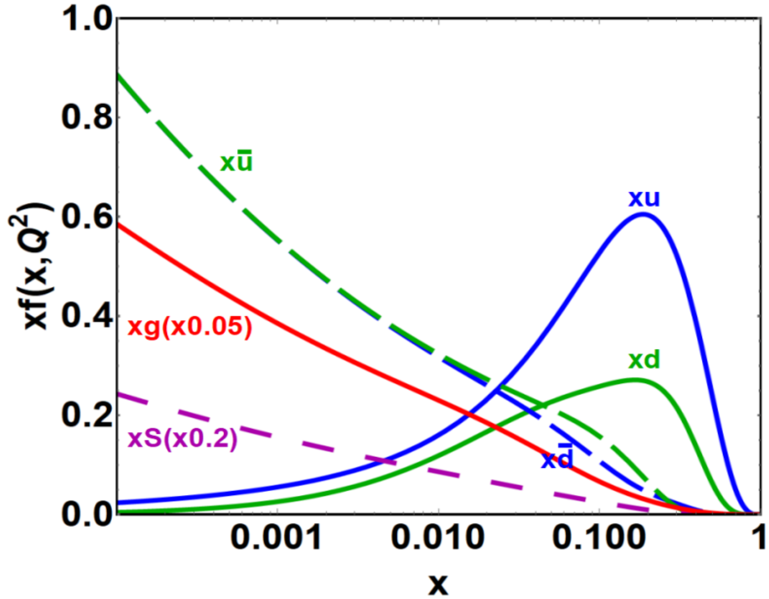
- Based on the HIAF (the Heavy Ion high Intensity Accelerator Facility, approved in 2015
- The EicC will be in two steps, i.e. EicC-I and EicC-II



Comparisons: Luminosity and Energy



Kinematics Coverage



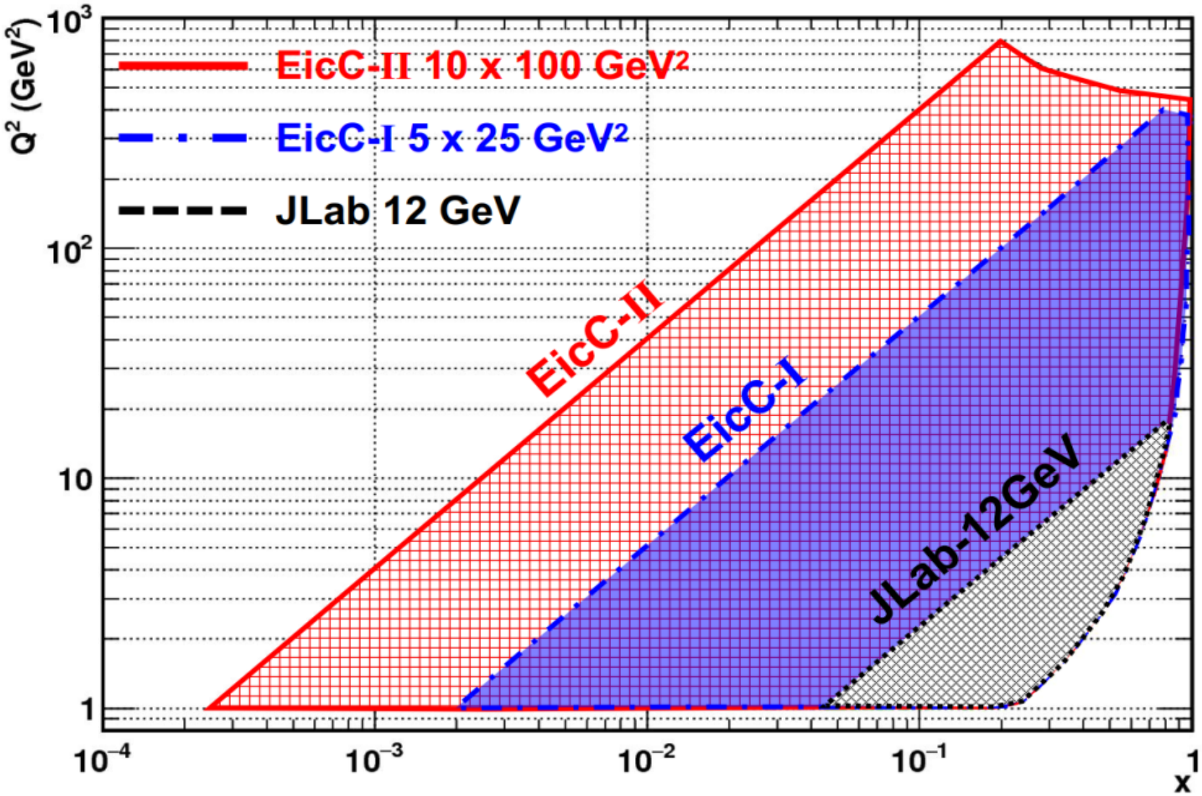


Figure of Merit Comparison

- **Figure-of Merit for double polarization experiments**

  $FOM = L * P_e^2 * P_N^2 * D^2$

  L=Luminosity, P=Polarization, D=Dilution

- **FOM Comparison of EIC@HIAF (1) with COMPASS (2)**

  HIAF: $L=1*10^{33}$, D=1

  COMPASS: $L=10^{32}$, D=0.13 (NH_3 target)

  Unpolarized:

  FOM(1)/FOM(2) = L(1)/L(2) ~ 10

  Polarized:

  FOM(1)/FOM(2) = L(1)/L(2) * $[D(1)^2 / D(2)^2]$ ~ 500

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:

“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
- Future Electron-Ion Collider
- EIC goes into new region: understand sea quarks and gluons

Physics with an Electron-Ion Collider

II: From Factors

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

Pre-Workshop Lectures, Hadron-China2018, July 25, 2018

- Electron Scattering
- Elastic Scattering: From Factors

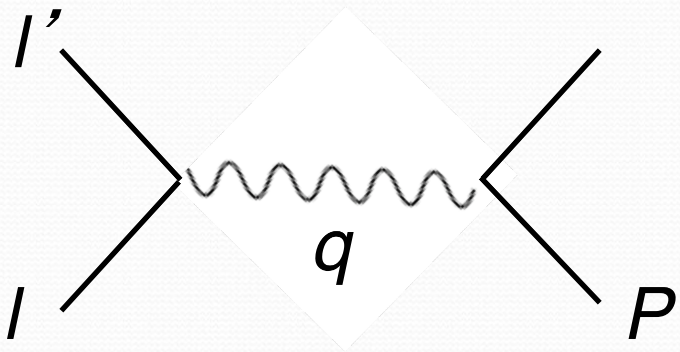
  Surprise: G_E^p @ high Q^2 : proton shape, 2-γ exchange

  Proton radius puzzle

Nucleon Form Factors

Charge and Magnetization Distributions
Transverse Density

Elastic Electron Scattering



$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} K_{\mu\nu\,\text{nucleon}}$$

The lepton tensor is calculable:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k\cdot k')\right)$$

The nucleon tensor is not; it's general (spin-independent, parity conserved) form is:

$$K_{\mu\nu\,\text{nucleon}} = -K_1 g_{\mu\nu} + \frac{K_2}{M^2} p_\mu p_\nu + \frac{K_4}{M^2} q_\mu q_\nu + \frac{K_5}{M^2}\left(p_\mu q_\nu + p_\nu q_\mu\right)$$

Charge conservation at the proton vertex reduces the number of structure functions:

$$q_\mu K^{\mu\nu}_{\text{nucleon}} \quad \rightarrow \quad K_4 = f(K_1, K_2), \quad K_5 = g(K_2)$$

and one obtains the Rosenbluth form, with electric and magnetic form factors:

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4ME\sin^2(\theta/2)}\right)^2 \frac{E'}{E}\left[2K_1\sin^2(\theta/2) + K_2\cos^2(\theta/2)\right], \qquad K_{1,2}(q^2)$$

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.

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

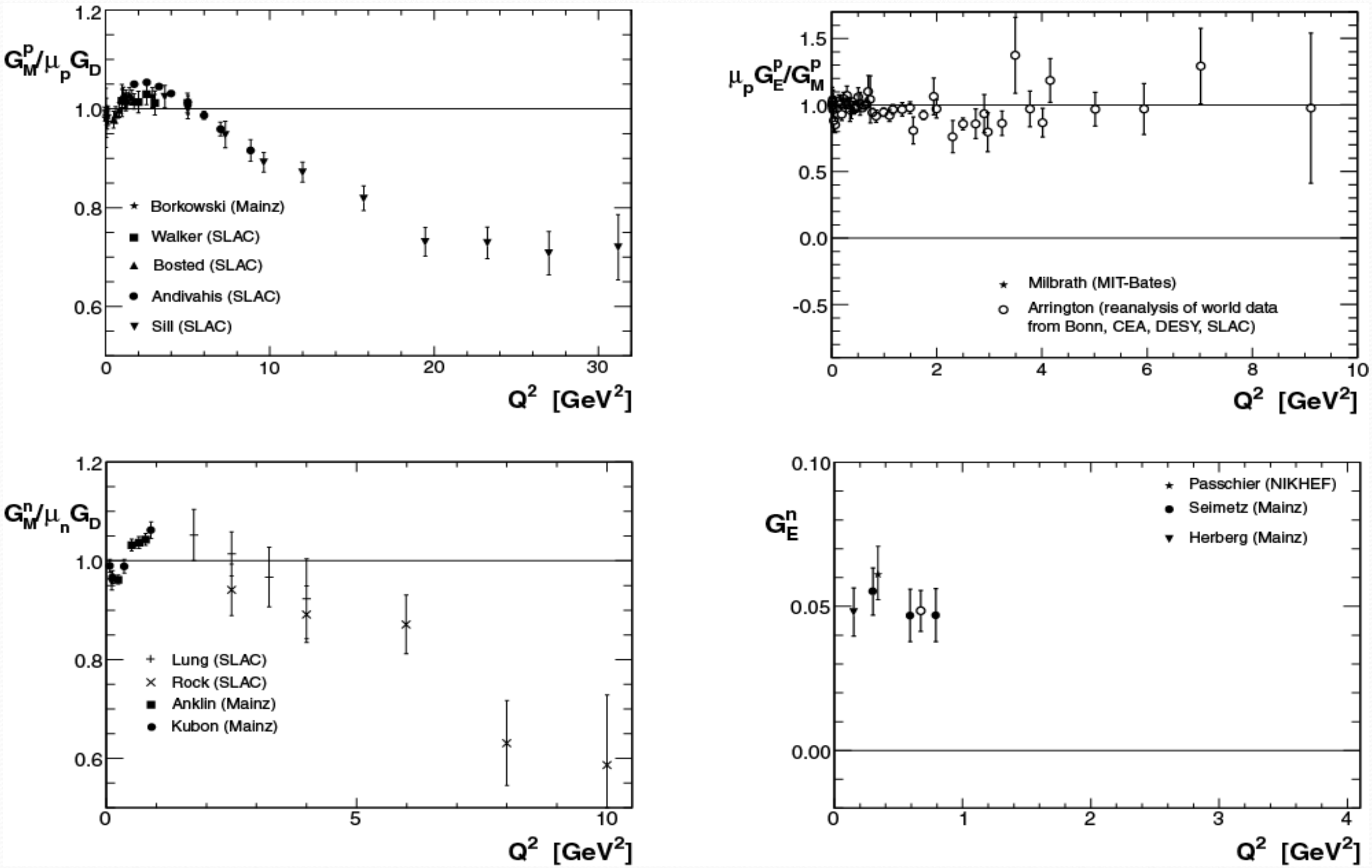
$Q^2 = 4\,E\,E'\sin^2(\theta/2)$ and $\tau = Q^2/4m_p^2$

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.

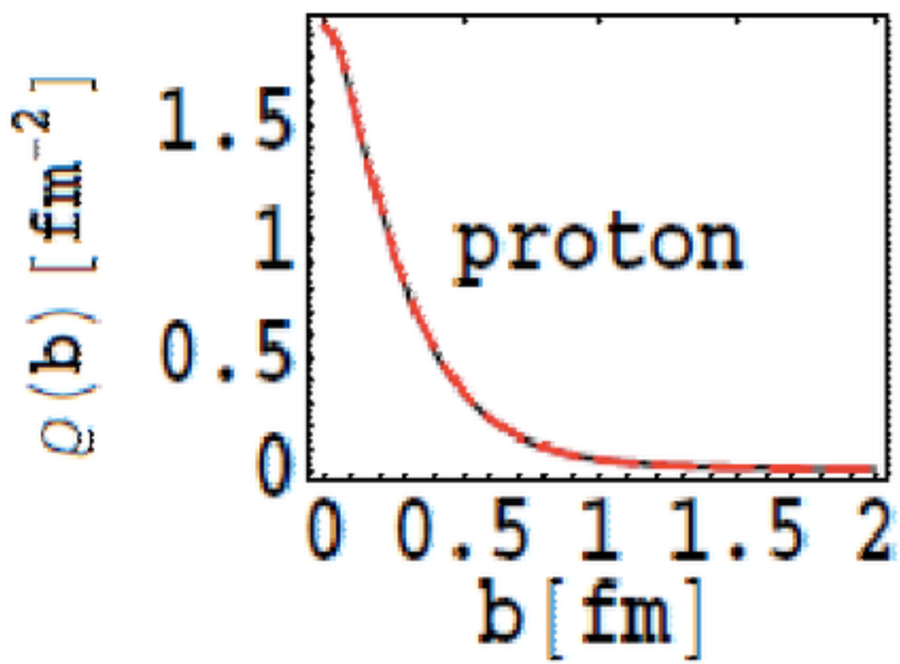
Before JLab and Recent non-JLab Data

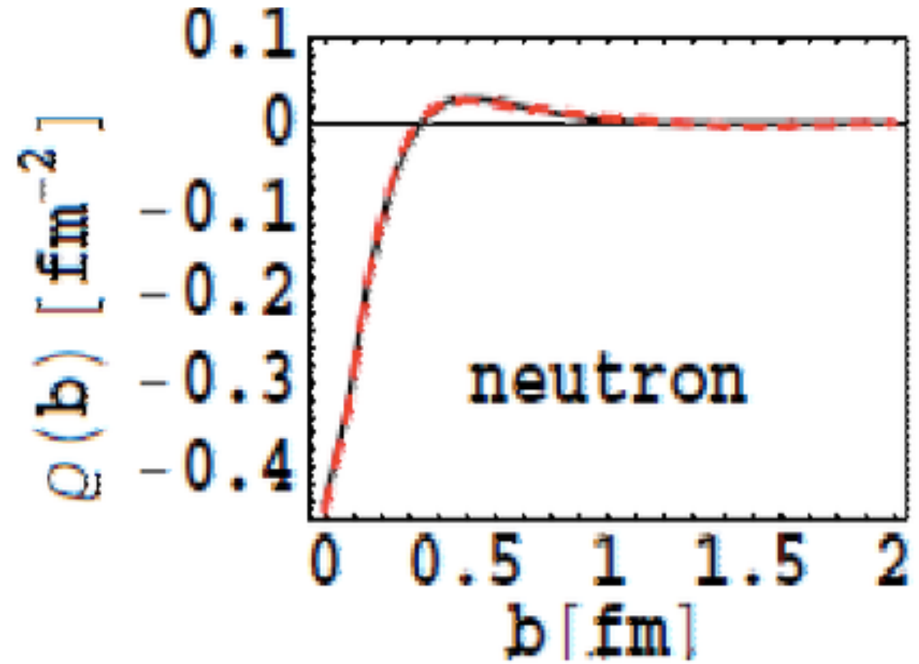


Form Factors → Charge/Current Distributions

(non-relativistic)

Elastic electric form factor ➡ Charge distributions



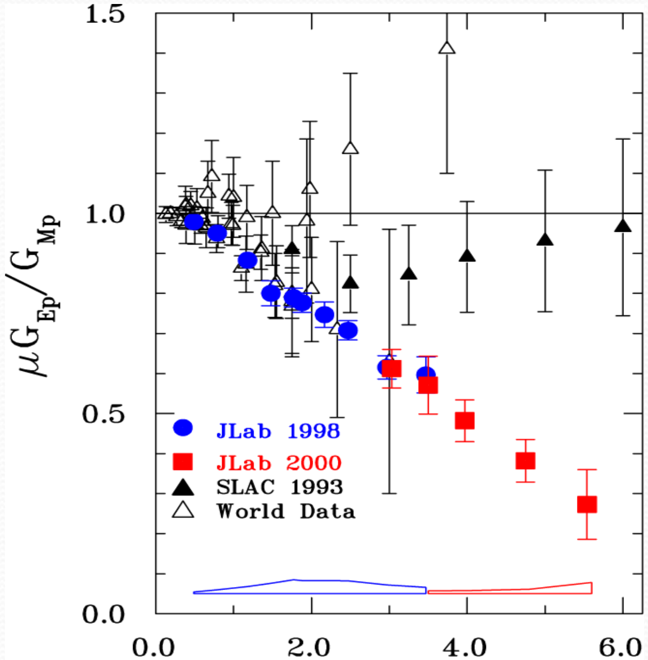


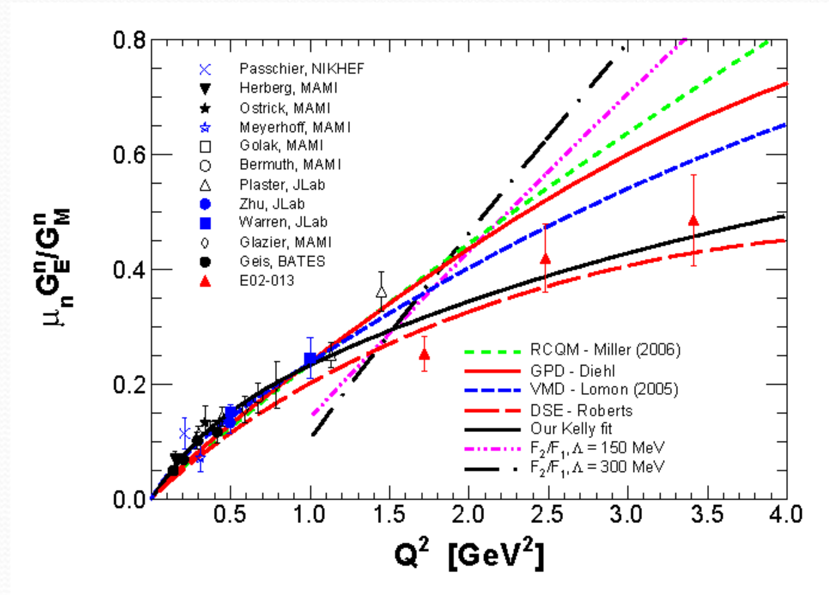
JLab Data on EM Form Factors

Testing Ground for Theories of Nucleon Structure

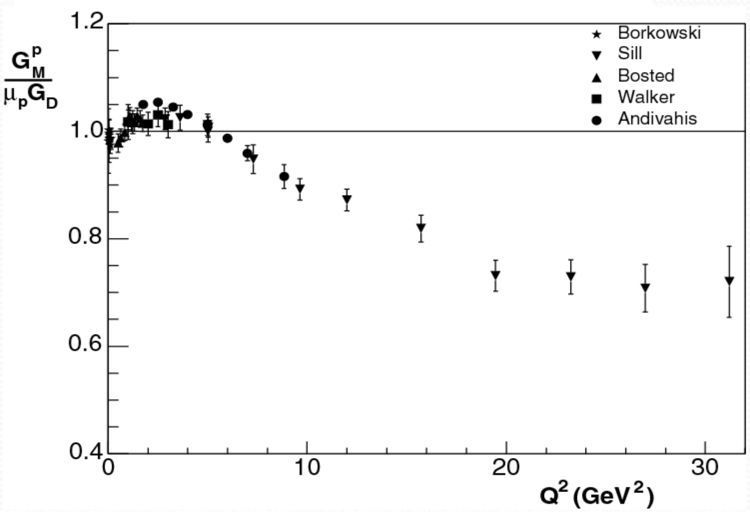
Proton | **Neutron**

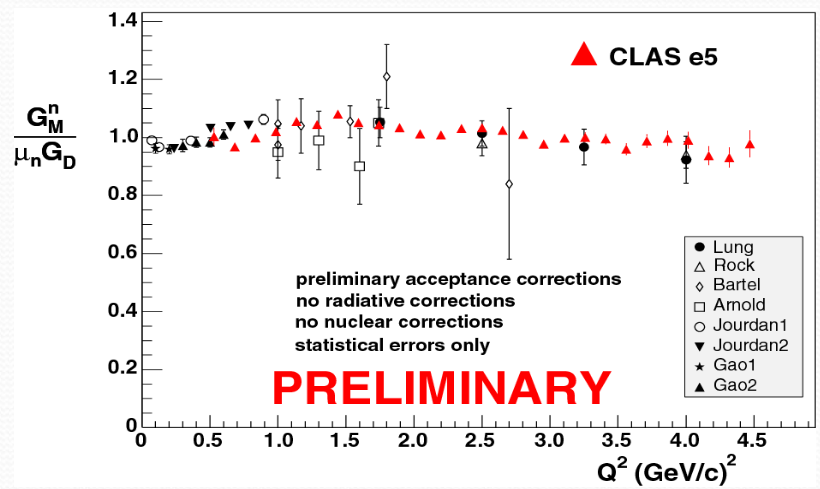
Electric





Magnetic

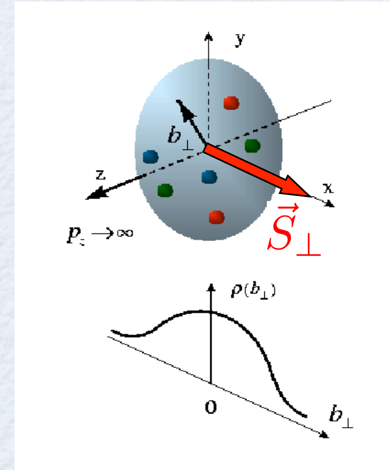


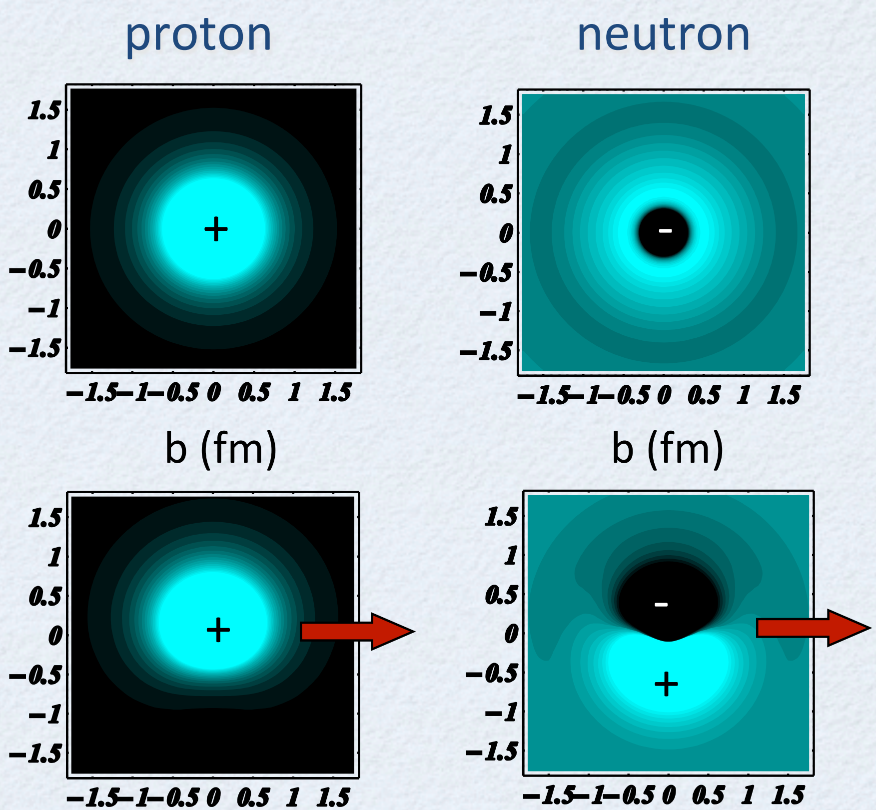


Form factors: 2D light-front densities of hadrons

$$\rho^N(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1(Q^2)$$ → unpolarized Dirac FF F_1

$$+ \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(b\,Q) F_2(Q^2)$$ → transverse polarization Pauli FF F_2





unpolarized charge density

density for transverse polarization

Burkardt (2000,2003)

Miller(2007)

Carlson, Vdh(2008)

G_E^p: JLab Polarization-Transfer Data

Using Focal Plane Polarimeter in Hall A

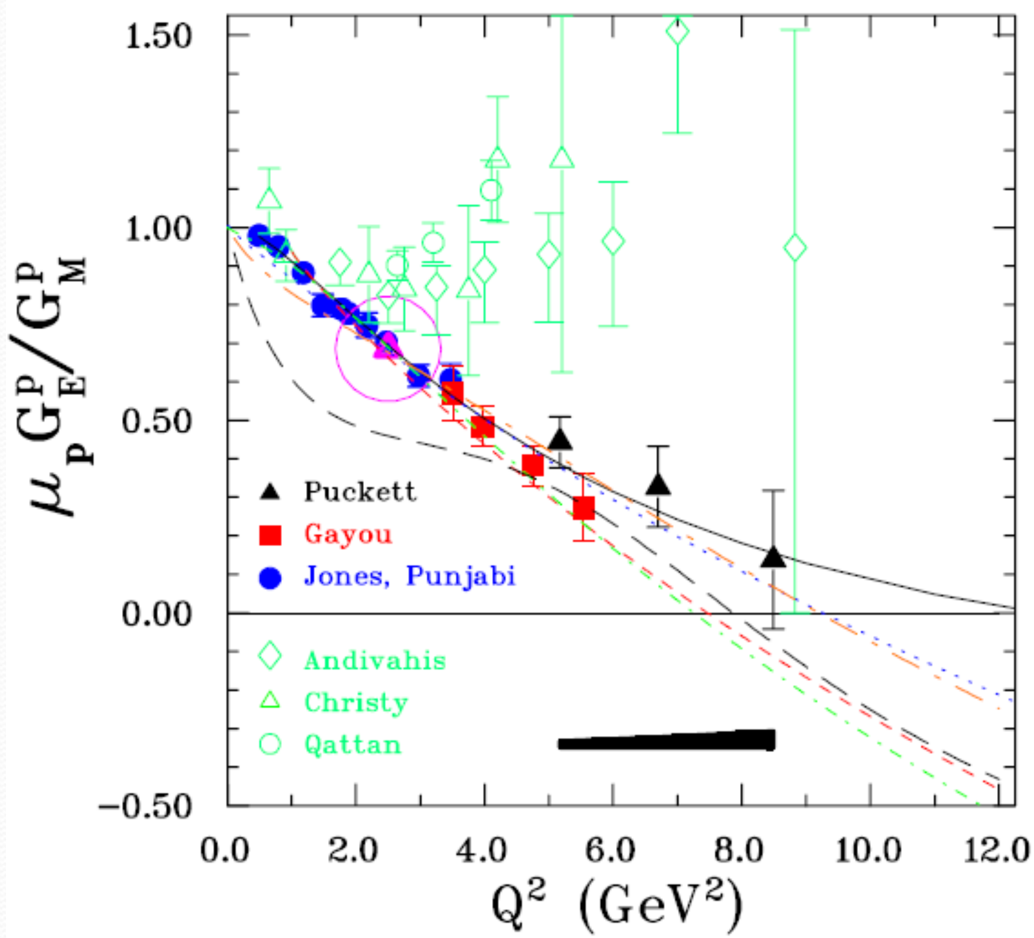
- E93-027 PRL 84, 1398 (2000)
- E99-007 PRL 88, 092301 (2002)
- E04-108, arXiv:1005.3419v2 (2010)

Clear discrepancy between polarization transfer and Rosenbluth data

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

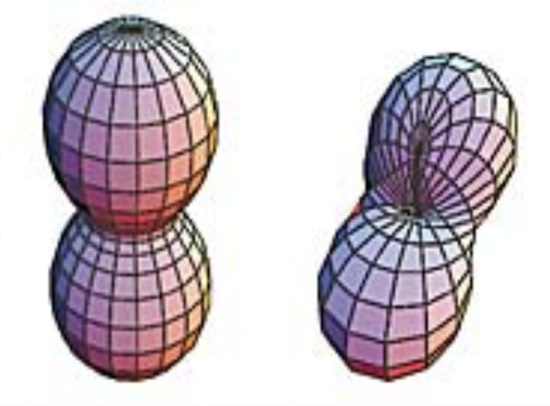
Information on the shape of the proton and the orbital angular momentum.

Transverse density .



The Proton's Shape

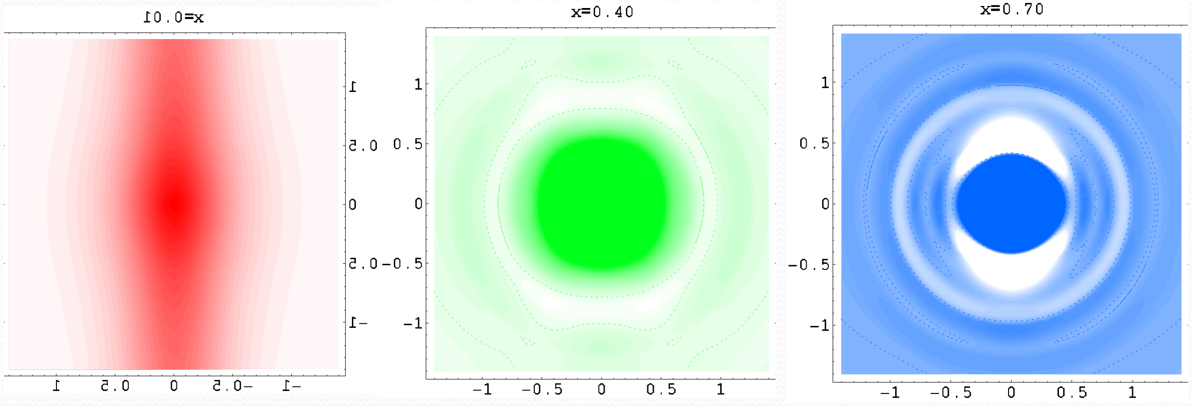
It's a Ball. No, It's a Pretzel.
Must Be a Proton.
(K. Chang, NYT, May 6, 2003)

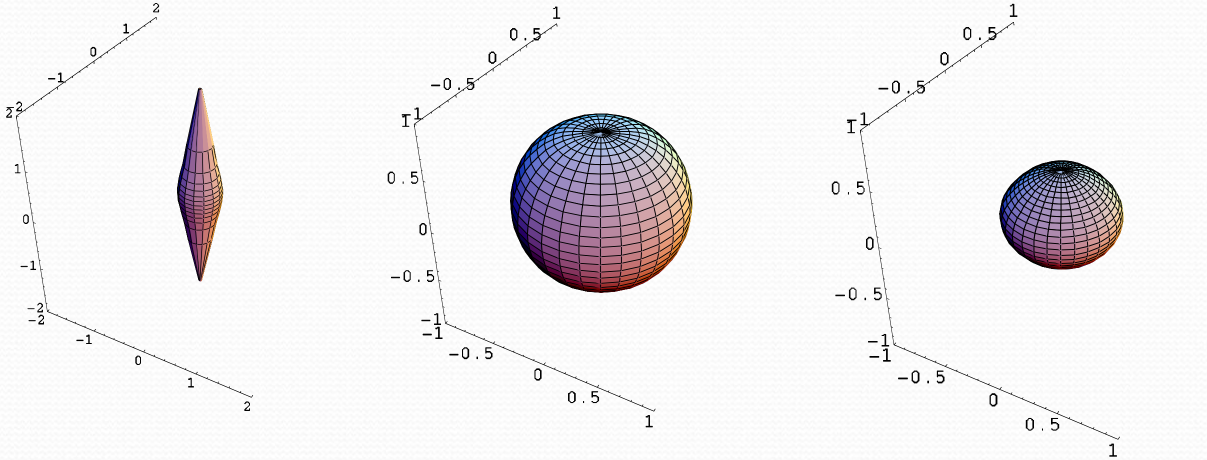


quark spin parallel to that of the proton (left), quark spin perpendicular to the proton spin (right).

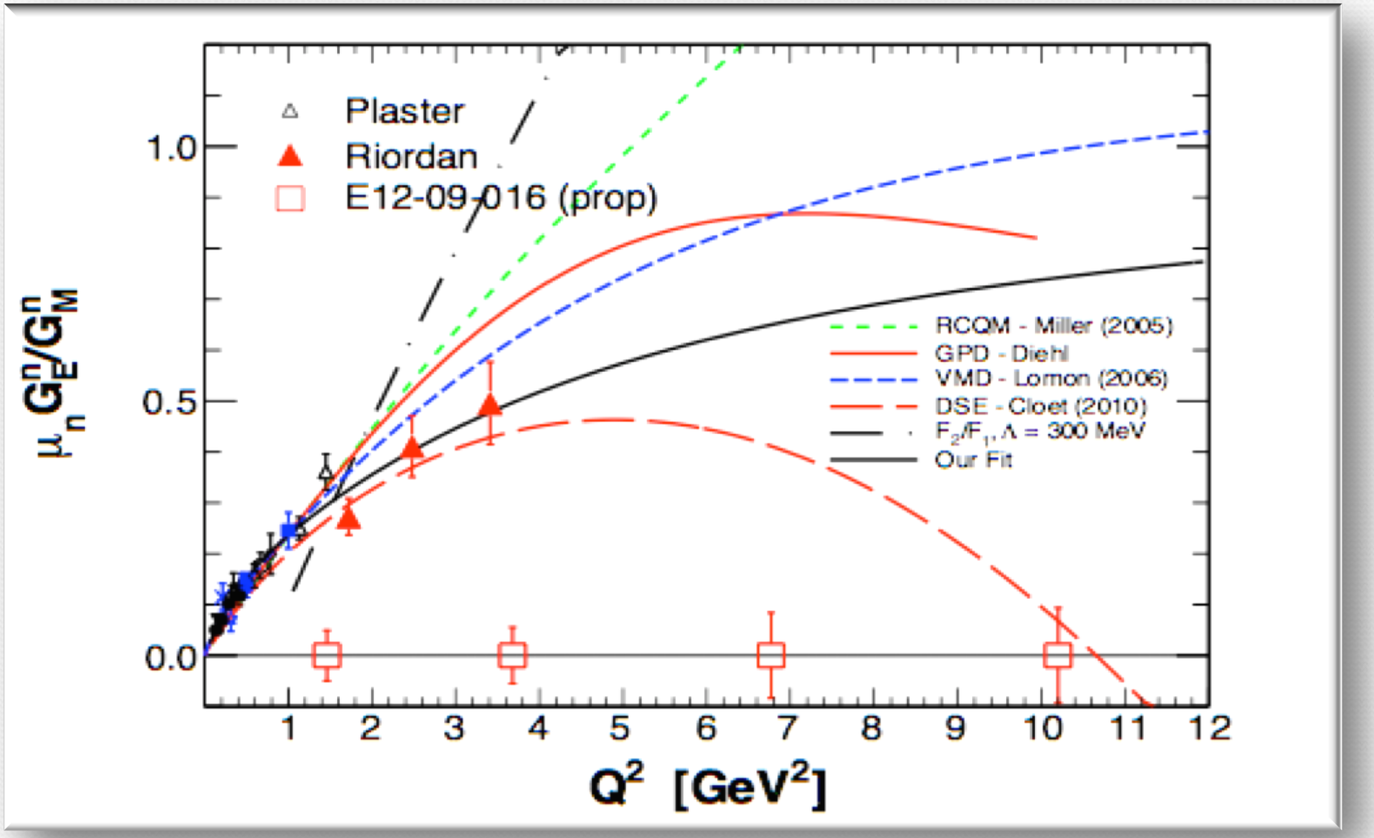
G. Miller, PRC 68, 022201 (03)

Belitsky, Ji and Yuan: PRD 69, 074014(04)



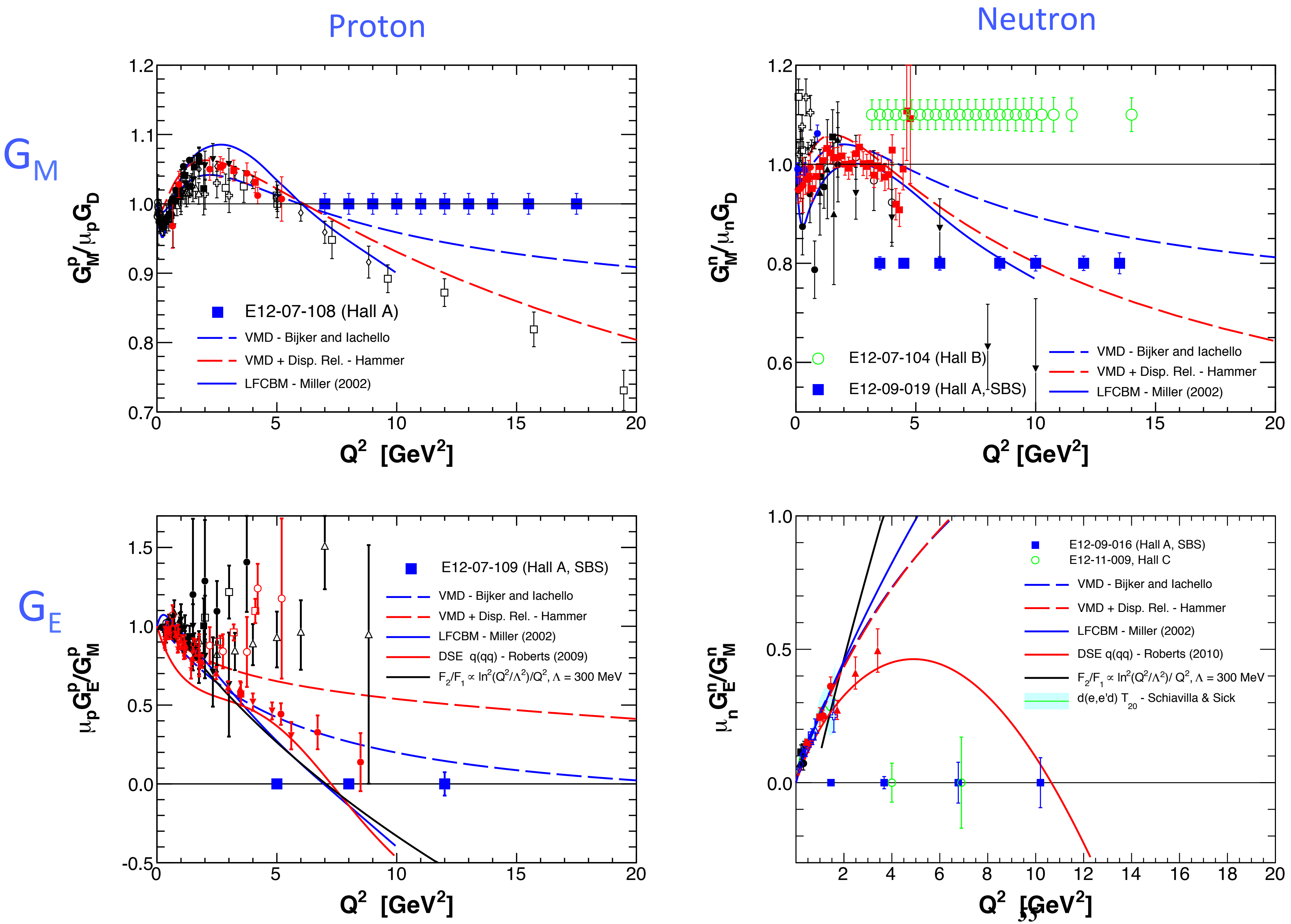


G_E^n: 6 GeV Results and 12 GeV Plan



- *The dramatic turnover of the Argonne DSE model would be clearly visible.*
- *If the turnover is seen, it would provide strong evidence for the importance of diquark degrees of freedom in the nucleon form factors.*

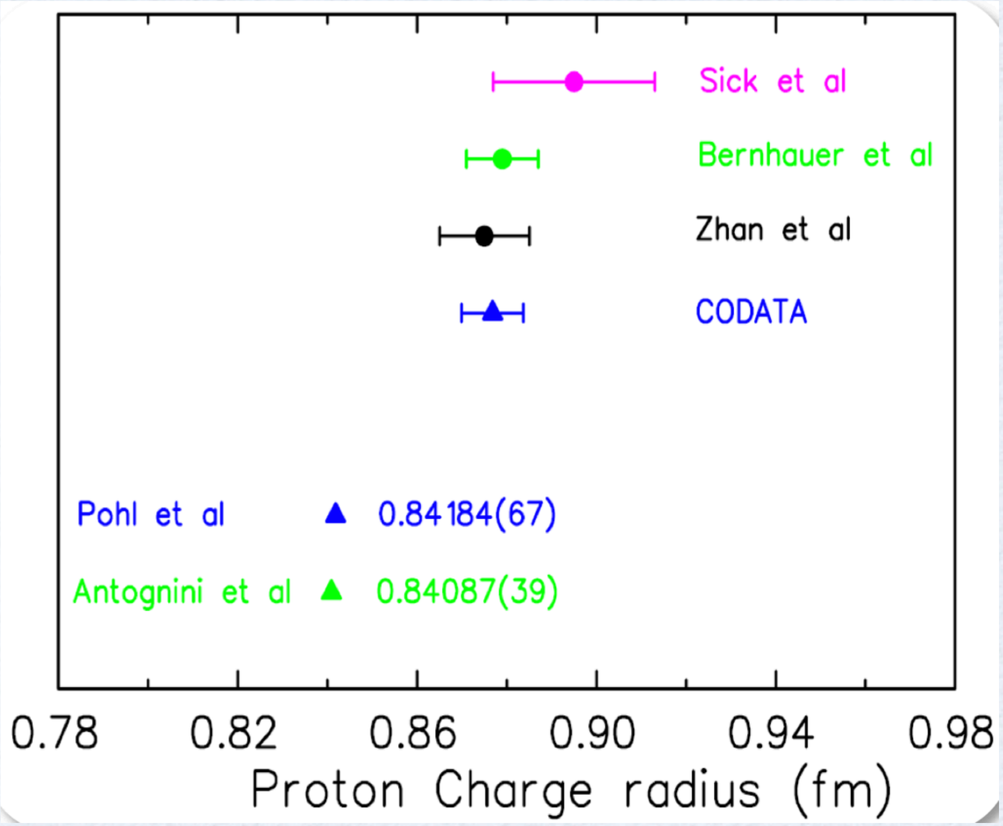
Planned JLab Measurements of Form Factors



Proton Radius Puzzle

Electron probe vs. muon probe

Proton radius puzzle



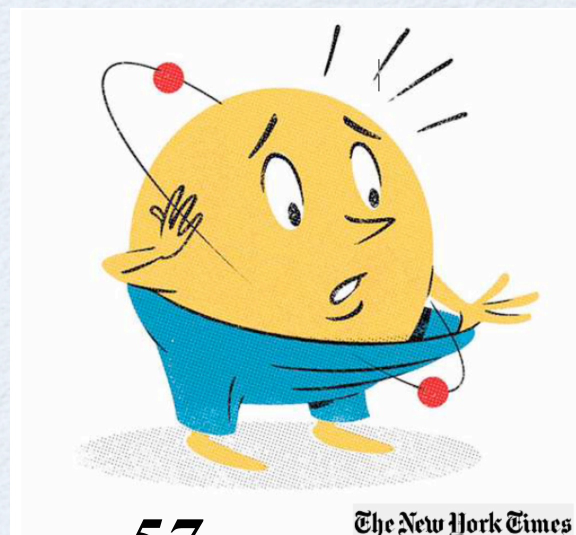
μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

Antognini et al. (2013)

7 σ difference !?

ep data: $R_E = 0.8775 \pm 0.0051$ fm



Charge Radius of the Proton

- Proton G_E has no measured minima and it is too light for the Fourier transformation to work in a model independent way.
- Thus for the proton we make use of the fact that as Q^2 goes to zero the charge radius is proportional to the slope of G_E

$$G_E(Q^2) = 1 + \sum_{n\geq 1} \frac{(-1)^n}{(2n+1)!} \langle r^{2n} \rangle \, Q^{2n}$$

$$r_p \equiv \sqrt{\langle r^2 \rangle} = \left(-6 \, \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \Big|_{Q^2=0} \right)^{1/2}$$

We don't measure to Q^2 of zero, so this is going to be an extrapolation problem.

Proton radius puzzle: what's next ?

- μH Lamb shift: muonic D, muonic ^{3}He, ^{4}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: 2π cut)
  - radiative corrections, two-photon exchange corrections

  new fit $R_E = 0.904\ (15)$ fm (4σ from μH) **Lee, Arrington, Hill (2015)**

- electron scattering experiments:

  new G_{Ep} experiments down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

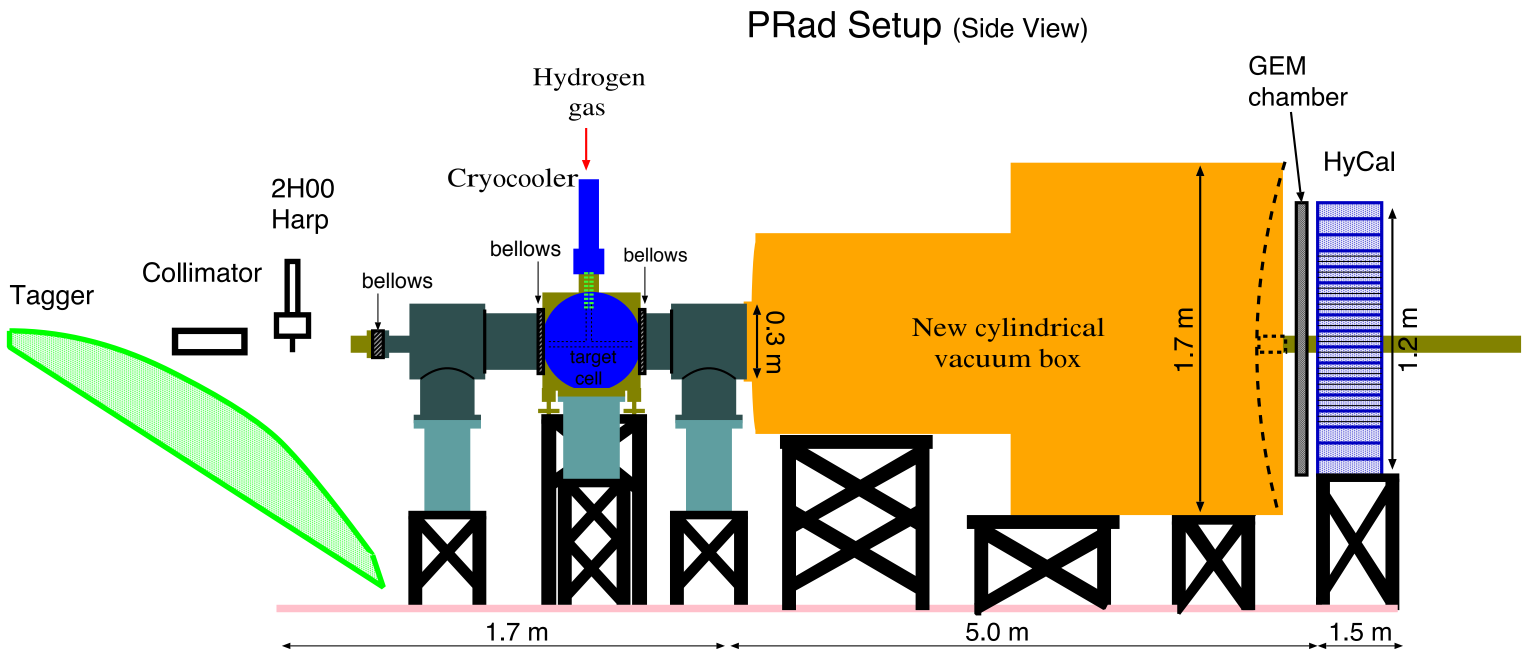
  - MAMI/A1: Initial State Radiation (2013/4)
  - JLab/Hall B: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)
  - MESA: low-energy, high resolution spectrometers (2019)

  see talk: H. Gao

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

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

PRad Experimental Setup in Hall B at JLab



- **High resolution, large acceptance calorimeter**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **GEM detectors**
- **Q^2 range of $2x10^{-4} – 0.14$ GeV^2**

Future sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) µp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

Summary

- Electron Scattering to study Nucleon Structure
- Elastic: Form Factors

    charge/current distributions

    transverse density

    G_E^p @ large Q^2 surprise → shape of proton, 2-γ effects

    proton radius puzzle