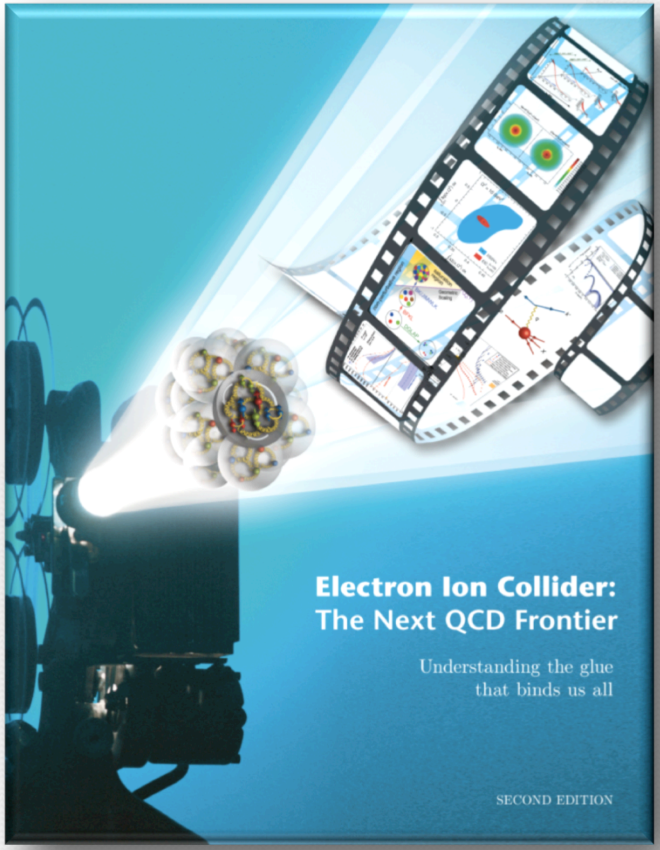
Physics in Electron-Ion Collider Experiments

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

Huada School on QCD 2016: QCD in the EIC Era , May 23 – June 3, 2016

- *I: Introduction and Overview*
- *II: Form Factors and Parton Distributions*
- *III: Spin Structure*
- *IV: 3-d Structure: TMDs and GPDs*
- *V: Quark Gluon Structure of Nuclei*

  Parity Violation



Physics in Electron-Ion Collider Experiments
I: Introduction and Overview

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Huada School on QCD 2016: QCD in the EIC Era , May 23 – June 3, 2016

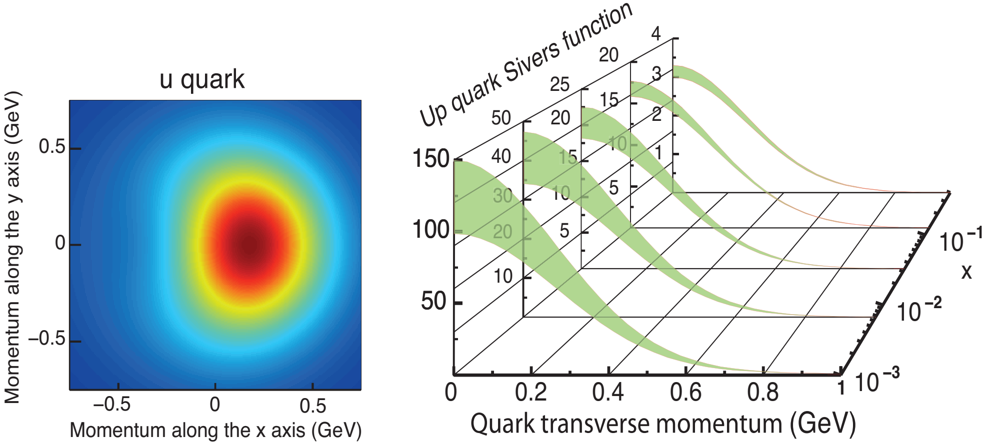
- Introduction and History
- Electron (Lepton) As A Clean Probe
- Facilities:

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

  Eelectron-Ion Collider : HERA, Future EIC
- EIC Experiments:

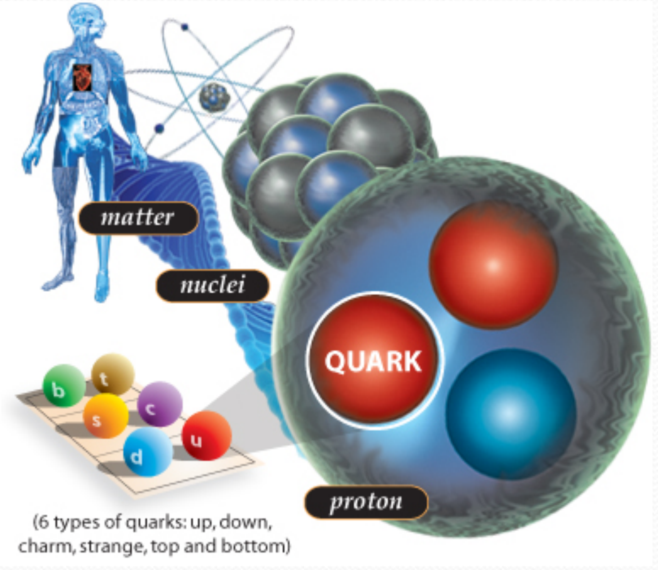
  Focus on e-N

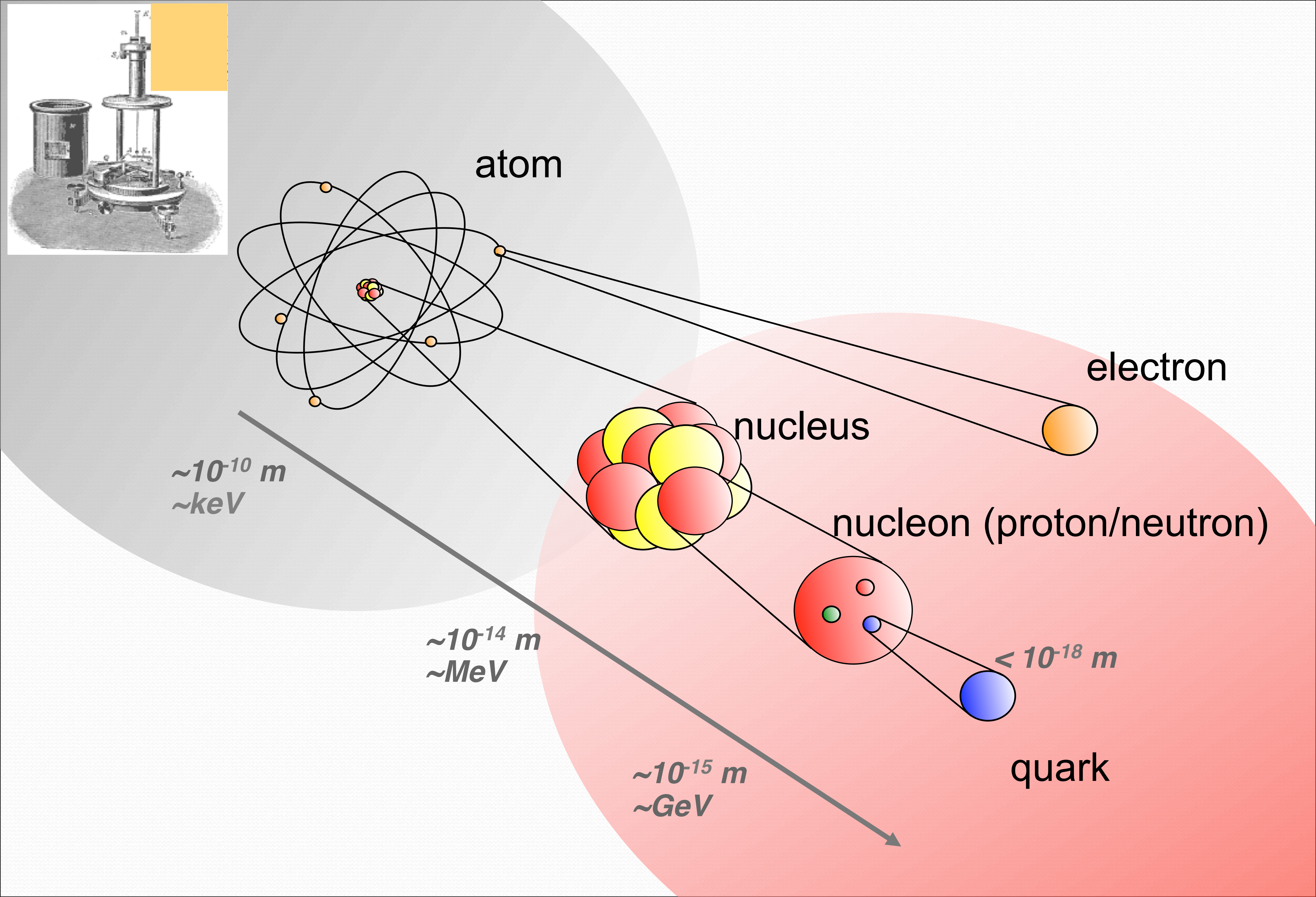
  Touching on e-A, parity



Introduction: What and Why

Nucleon Structure and Strong Interaction (QCD)

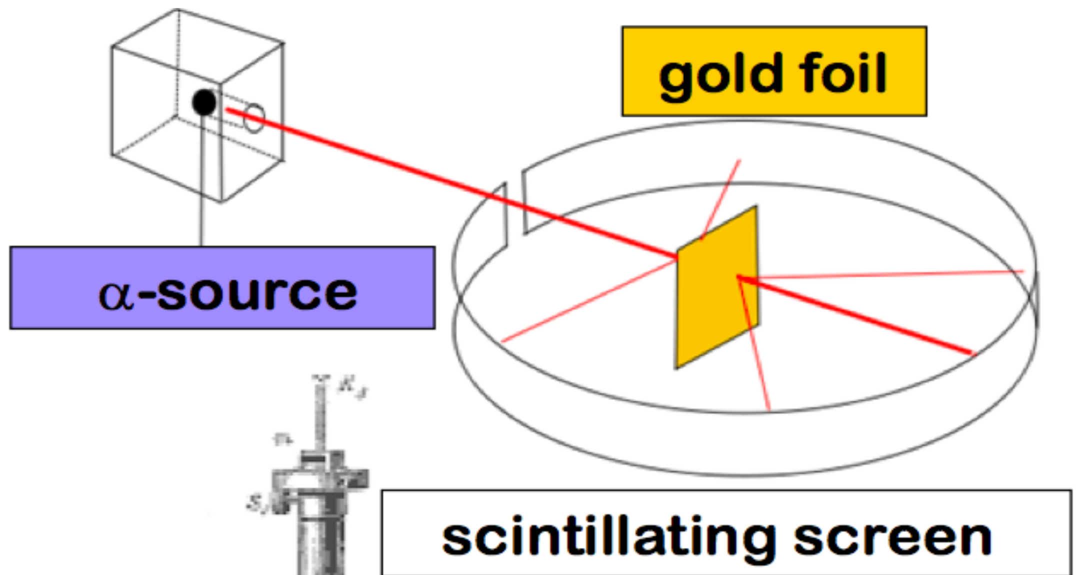


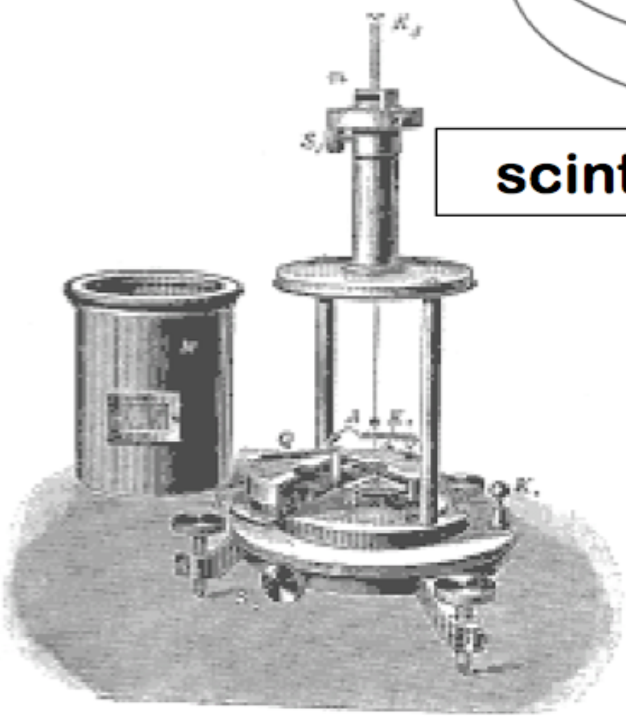

atom
electron
nucleus
nucleon (proton/neutron)
quark
~10^-10 m
~keV
~10^-14 m
~MeV
~10^-15 m
~GeV
< 10^-18 m

Rutherford Scattering

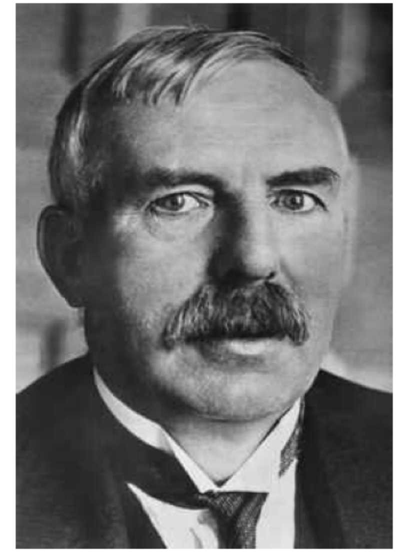
Discovery of Nucleus

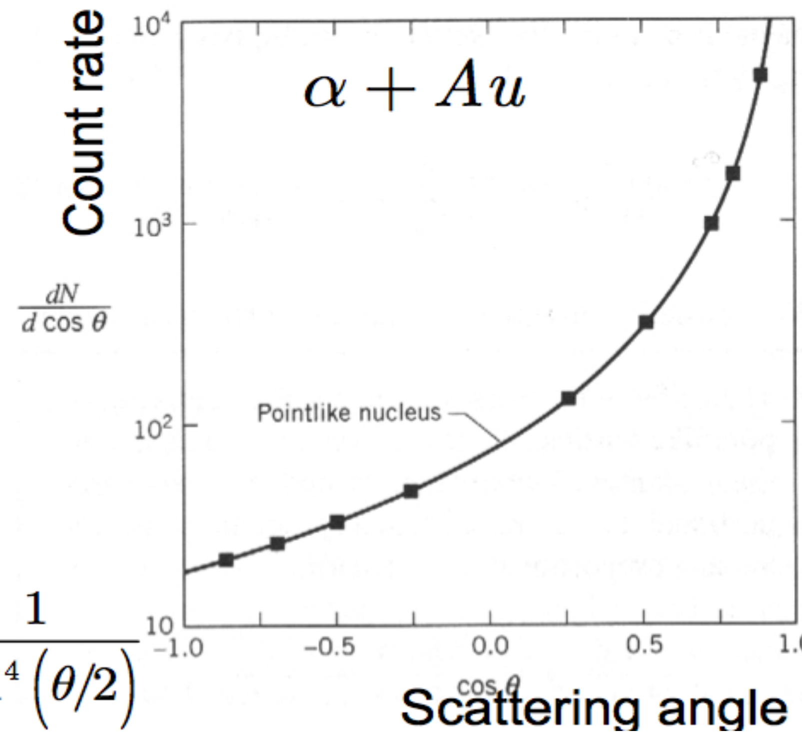
~5 MeV





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

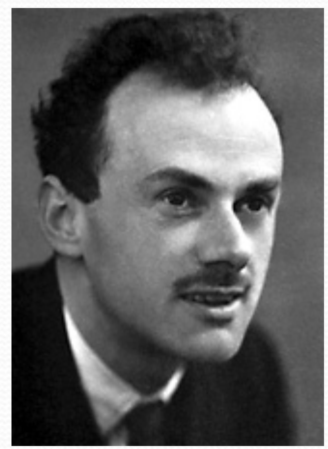
Uhlenbeck and Goudsmit, Pauli

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

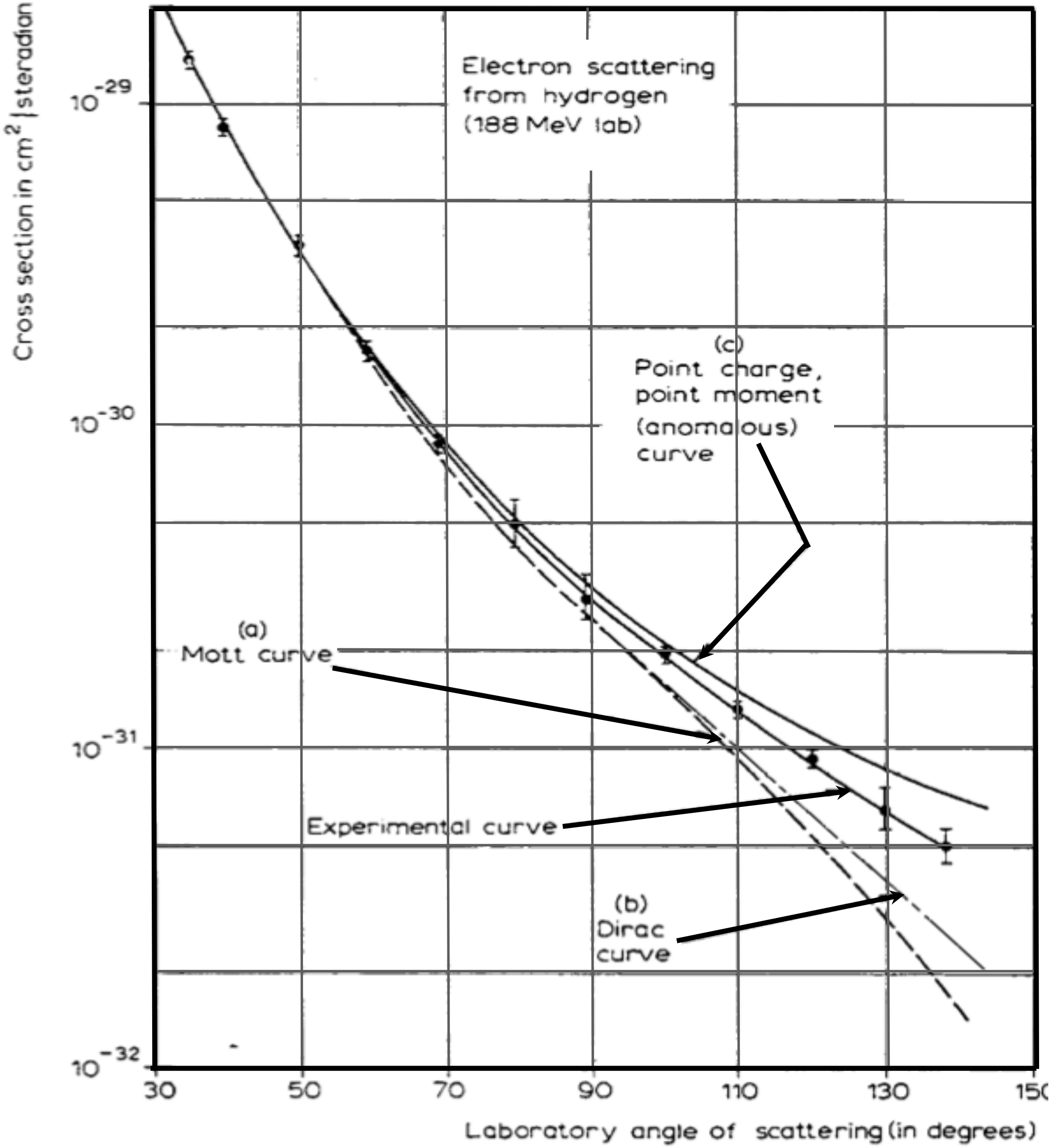
Cecil Frank Powell
Nobel Prize 195

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,

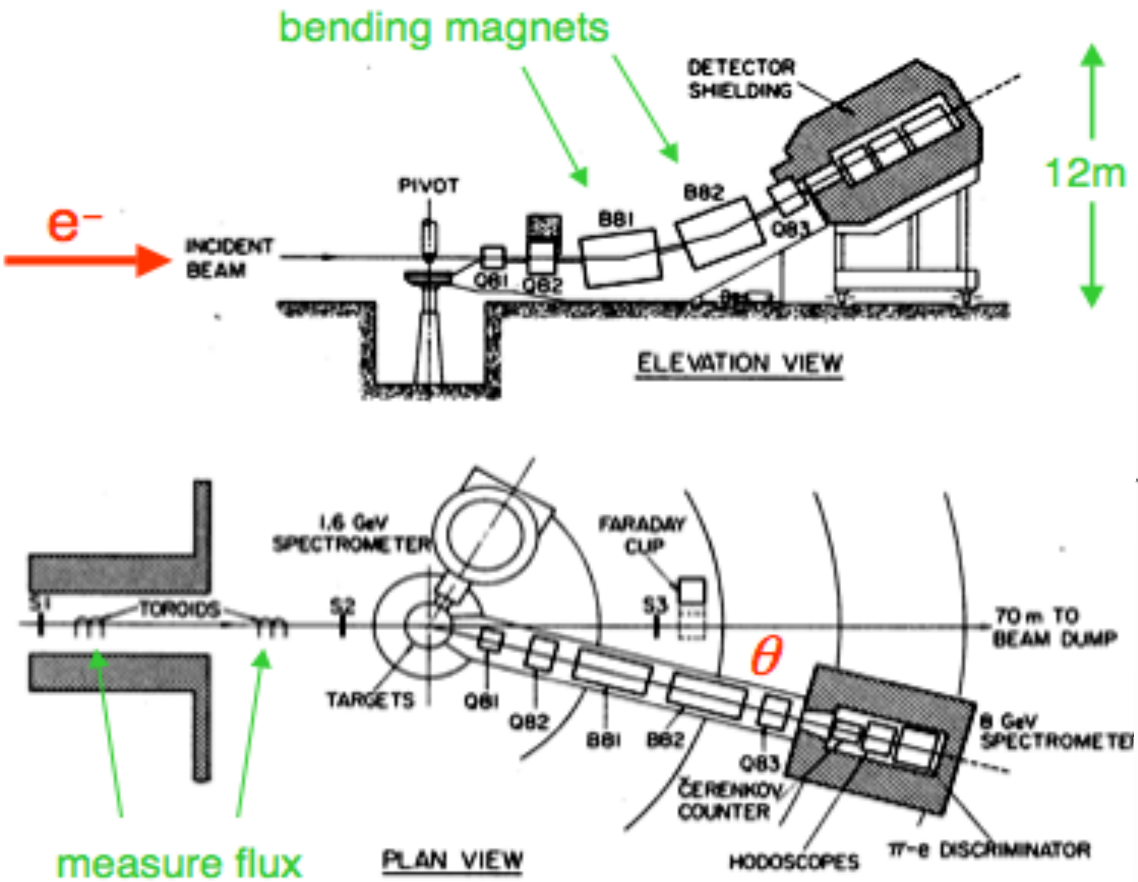
$$g_p \neq 2, \quad g_p \simeq 5.6$$

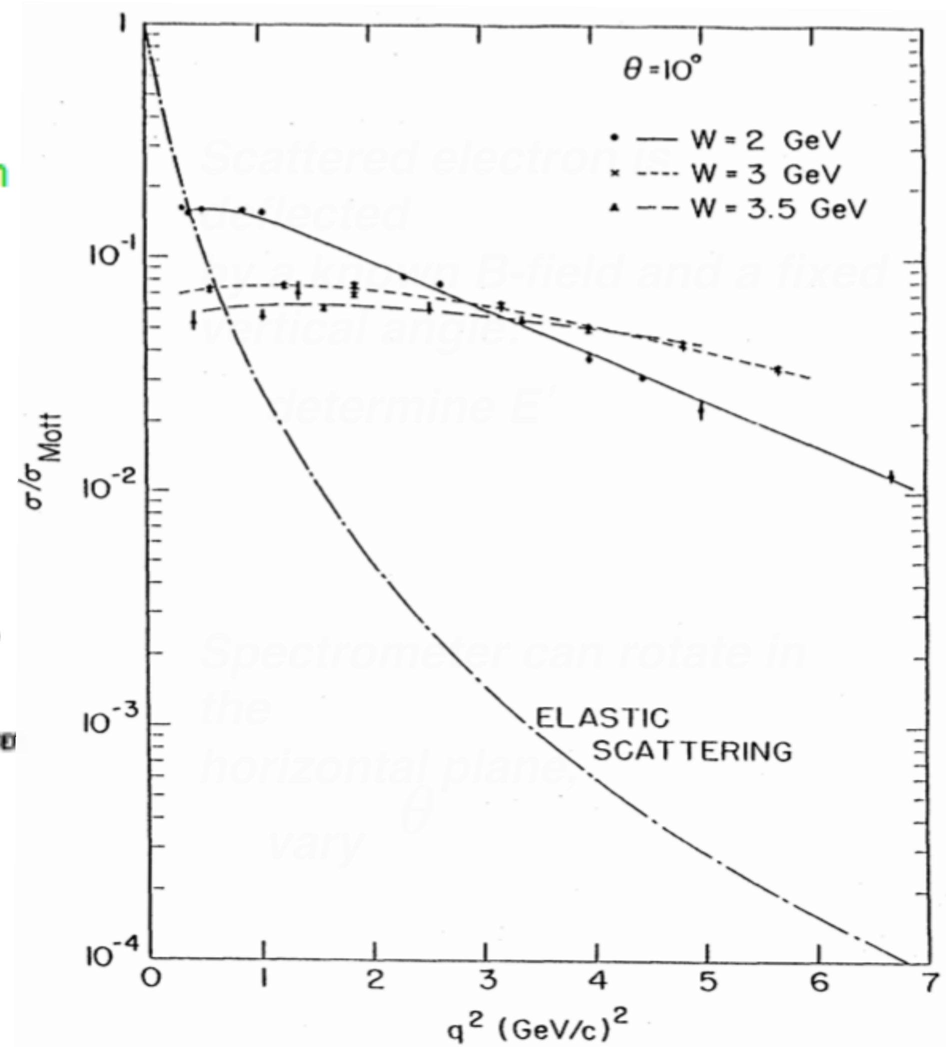
and, hence, internal (spin) structure.

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)

~10 GeV

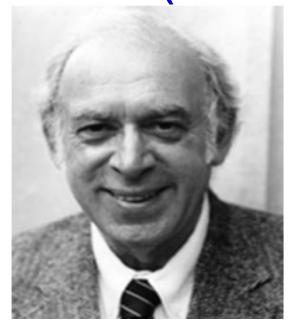




e.g. J.T.Friedman and H.W. Kendall, Ann.Rev.Nucl.Sci. 22 (1972) 203

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)



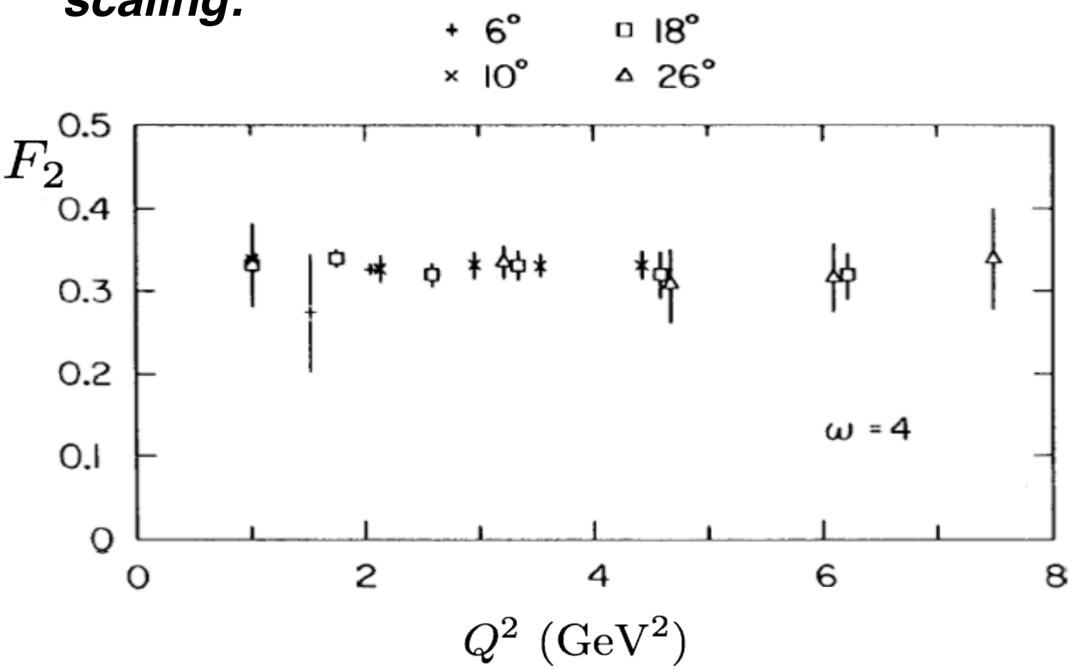
J.T. Friedman

R. Taylor

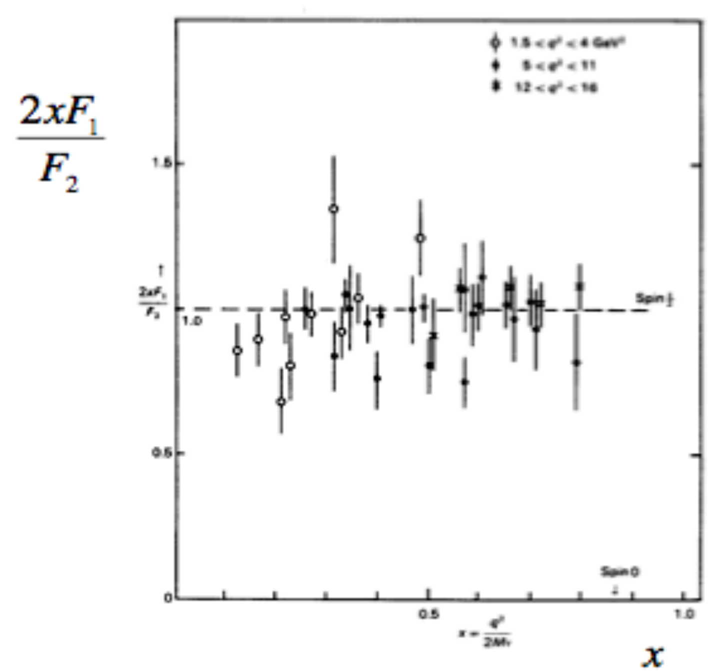
H.W. Kendall

Nobel Prize 1990

Bjorken scaling:



Callan-Gross relation:



spin 1/2

spin 0

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

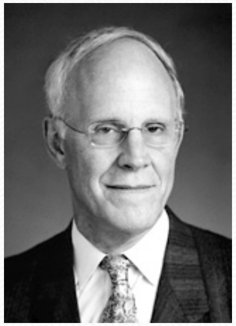
Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

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

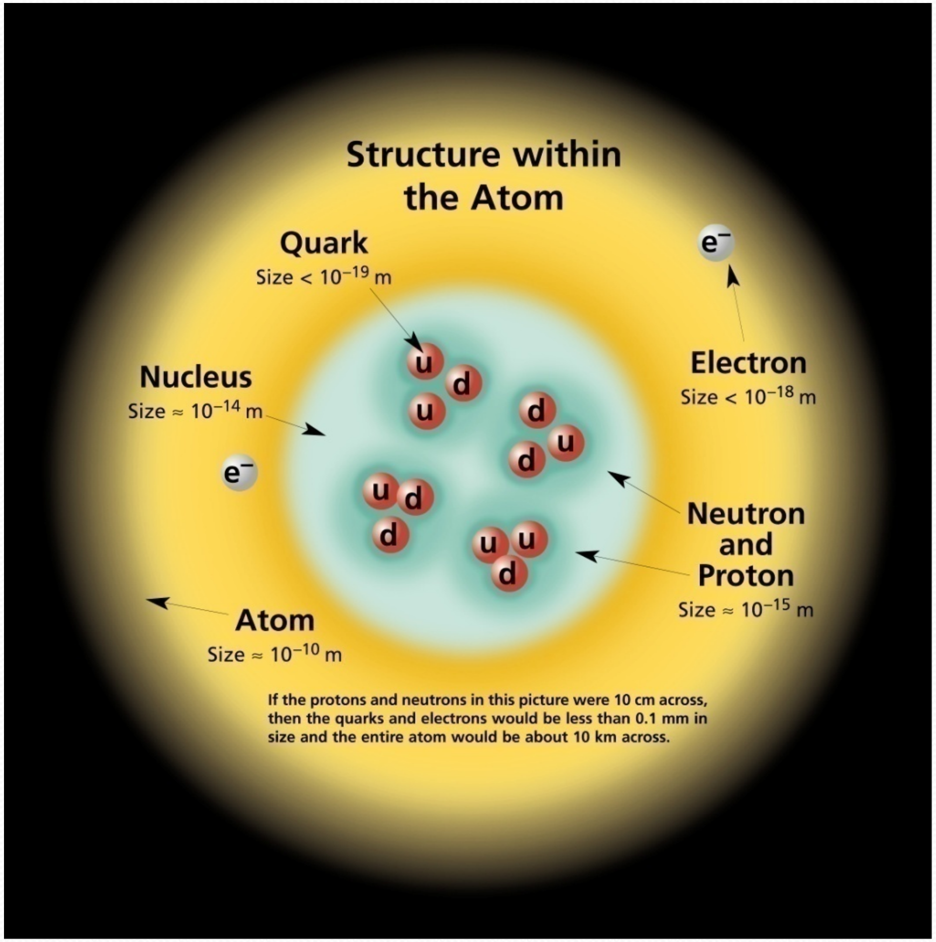


David Gross, H. David Politzer, Frank Wilczek
Nobel Prize 2004

What Is the World Made of?

Visible Matter → Atom → Electrons + Nucleus

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



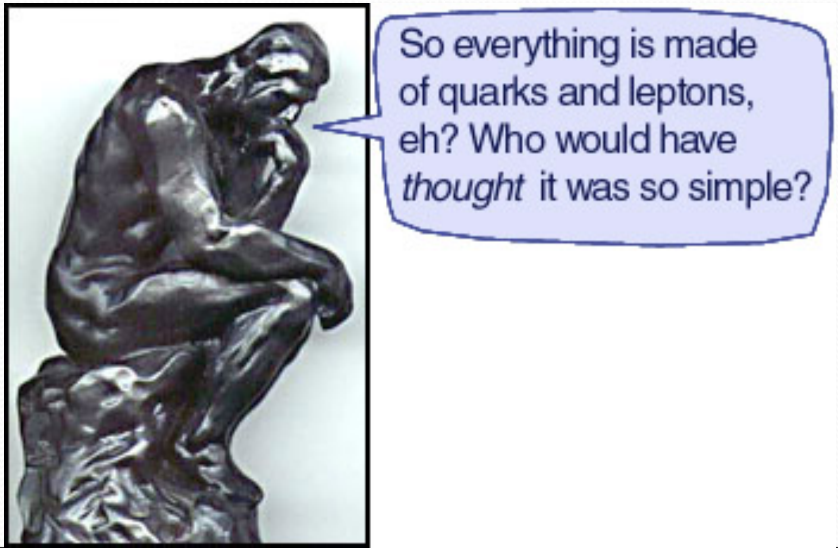
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

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

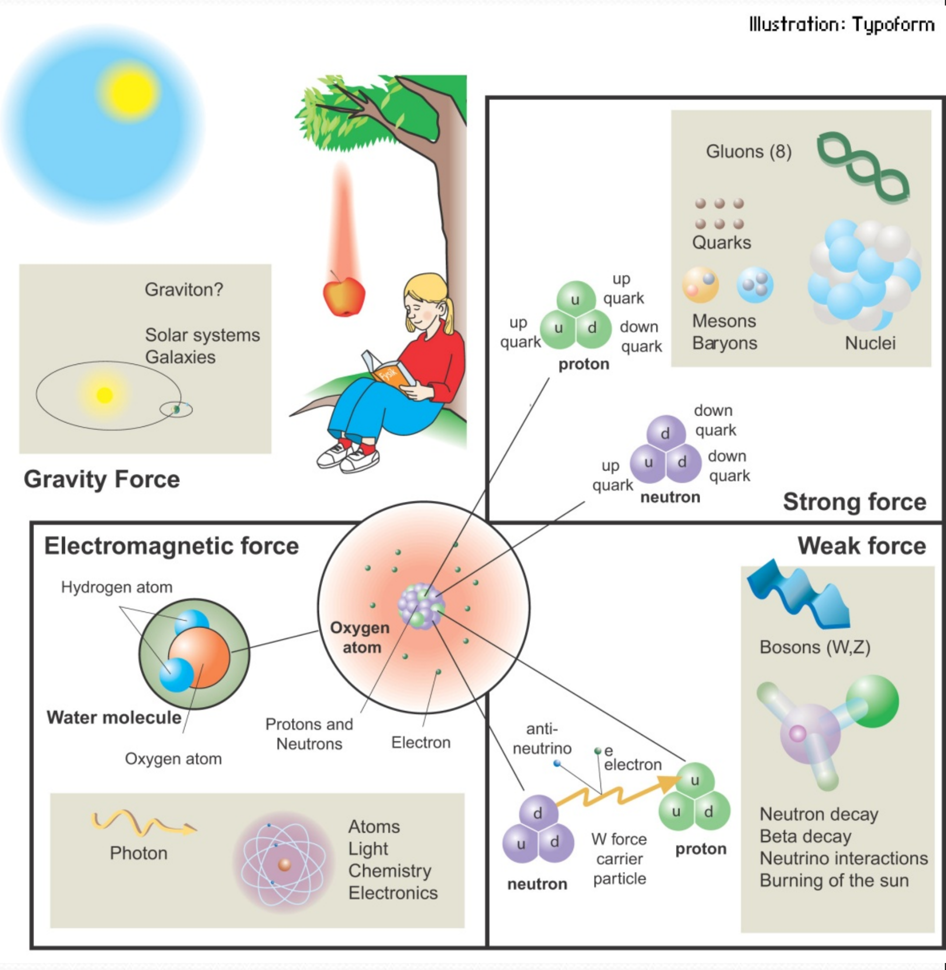
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3



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			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
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ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	–1	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

Interaction / Property	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

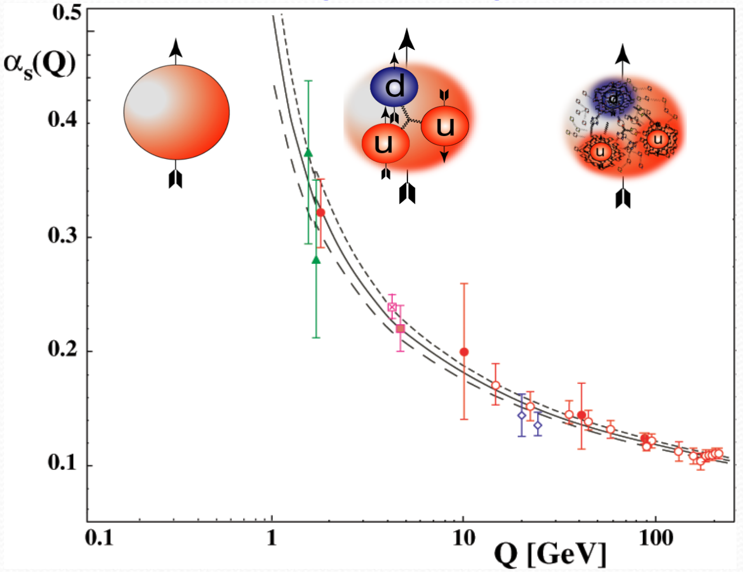
- Beyond Standard Model

  Energy frontier: LHC search Beyond SM

  Precision tests of Standard Model at low energy

  Precision information of nucleon structure needed

running coupling “constant”

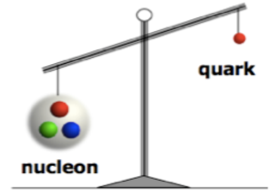


Nucleon Structure: A Universe Inside

- 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



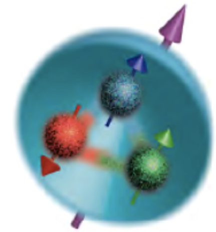
$m_q \sim 10$ MeV

$m_N \sim 1000$ 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?

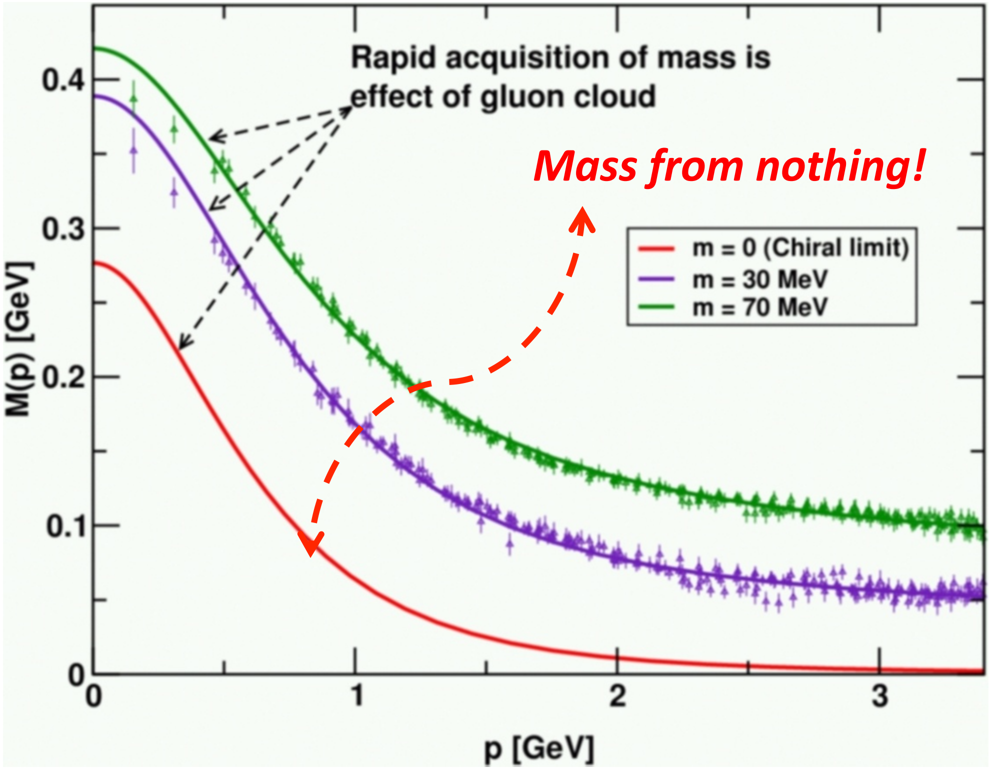
Recent Theoretical Developments

- **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 in TMD: Evolutions, …**
  - **……**

- **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)

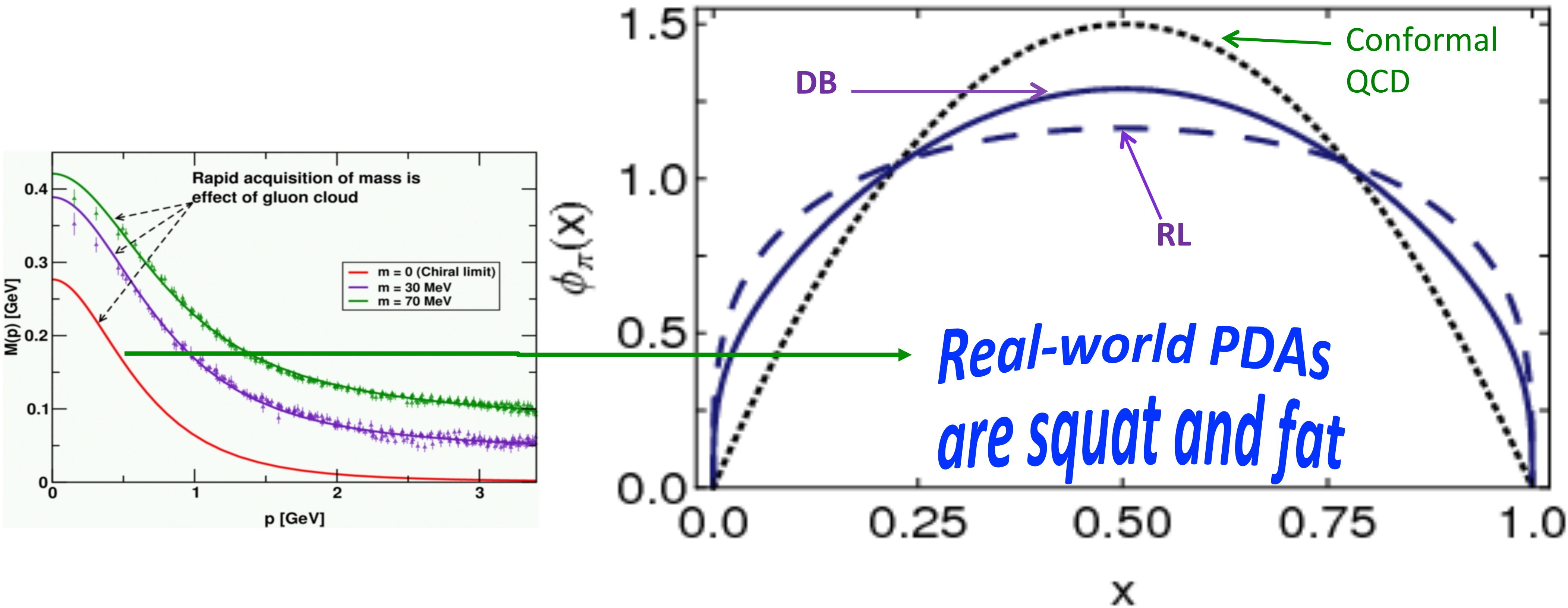


Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, et al., arXiv:1301.0324 [nucl-th],
Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Continuum-QCD prediction:

  marked broadening of $\varphi_\pi(x)$, which owes to DCSB



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

A Clean Probe To Study Nucleon Structure and QCD

Electron Scattering and Nucleon Structure

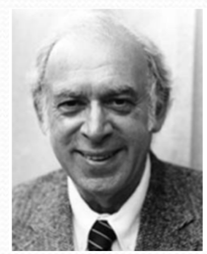
- Clean probe to study nucleon structure
  only electro-weak interaction, well understood

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



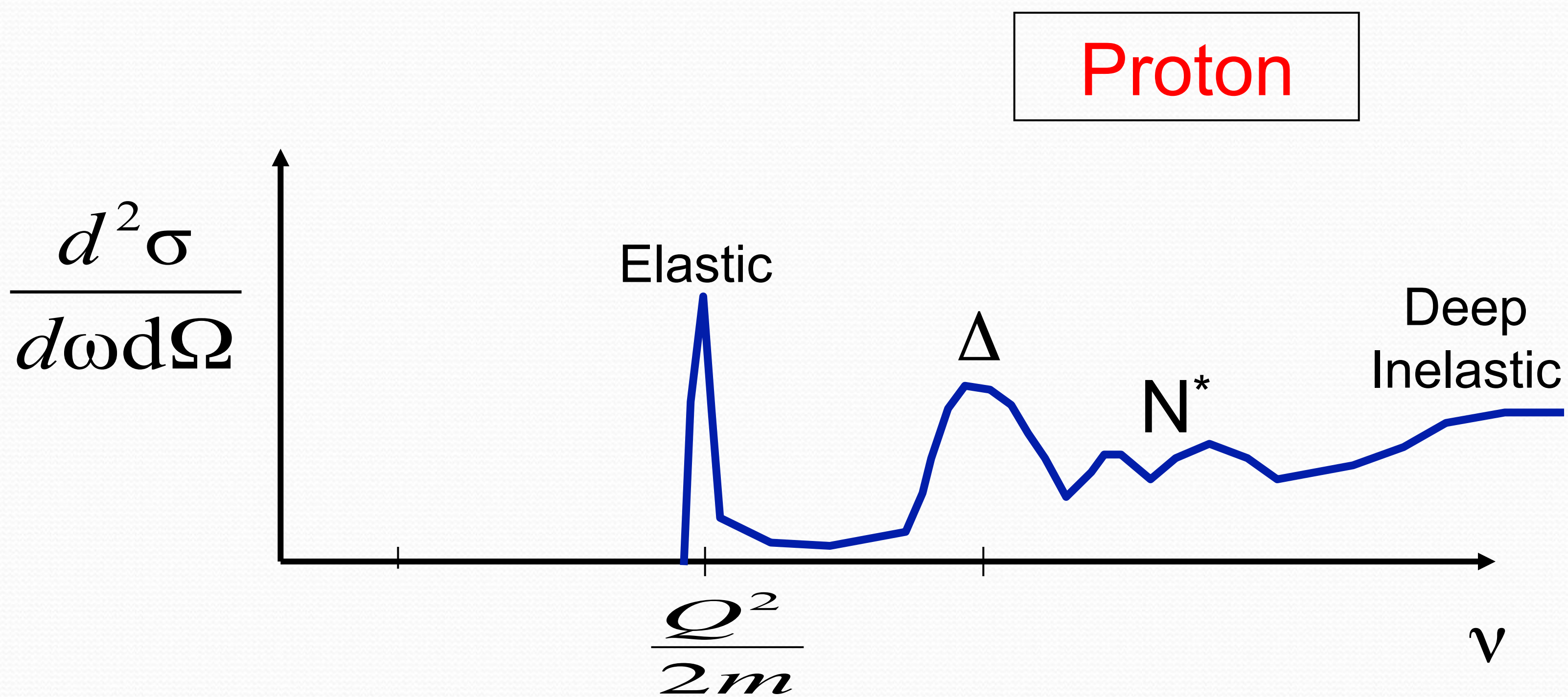
J.T. Friedman

R. Taylor

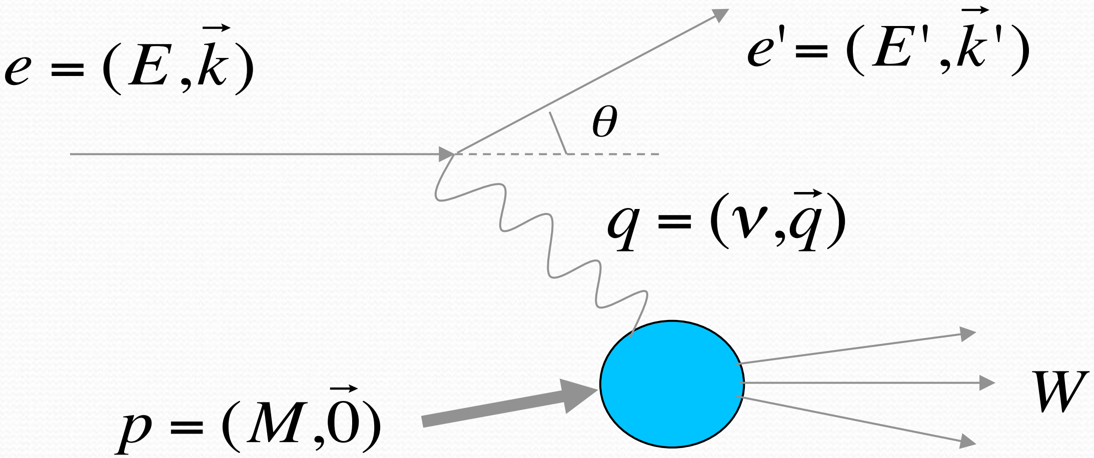
H.W. Kendall

Nobel Prize 1990

Typical Electron Scattering Spectra at Fixed Q^2



Inclusive Electron Scattering



<u>4-momentum transfer squared</u>

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

<u>Invariant mass squared</u>

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

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

Quark-Parton Model

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

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

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

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

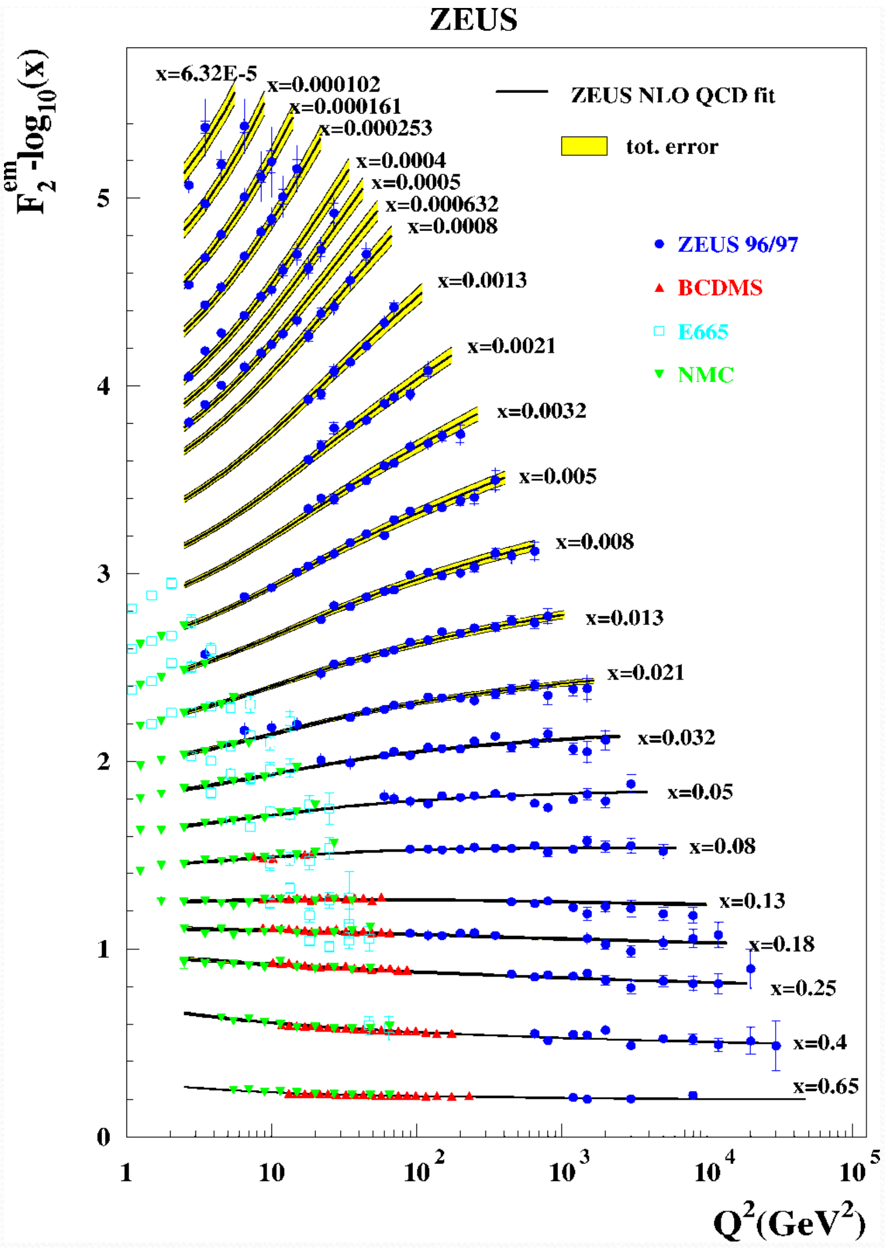
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

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

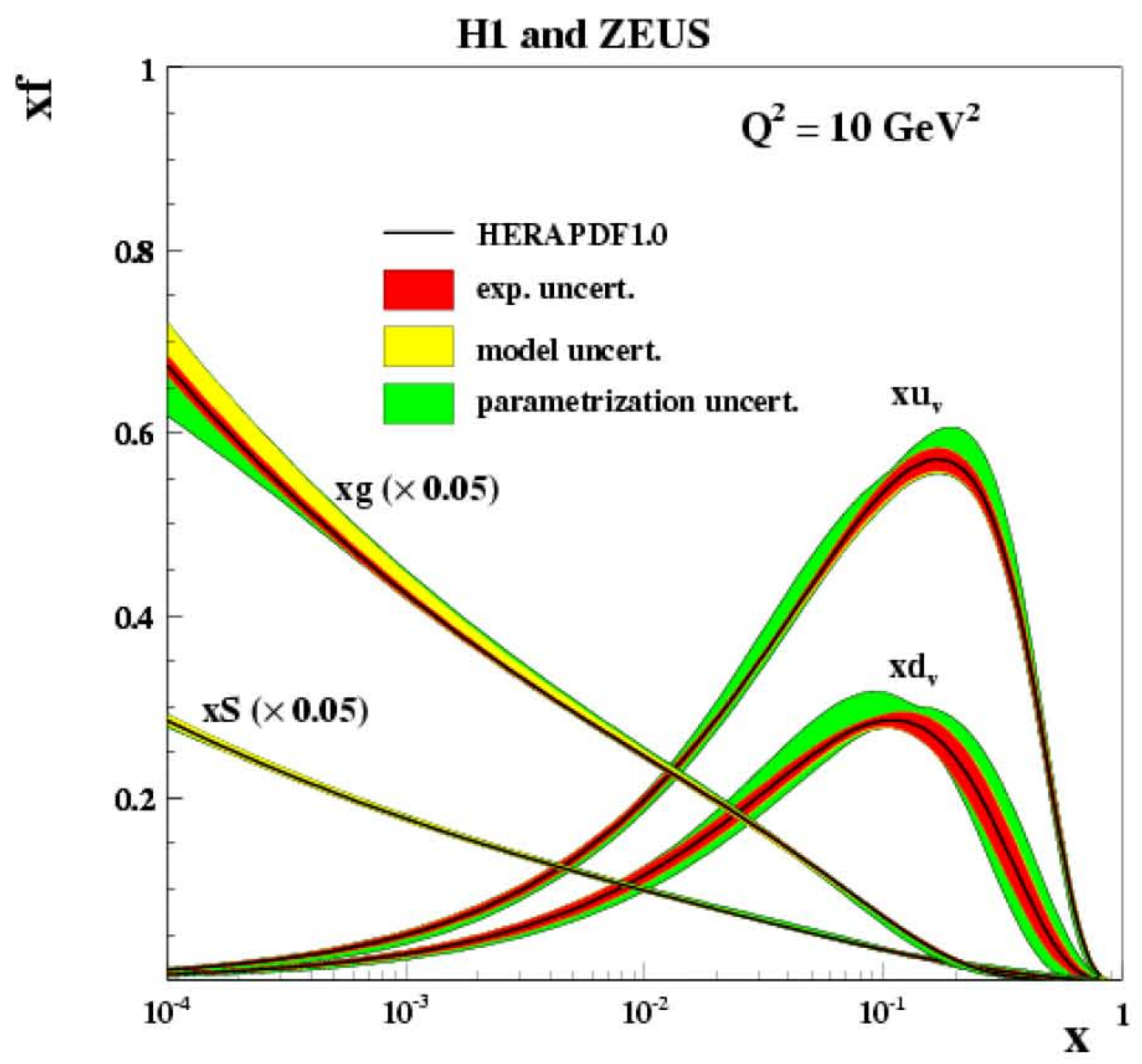
$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\Sigma\, \Delta q_i(x)}{\Sigma\, f_i(x)}$$

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**

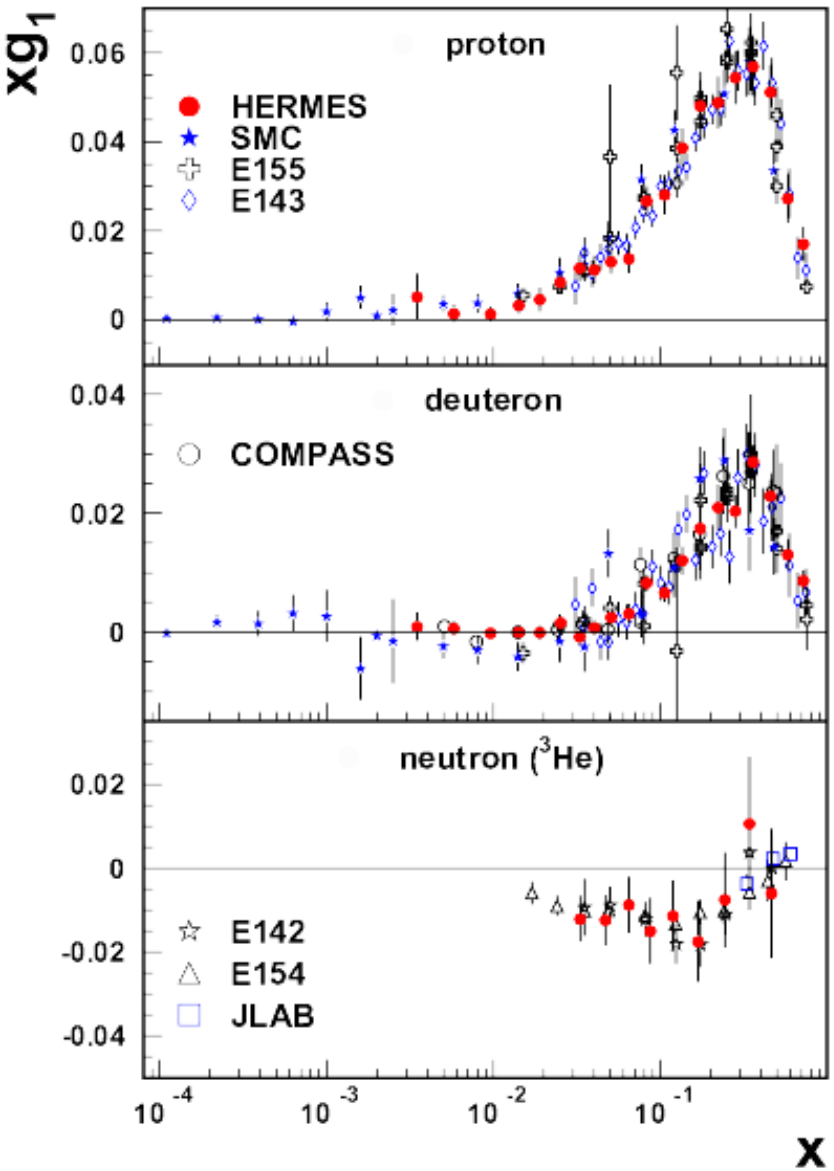


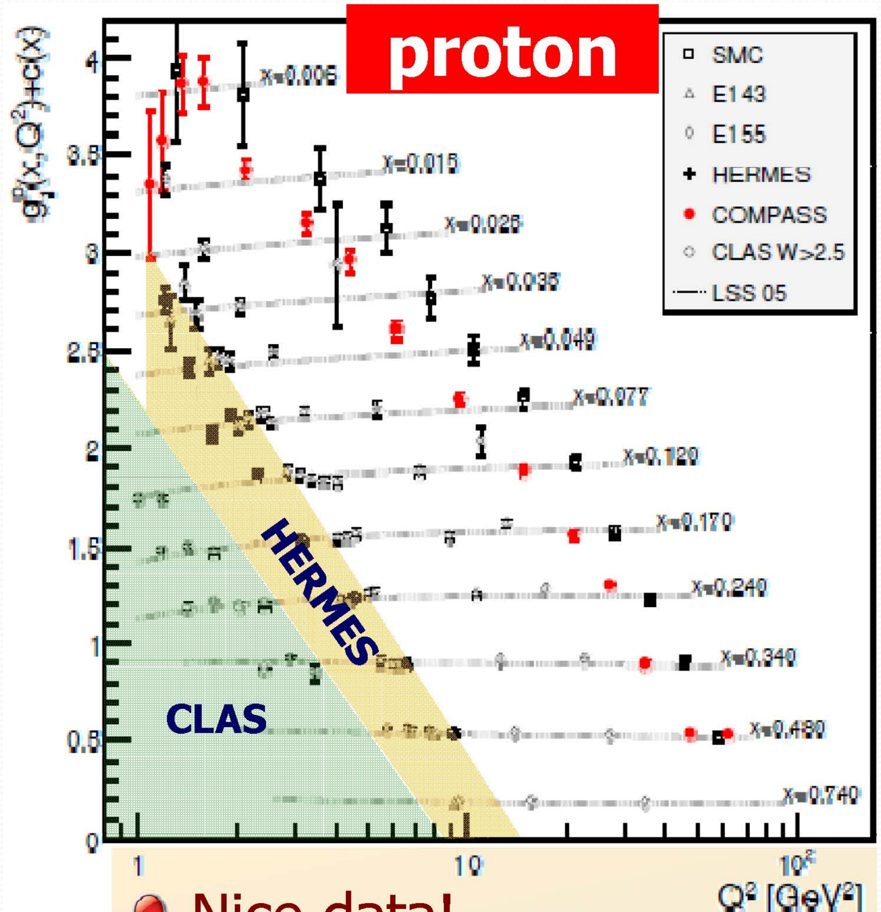
Parton Distribution Functions (CTEQ6)



JHEP 1001: 109 (2010)

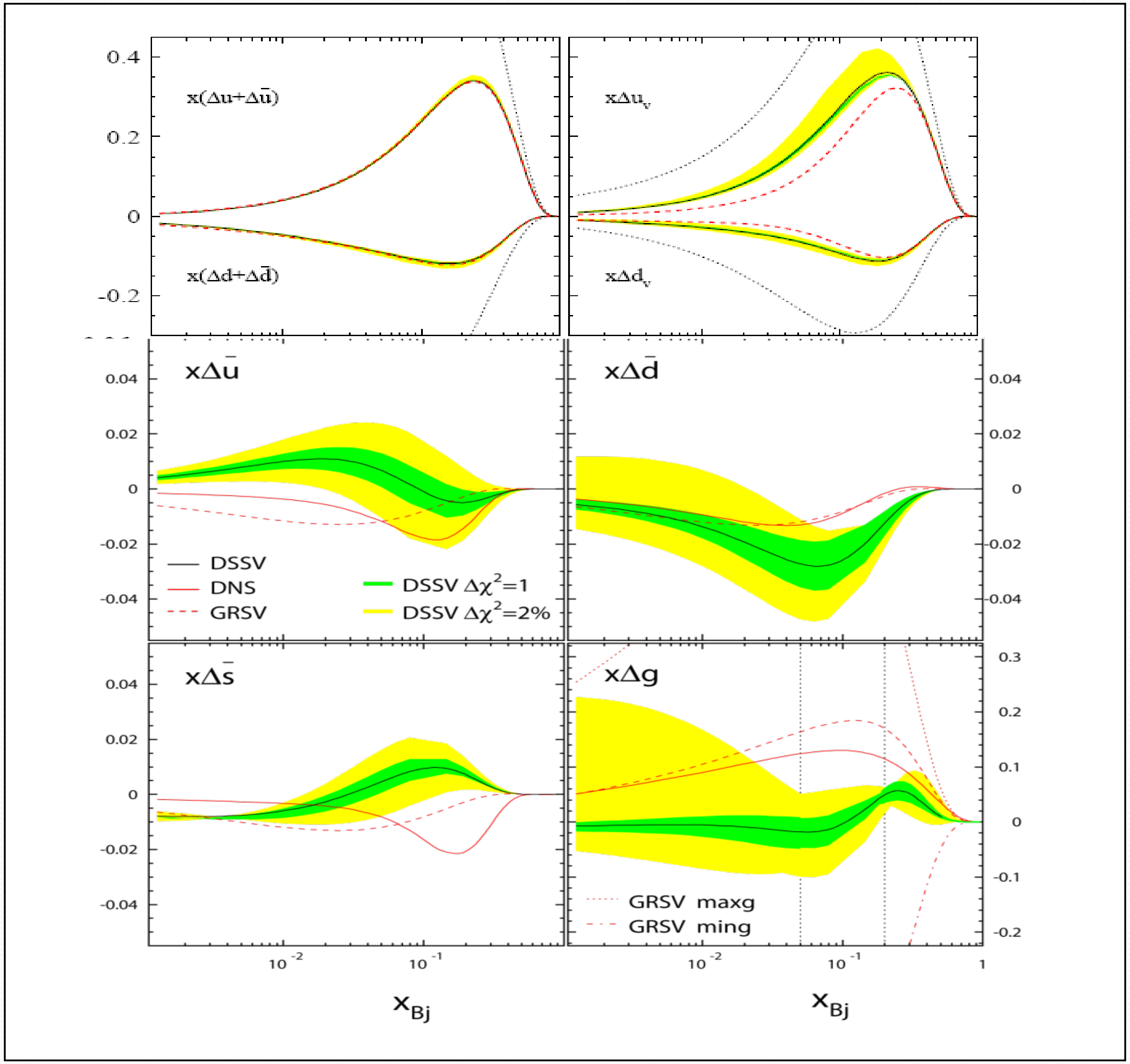
Polarized Structure functions





- Nice data!
- Q^2 dependence of g_1 data

Polarized Parton Distributions



DSSV, PRL101, 072001 (2008)

Facilities for e-N and e-A

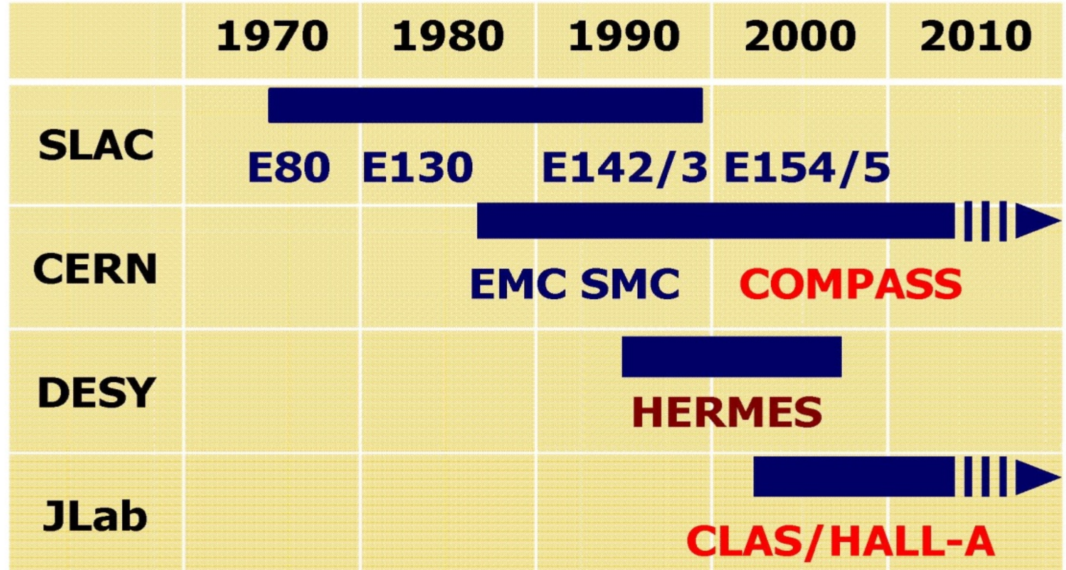
JLab 12 Program and Future EIC

Experimental Facilities for e-N (e-A)

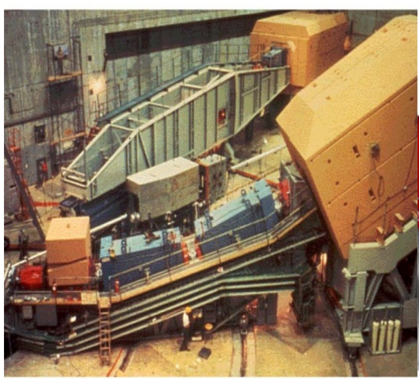
- SLAC: Fix target, 20/50 GeV (polarized) electron beam,, polarized p, d and ^{3}He
- CERN: EMC/NMC/SMC/COMPASS
  Fixed target, ~200 GeV polarized μ beam on polarized p, d
- DESY: HERA, unpolarized e-p collider. 27.5 GeV x 920 GeV
  HERMES, fixed target, polarized e-/e+ 27 GeV beam,
  polarized internal 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, …

Spin Structure Experiments

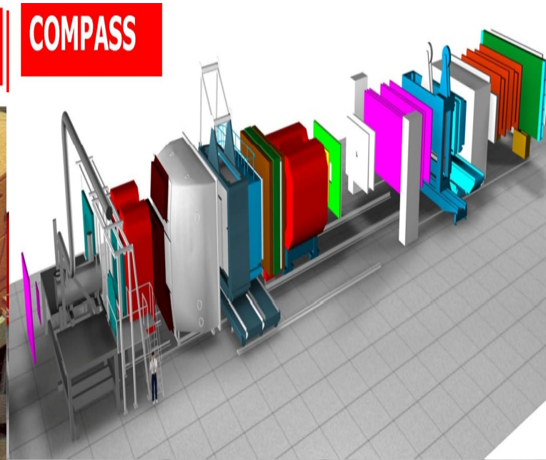
E80, E130	$\vec{e}\ \vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\ \vec{p}$	100–200 GeV
E142, 143	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\ \vec{p}, \vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\ \vec{p}, \vec{d}$	160 GeV
HALL A	$\vec{e}\ \vec{n}$	6 GeV
CLAS	$\vec{e}\ \vec{p}, \vec{d}$	6 GeV



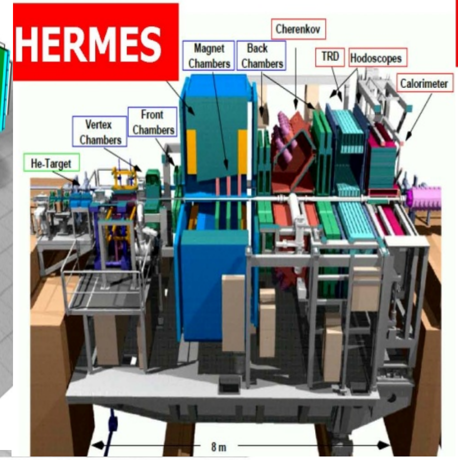
SLAC - End Station A



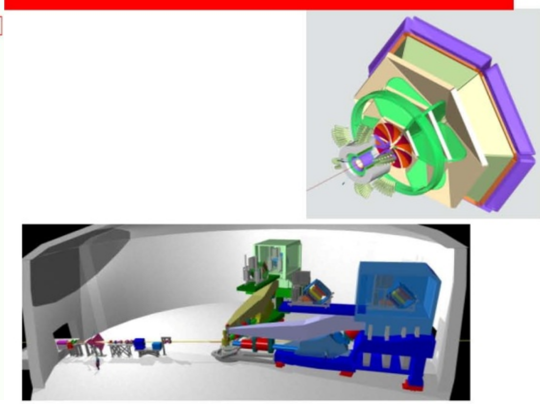
COMPASS



HERMES



Jlab - CLAS, Hall A



RHIC-Spin: Polarized p-p collider

Jefferson Lab at a Glance

CEBAF

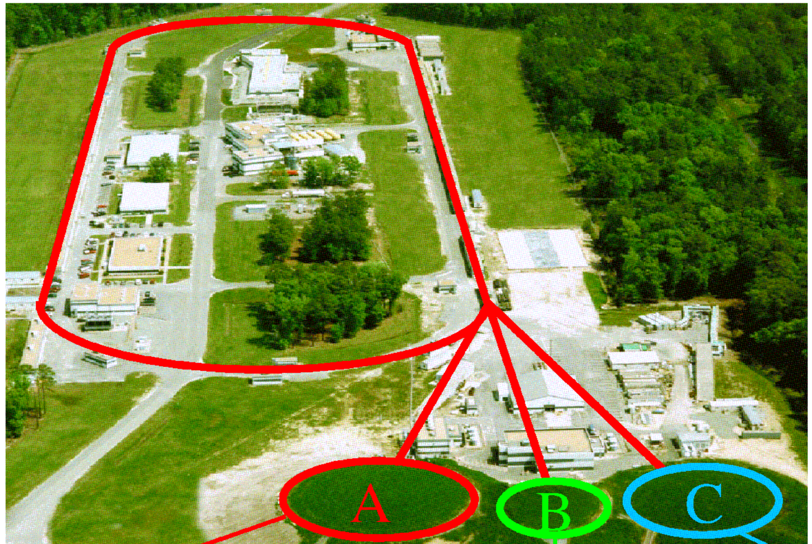
- **High-intensity** electron accelerator based on **CW SRF** technology
- **I_{max} = 200 μA**
- **Pol_{max} = 90%**
- **E_{max} = 6 GeV: 1995-2012**
- **Energy Upgrading to 12 GeV (2012-now)**
- **12 GeV data taking started**

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

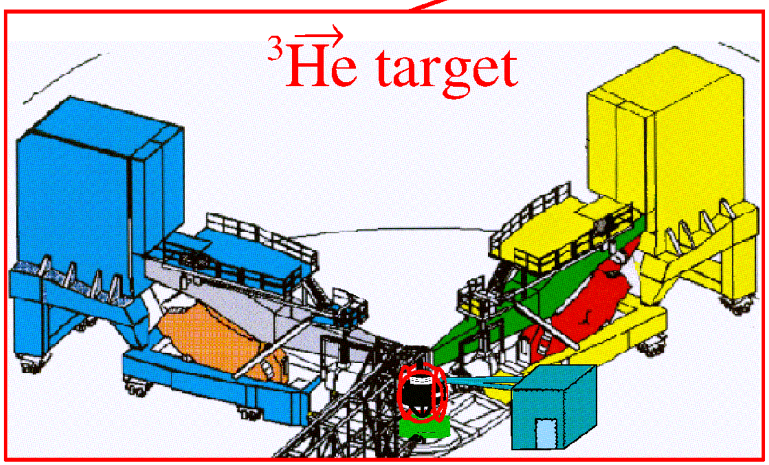
Thomas Jefferson National Accelerator Facility

Newport News, Virginia, USA

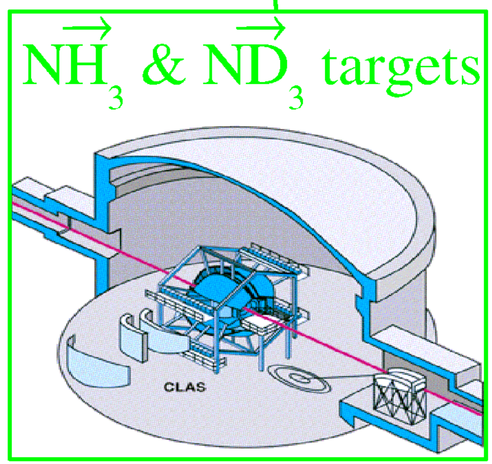
6 GeV polarized
CW electron beam
Pol=85%, 200μA
Luminosity ~ 10^{39}



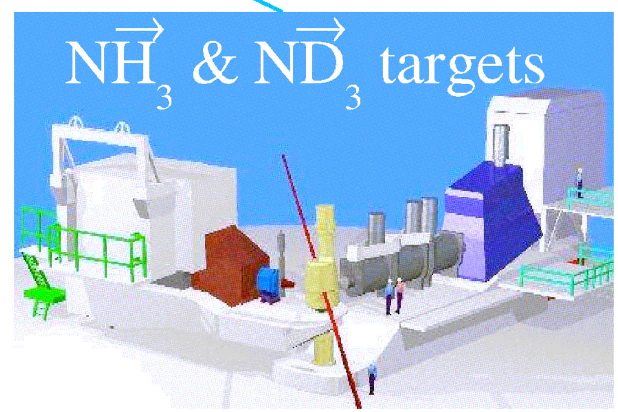
Upgrading to 12 GeV nearly complete



HallA: two HRS'

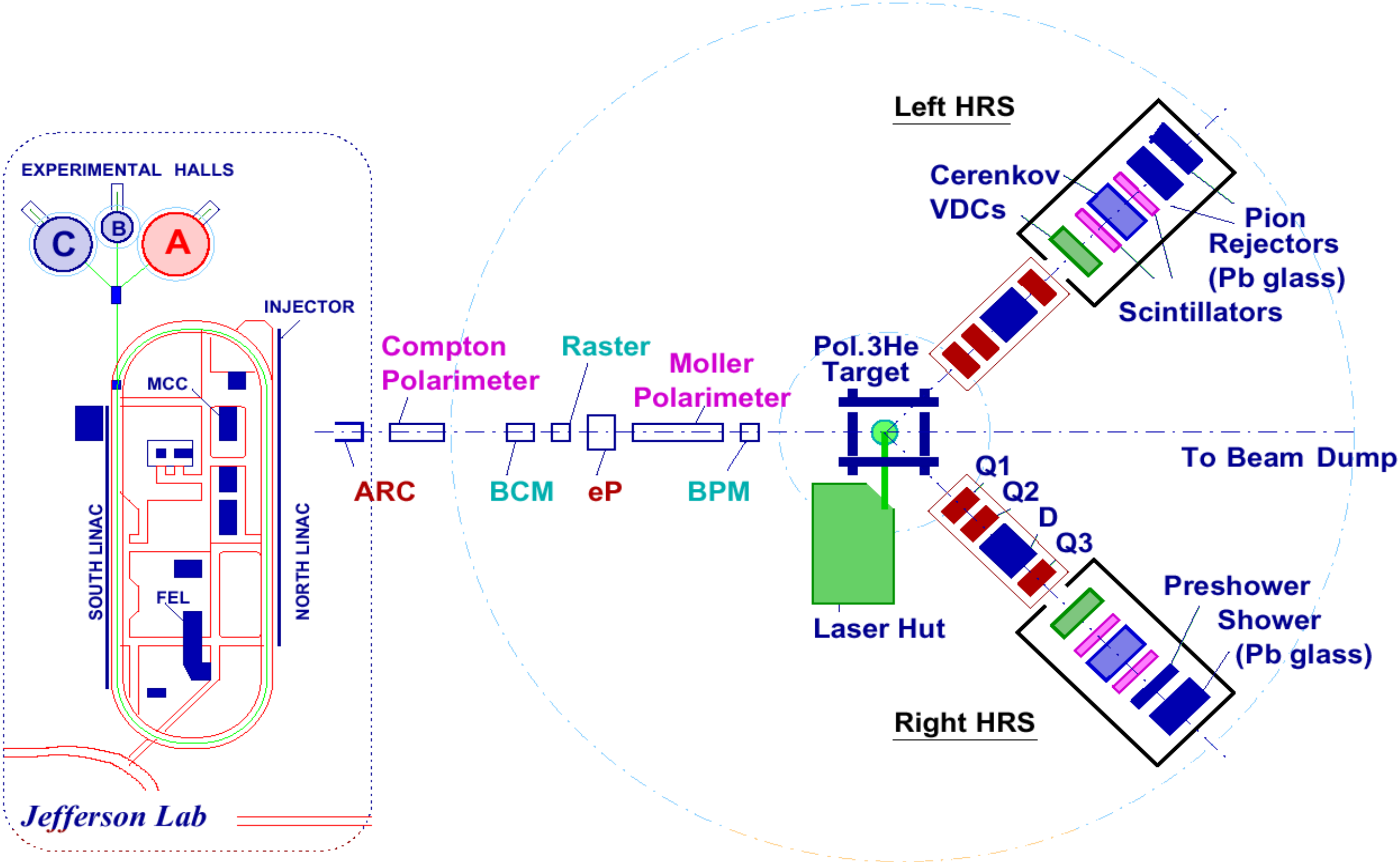


Hall B:CLAS



Hall C: HMS+SOS

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



JLab's Scientific Mission

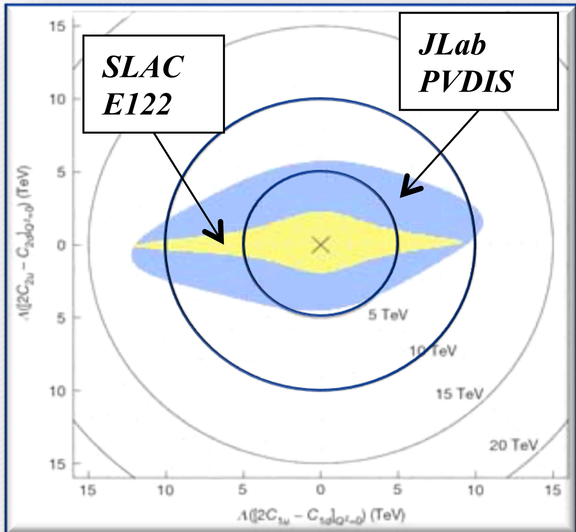
- How are the hadrons constructed from the quarks and gluons of QCD?
- Where are the limits of our understanding of nuclear structure?
- Is the "Standard Model" complete?

Critical issues in "strong QCD":

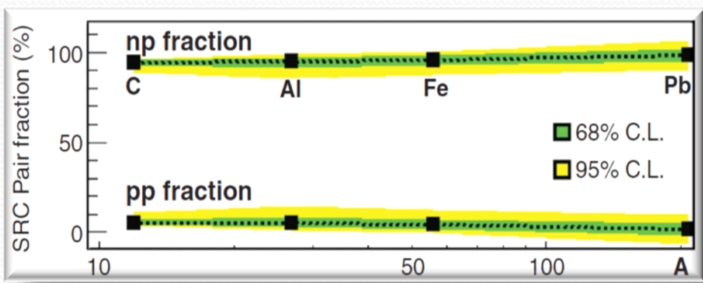
- What is the mechanism of confinement?
- How and where does the dynamics of the q-g and q-q interactions make a transition from the strong (confinement) to the perturbative QCD regime?
- What is the multi-dimensional structure of the nucleon?

JLab 2014 | Near-Future | Future

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



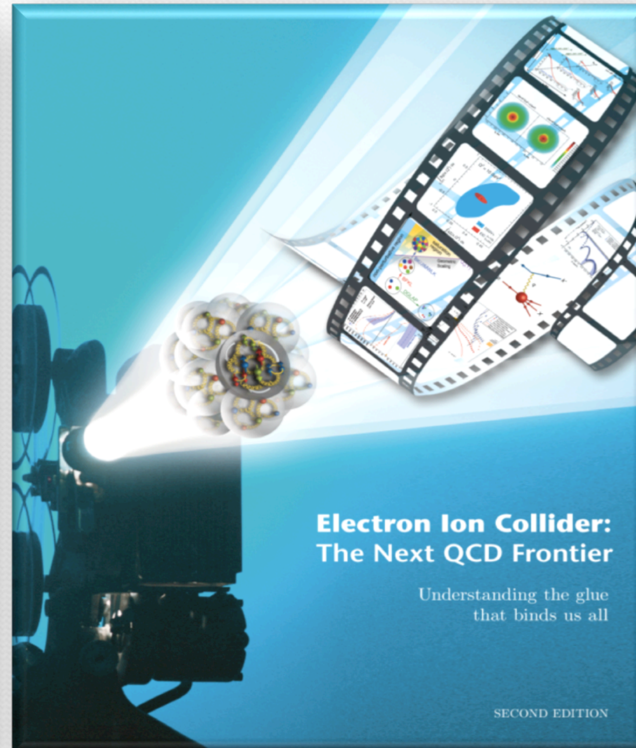
Science 346, 614 (October 2014)
Short Range NN Correlations



Decade of Experiments Approved
Eager to Start 12 GeV Science!

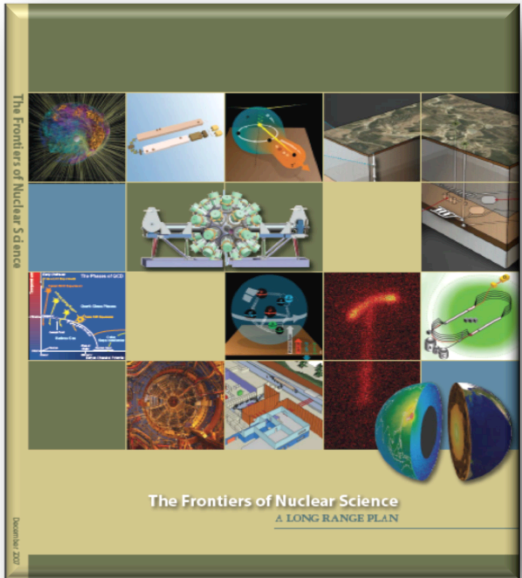
- ***Confinement***
- ***Hadron Structure***
- ***Nuclear Structure and Astrophysics***
- ***Fundamental Symmetries***

Electron Ion Collider
The Next QCD Frontier

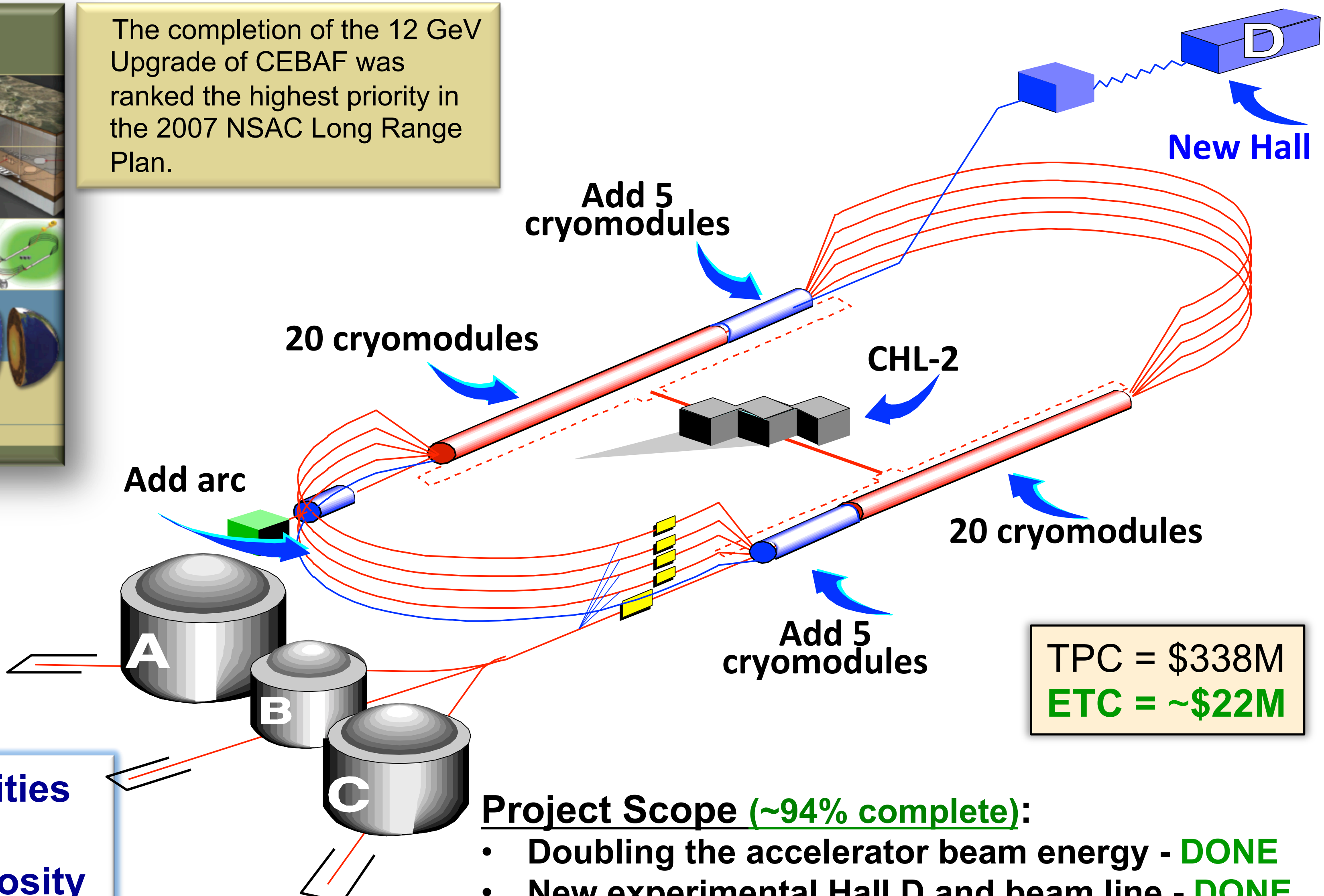


Role of Gluons in Nucleon and Nuclear Structure

12 GeV Upgrade



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.



TPC = $338M
ETC = ~$22M

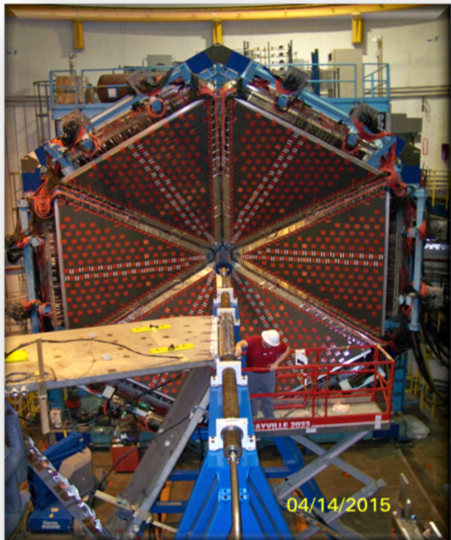
- **Enhanced capabilities in existing Halls**
- **Increase of Luminosity** 10^{35} **- ~**10^{39} **cm**$^{-2}$**s**$^{-1}$

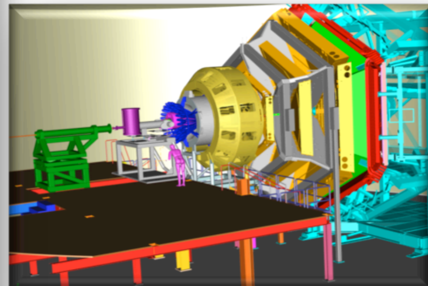
Project Scope (~94% complete):

- **Doubling the accelerator beam energy - DONE**
- **New experimental Hall D and beam line - DONE**
- **Civil construction including Utilities - ~98%**
- **Upgrades to Experimental Halls B & C - ~85%**

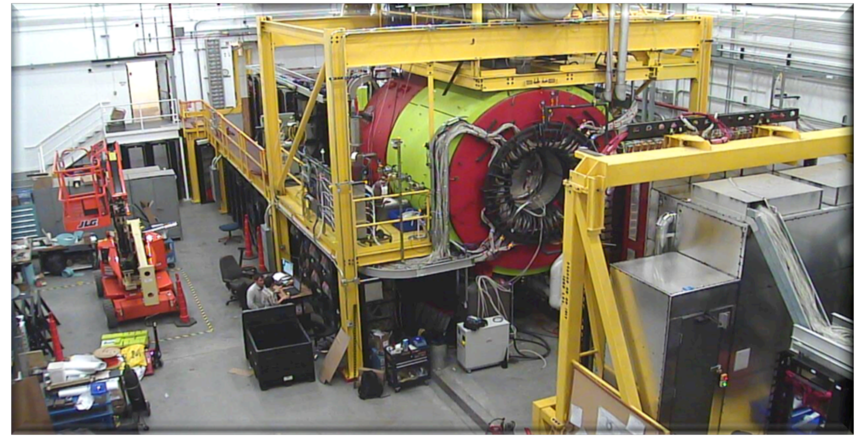
12 GeV Scientific Capabilities

Hall B – understanding nucleon structure via generalized parton distributions

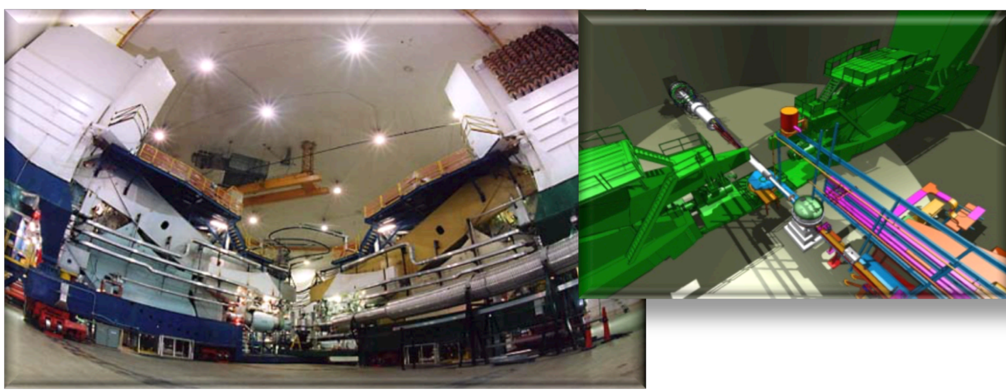




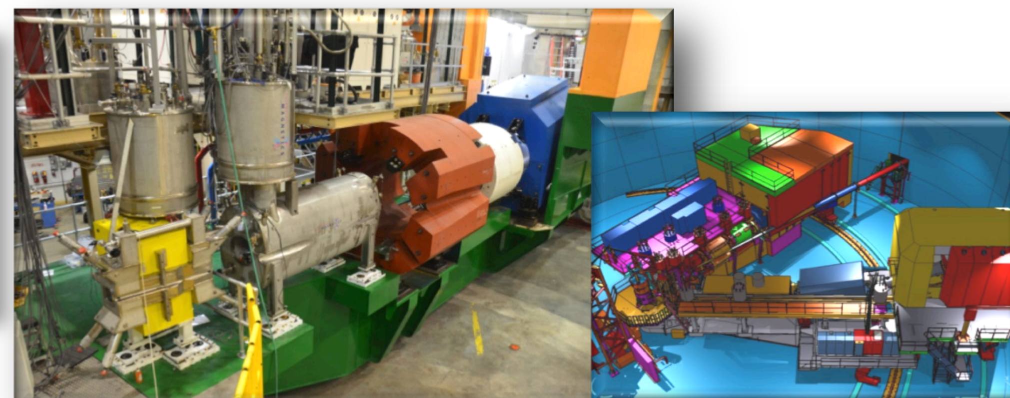
Hall D – exploring origin of confinement by studying exotic mesons



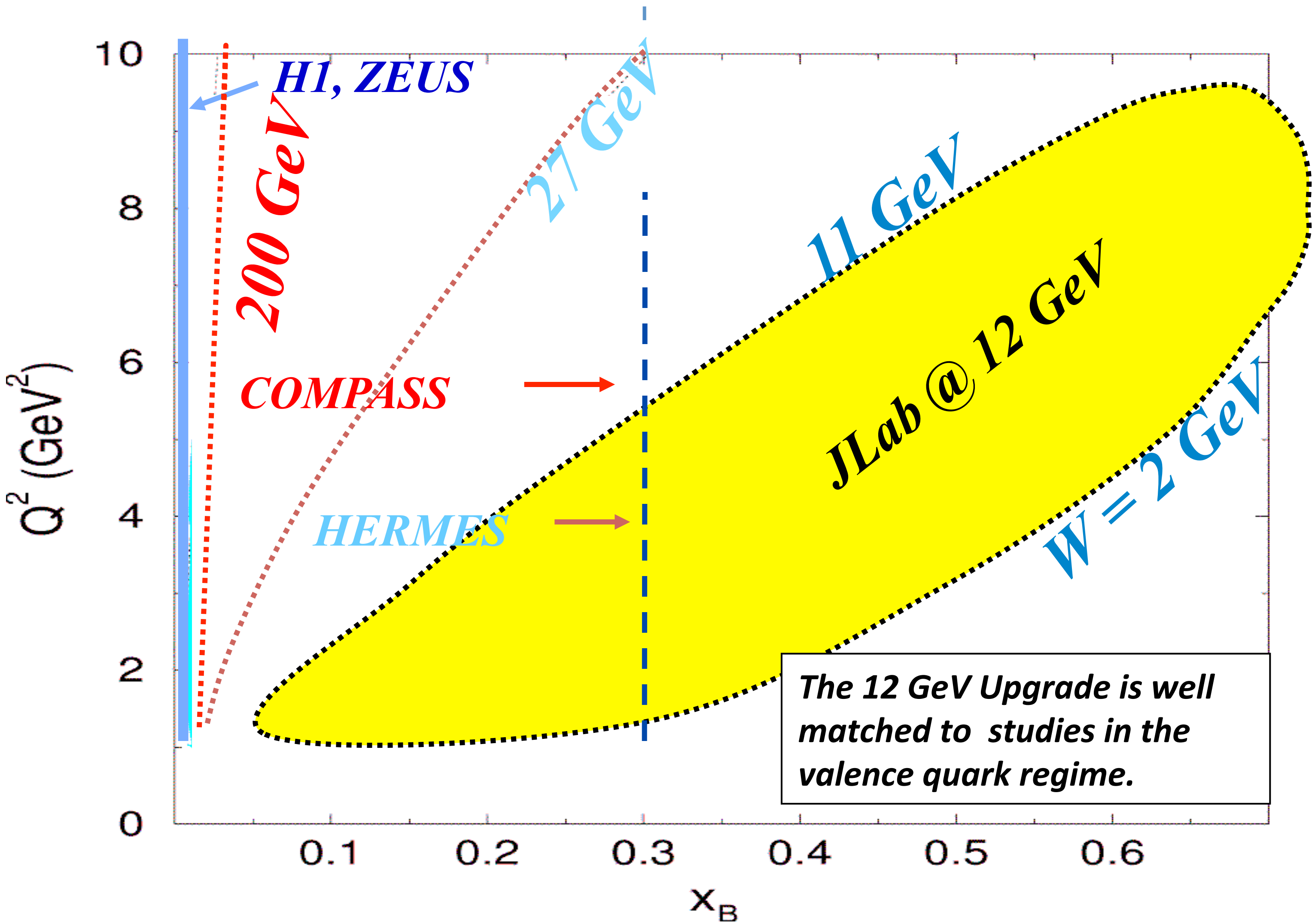
Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)



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

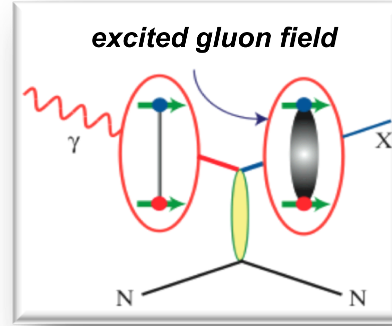


Kinematics Coverage of the 12 GeV Upgrade

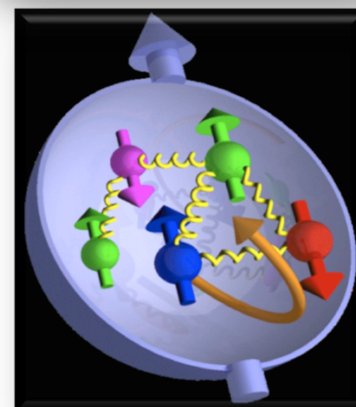


The 12 GeV Upgrade is well matched to studies in the valence quark regime.

Jefferson Lab @ 12 GeV Science Questions

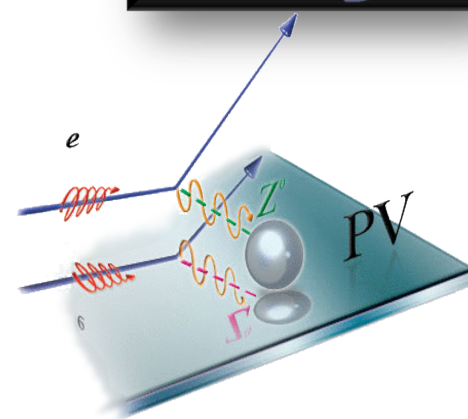


- What is the role of gluonic excitations in the spectroscopy of light mesons?



- 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?

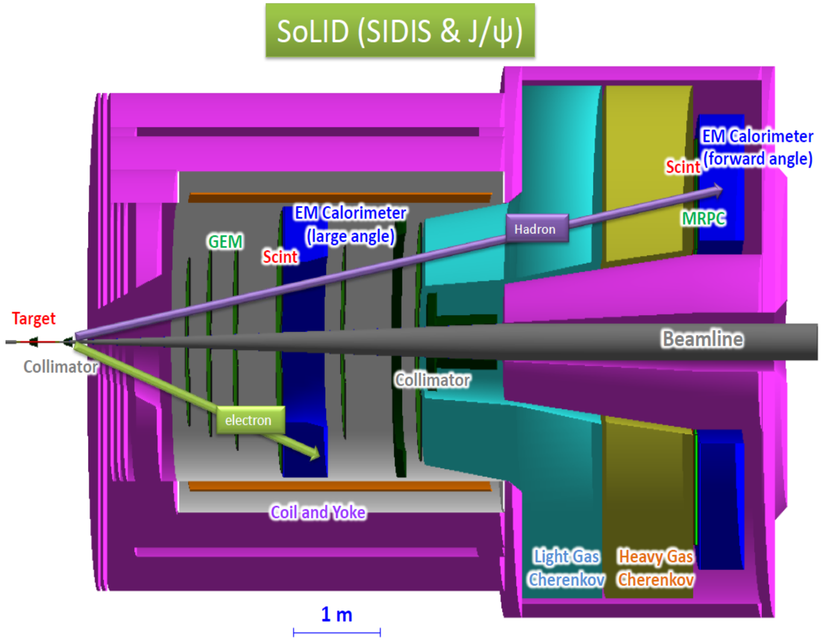
12 GeV Approved Experiments by Physics Topics

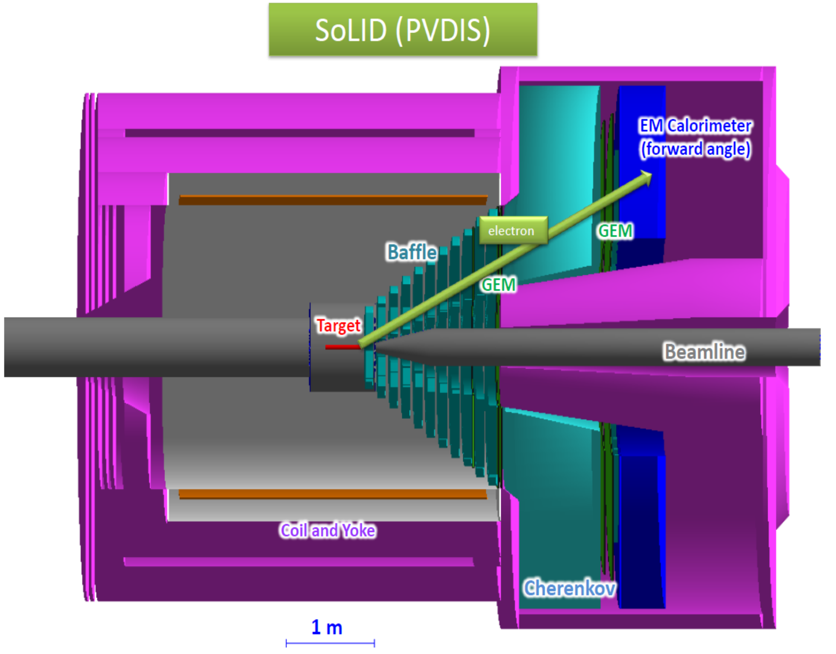
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GlueX and heavy baryon and meson spectroscopy)		1		3		4
The transverse structure of the hadrons (Elastic and transition Form Factors)	5	3	2	1		11
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	3	6			11
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	9	7			21
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	6	3	7		1	17
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1		1	1	6
TOTAL	21	20	22	5	2	70

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**
  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})
  Take advantage of latest development in detectors , data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ
- **5 highly rated experiments approved**
  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)





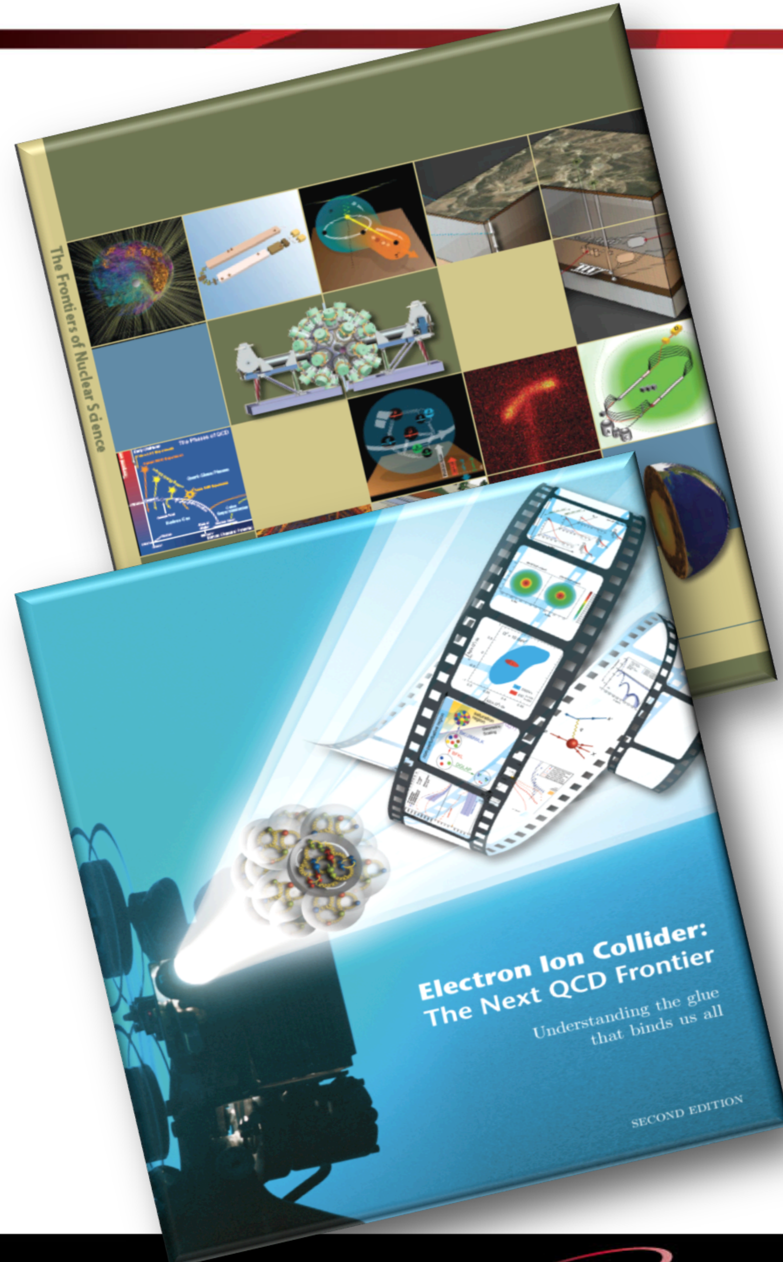
Electron Ion Collider

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."

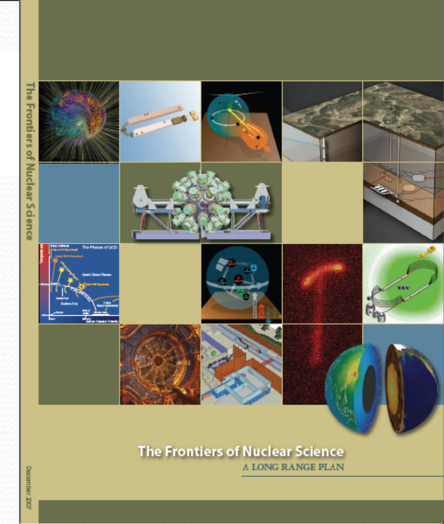


NSAC 2015 Long-Range Plan:

- EIC unanimously endorsed by QCD Town Meetings as next QCD frontier
- Community has reached consensus on parameters

EIC Community White Paper arXiv:1212.1701v2

EIC: Science Motivation



A High Luminosity, High Energy Electron-Ion Collider:
A New Experimental Quest to Study the Sea and Glue
How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

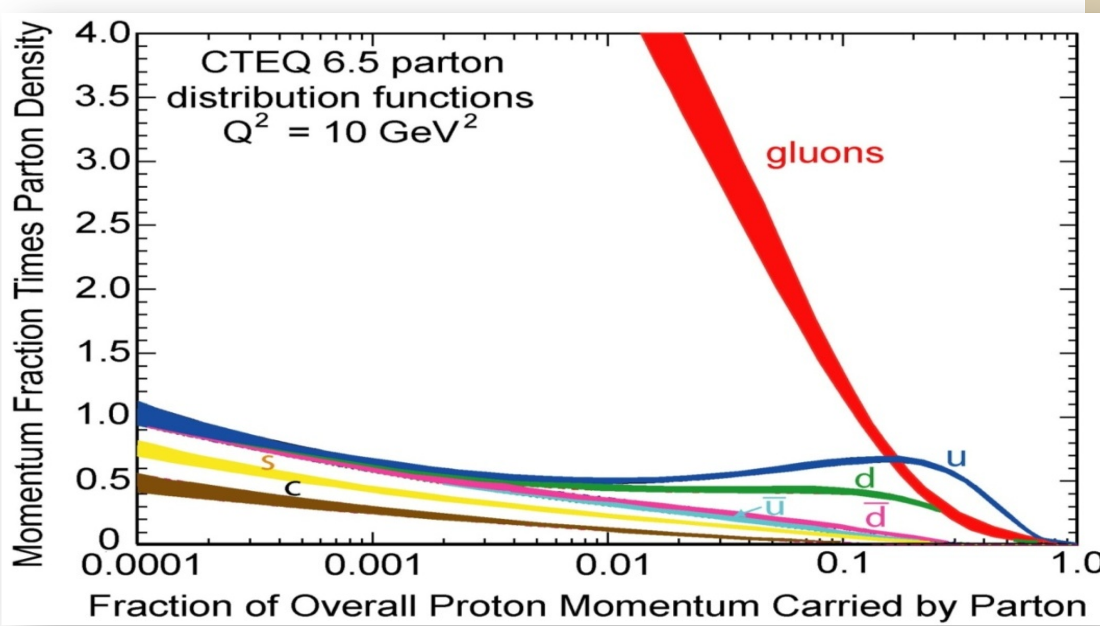
Precisely image the sea-quarks and gluons in the nucleon:

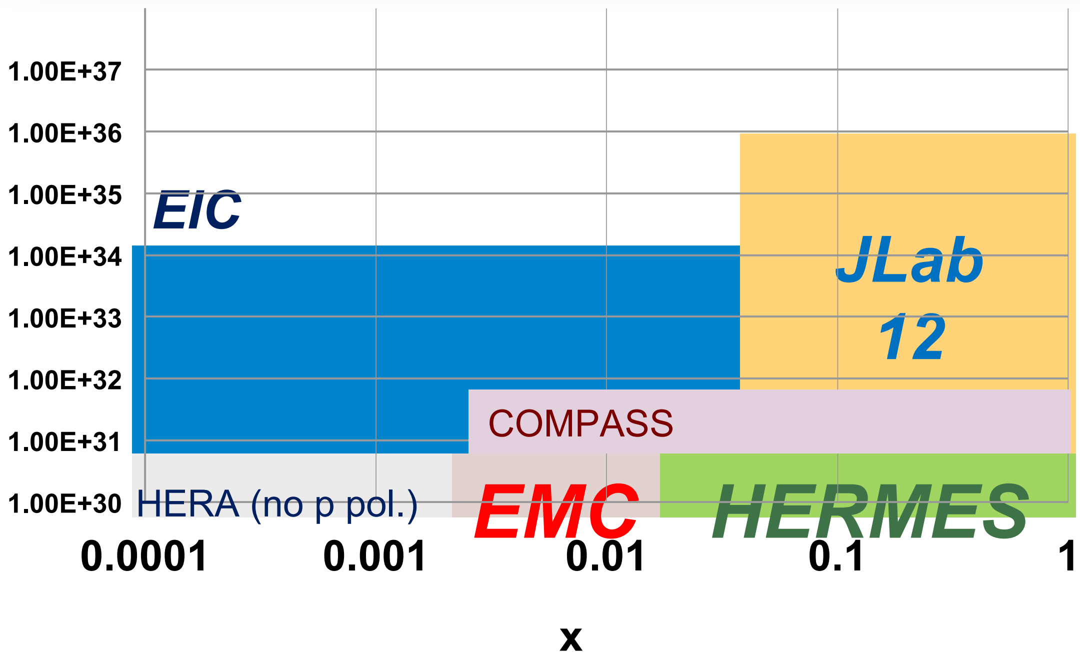
- How do the gluons and sea-quarks contribute to the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do hadronic final-states form in QCD?

Explore the new QCD frontier: strong color fields in nuclei:

- How do the gluons contribute to the structure of the nucleus?
- What are the properties of high density gluon matter?
- How do fast quarks or gluons interact as they traverse nuclear matter?

EIC:
The New QCD Frontier

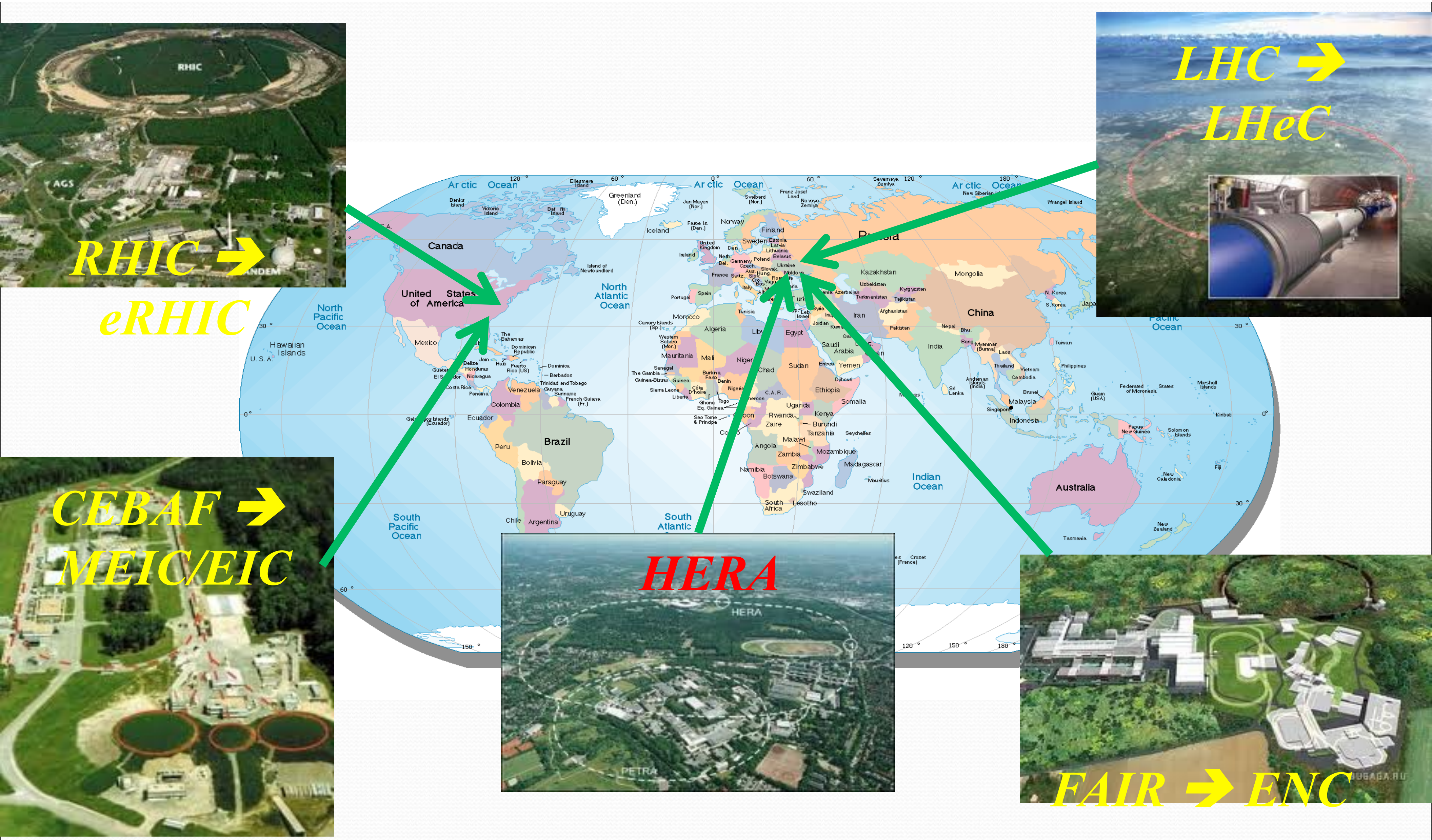




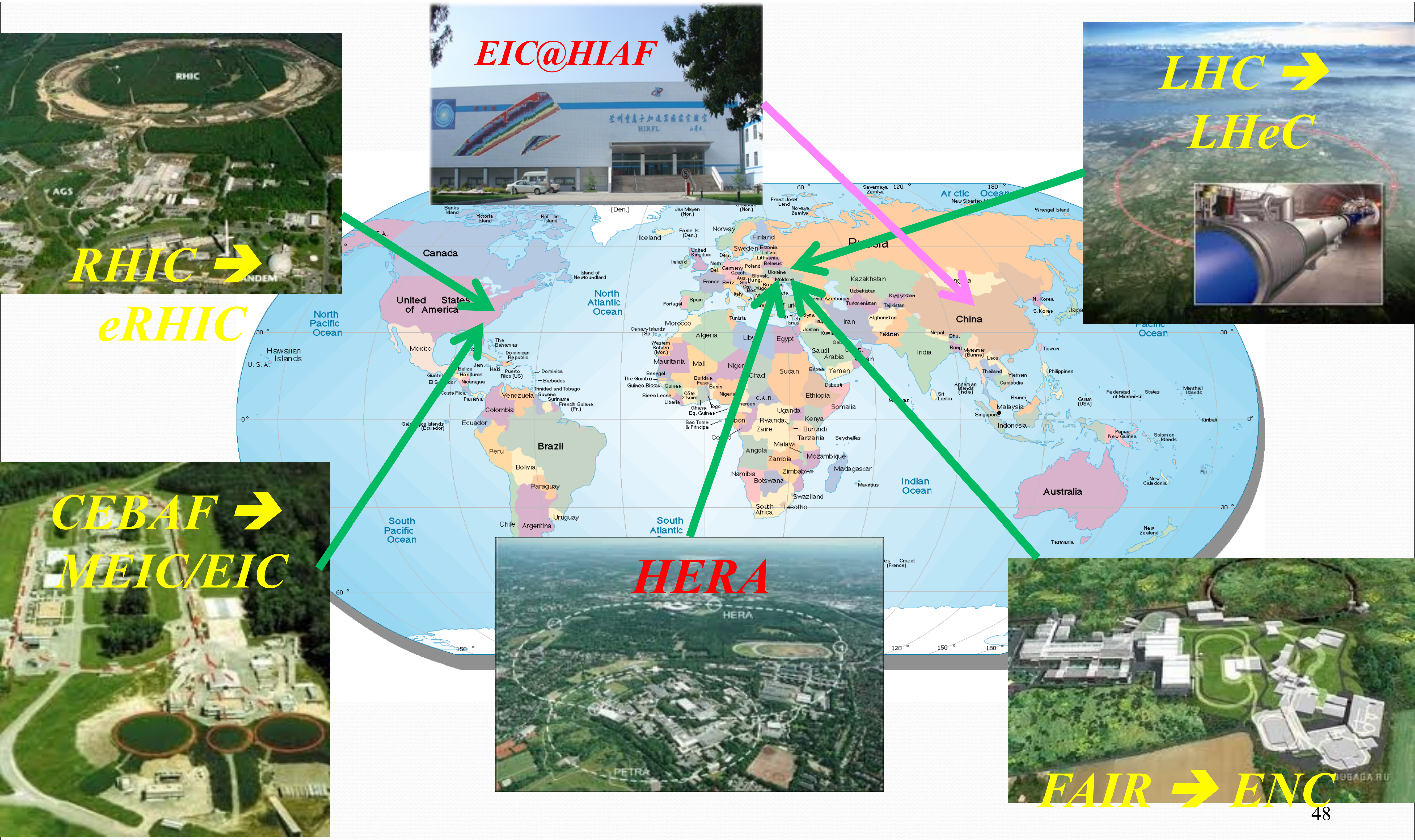
- ***High Luminosity***
  → 10^{34} $cm^{-2}s^{-1}$
- ***Low x regime***
  x → 0.0001
- ***High Polarization***
  → 70%

Discovery Potential!

Electron Ion Colliders on the World Map

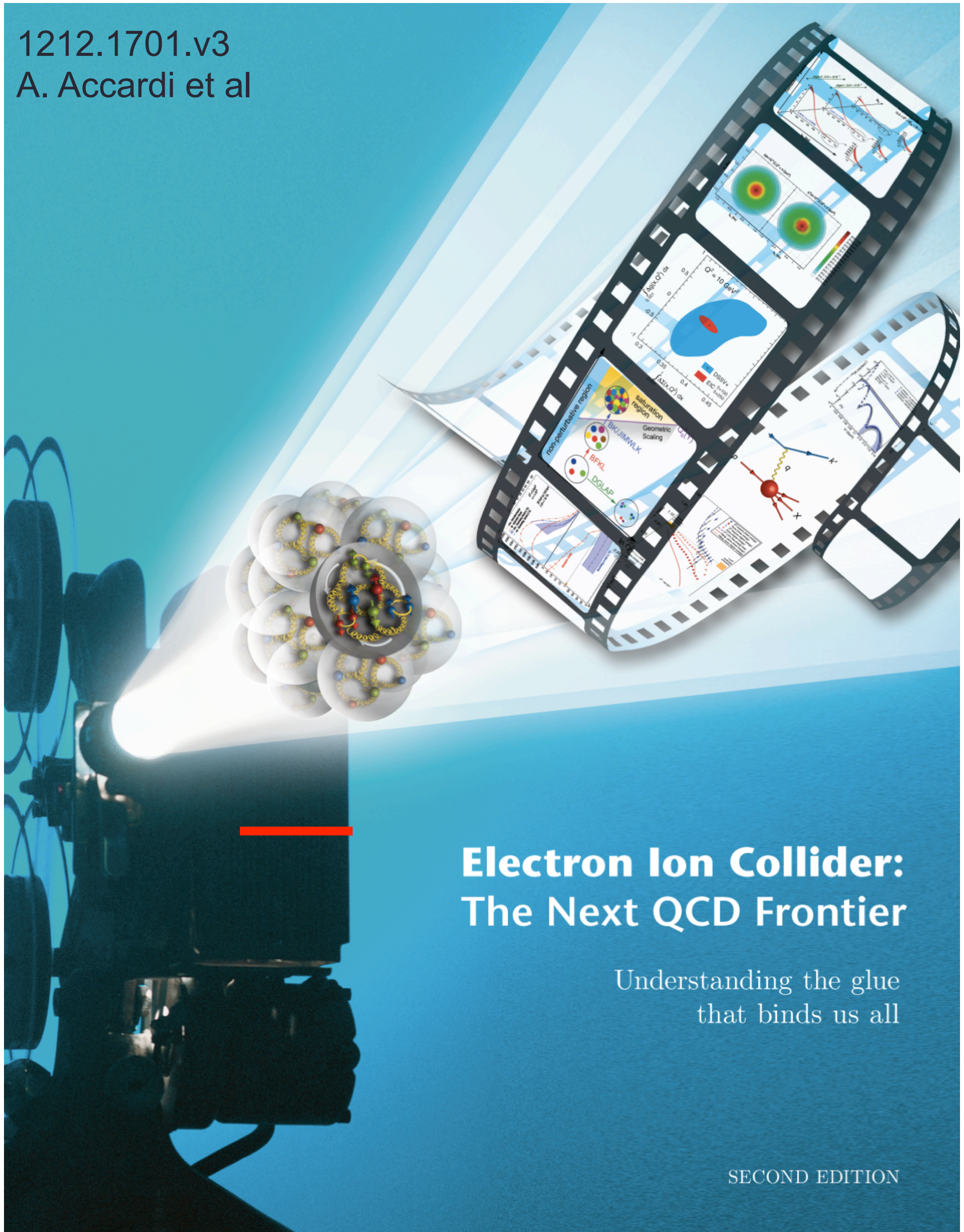


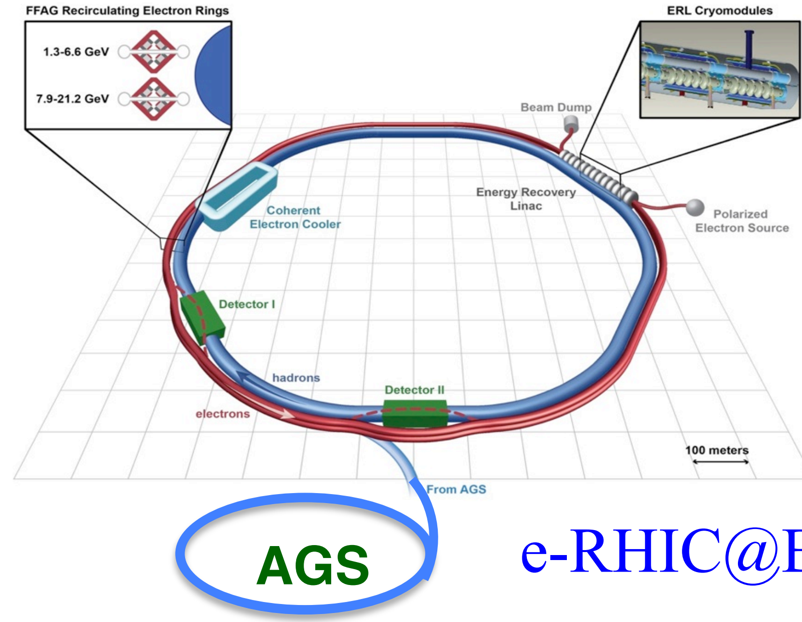
世界上主要EIC实验-分布图



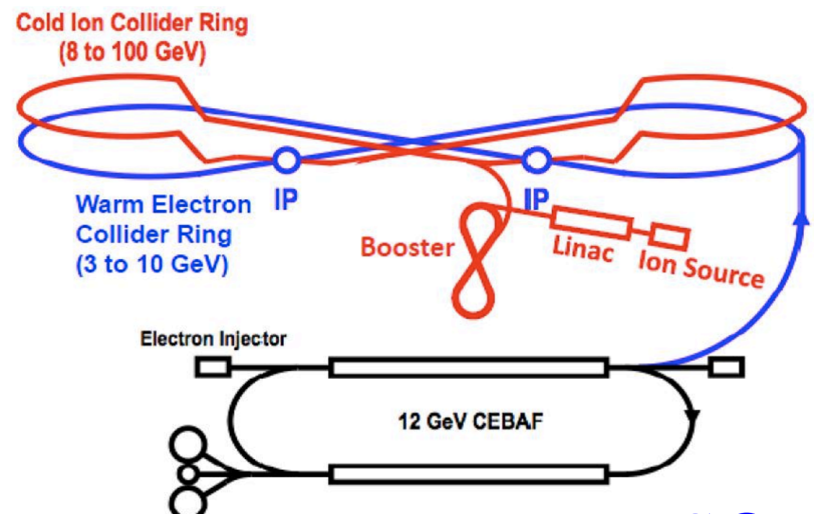
The Electron Ion Collider

Two proposals for realization of the Science Case



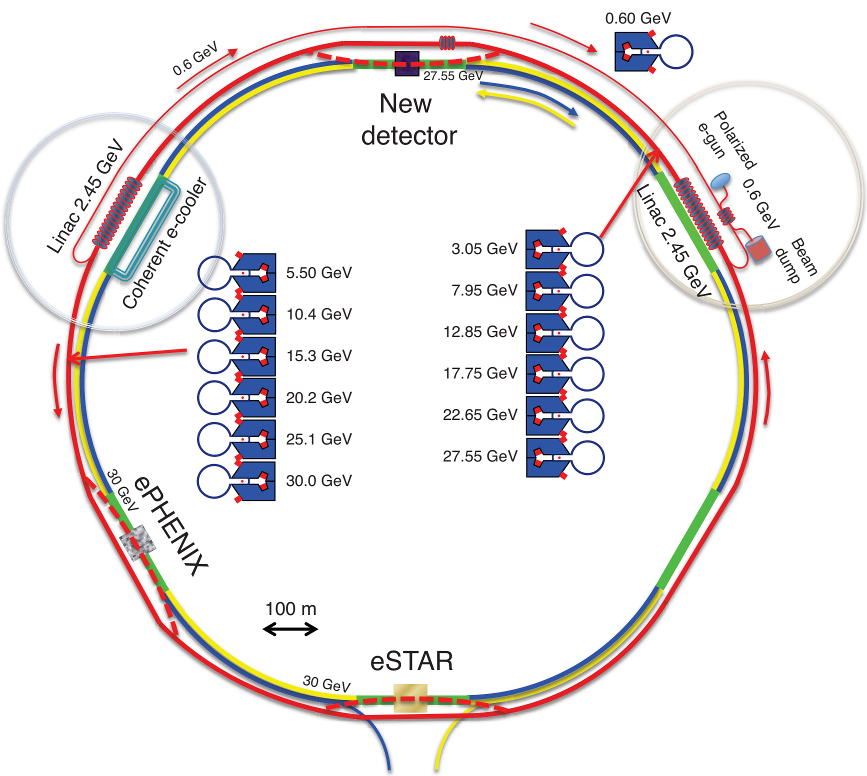


e-RHIC@BNL



MEIC@JLab

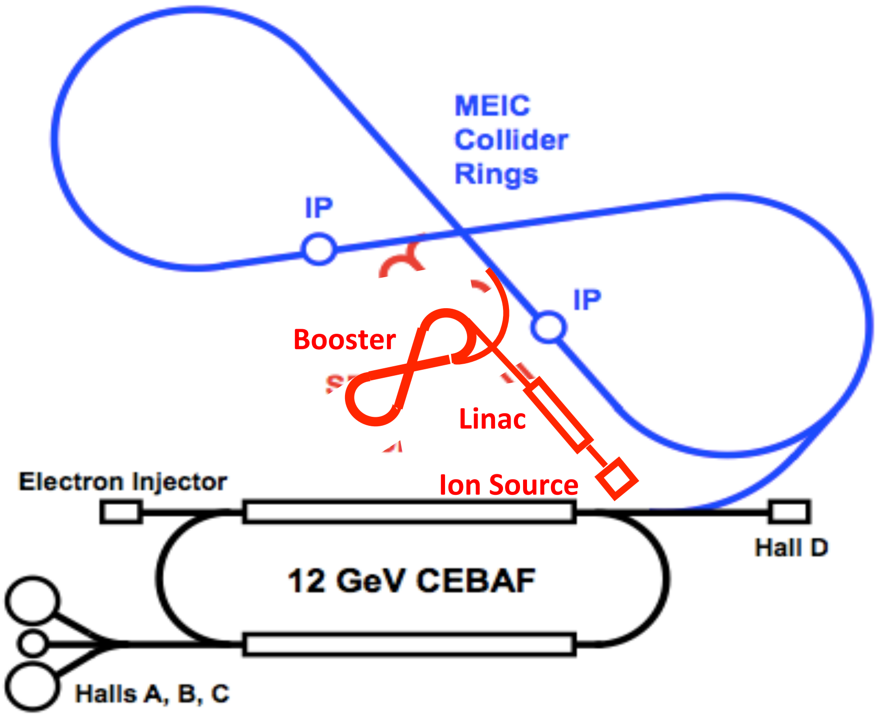
E-RHIC Design

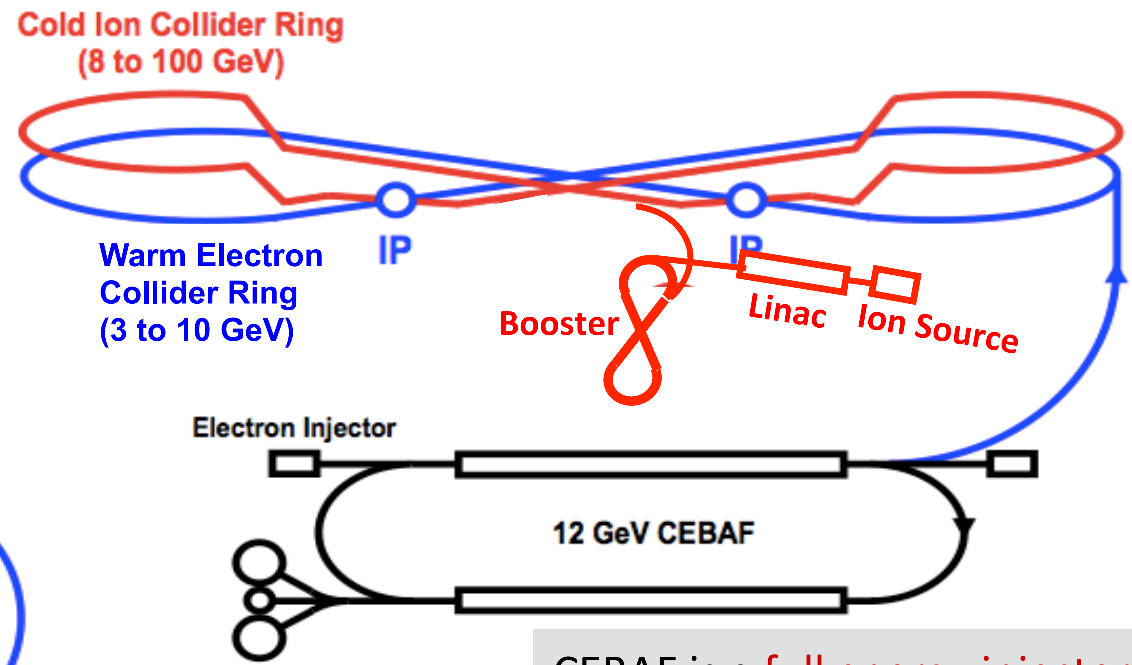


	electron	proton	Au
Max. beam energy [GeV/n]	10	250	100
Bunch frequency [MHz]	9.34	9.34	9.34
Bunch intensity (nucleons/electrons) $[10^{11}]$	0.36	4	6
Beam current [mA]	50	556	335
Polarization [%]	80	70	
RMS bunch length [mm]	2	50	50
RMS norm. emittance (e-p/e-Au) [μm]	16/40	0.2	0.2
β^* [cm]	5	5	5
Luminosity $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$		2.7	1.6

Table 5.1: Projected parameters and luminosities for the first stage of eRHIC.

JLEIC Baseline Layout

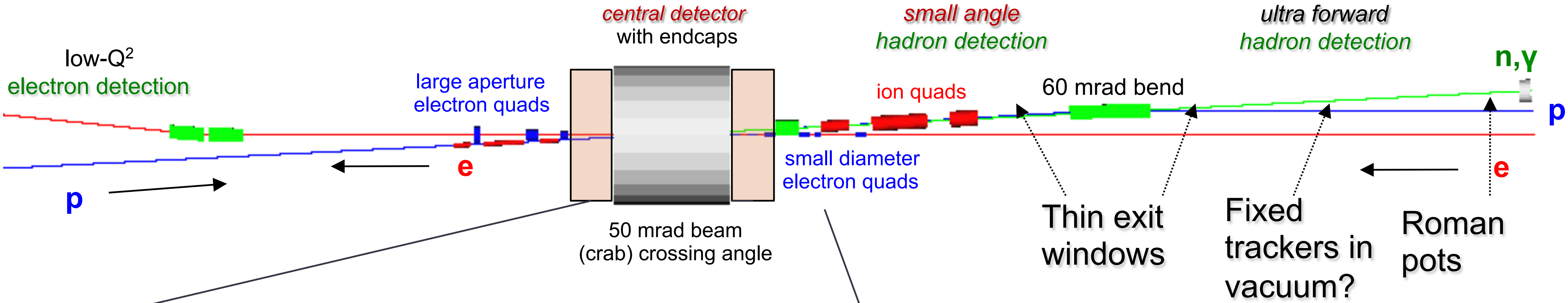


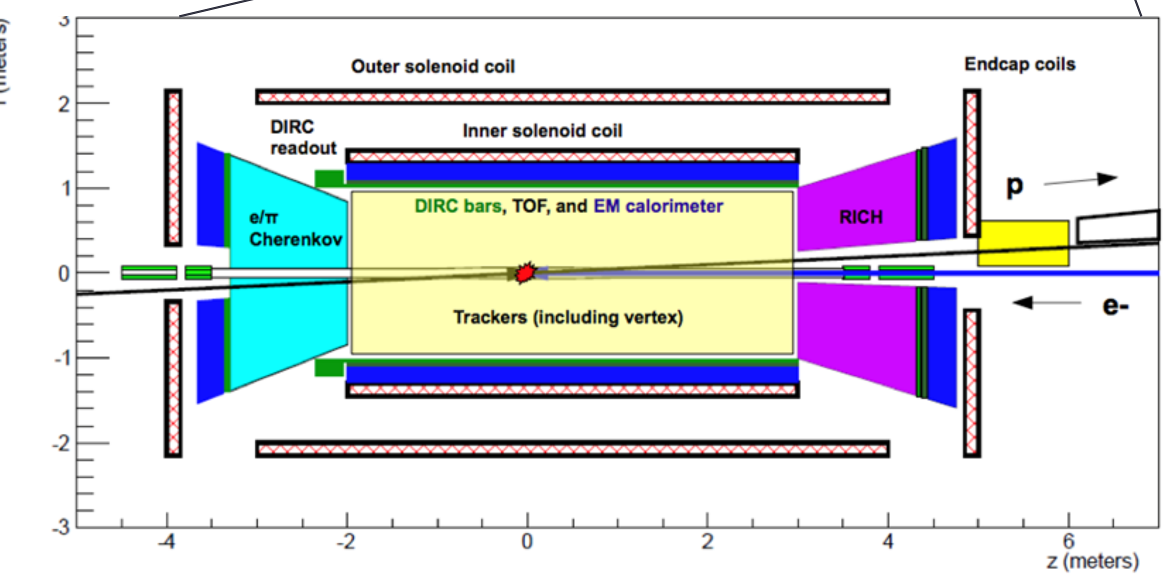


CEBAF is a full energy injector.

Design point	p energy (GeV)	e- energy (GeV)
low	30	4
medium	100	5
high	100	10

EIC at JLab: Integrated IR & Detector

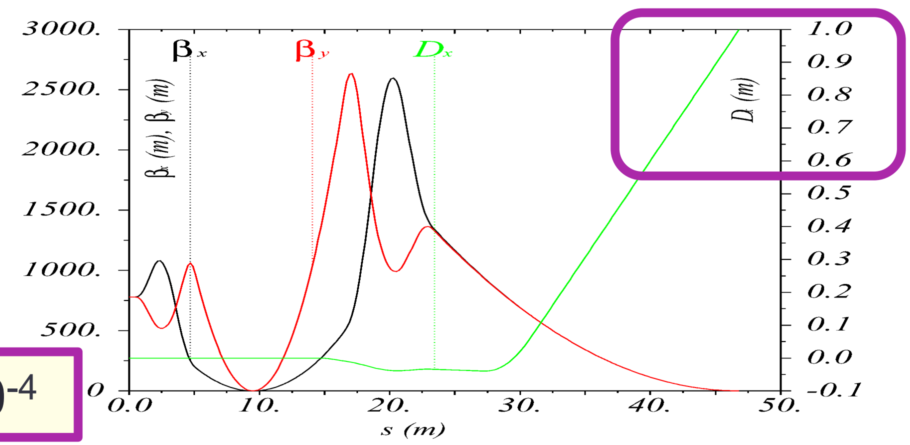




Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Hadron/Ion detection in 3 stages

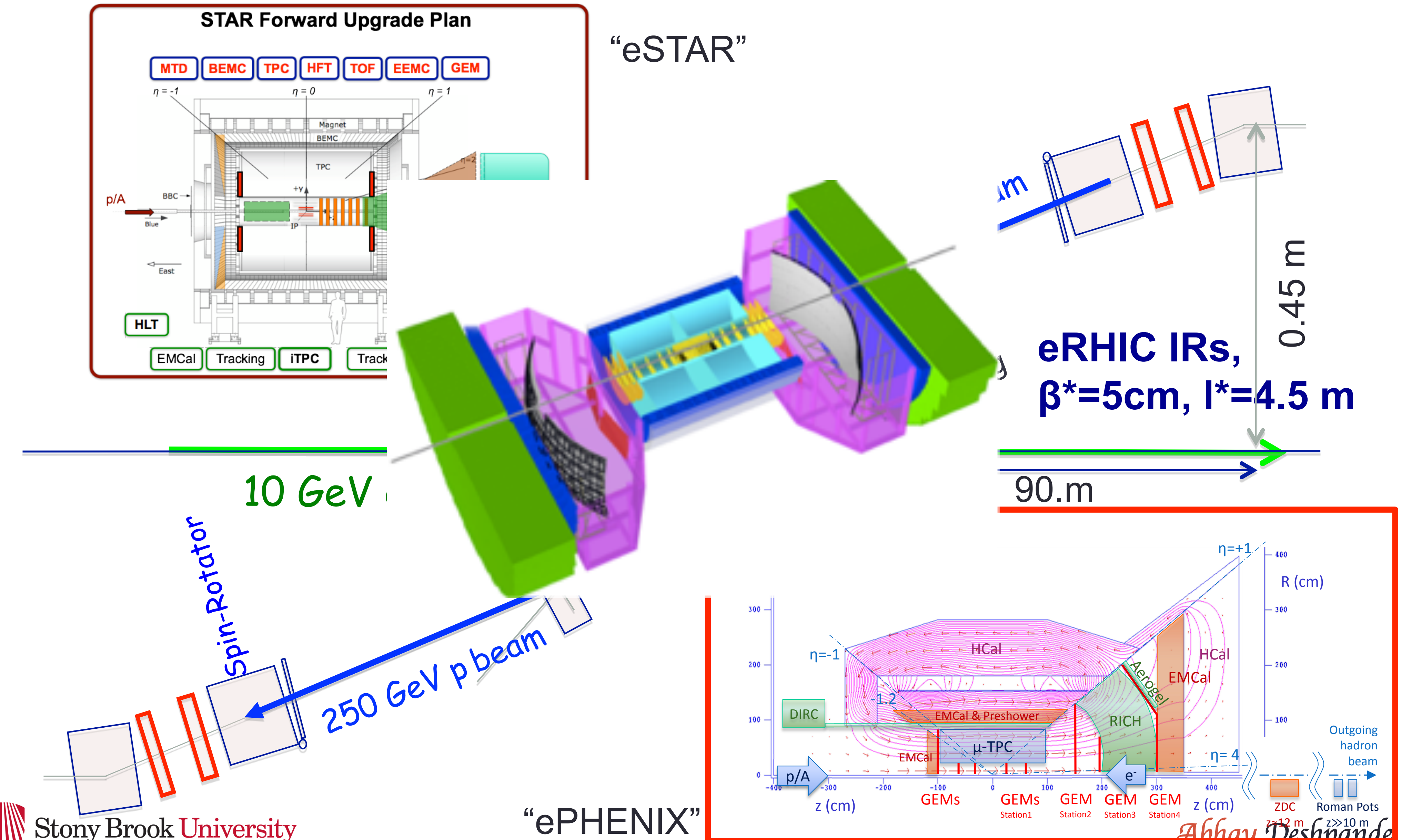
- ❑ Endcap with 50 mrad crossing angle
- ❑ Small dipole covering angles to a few degrees
- ❑ Ultra-forward up to one degree, for particles passing accelerator quads



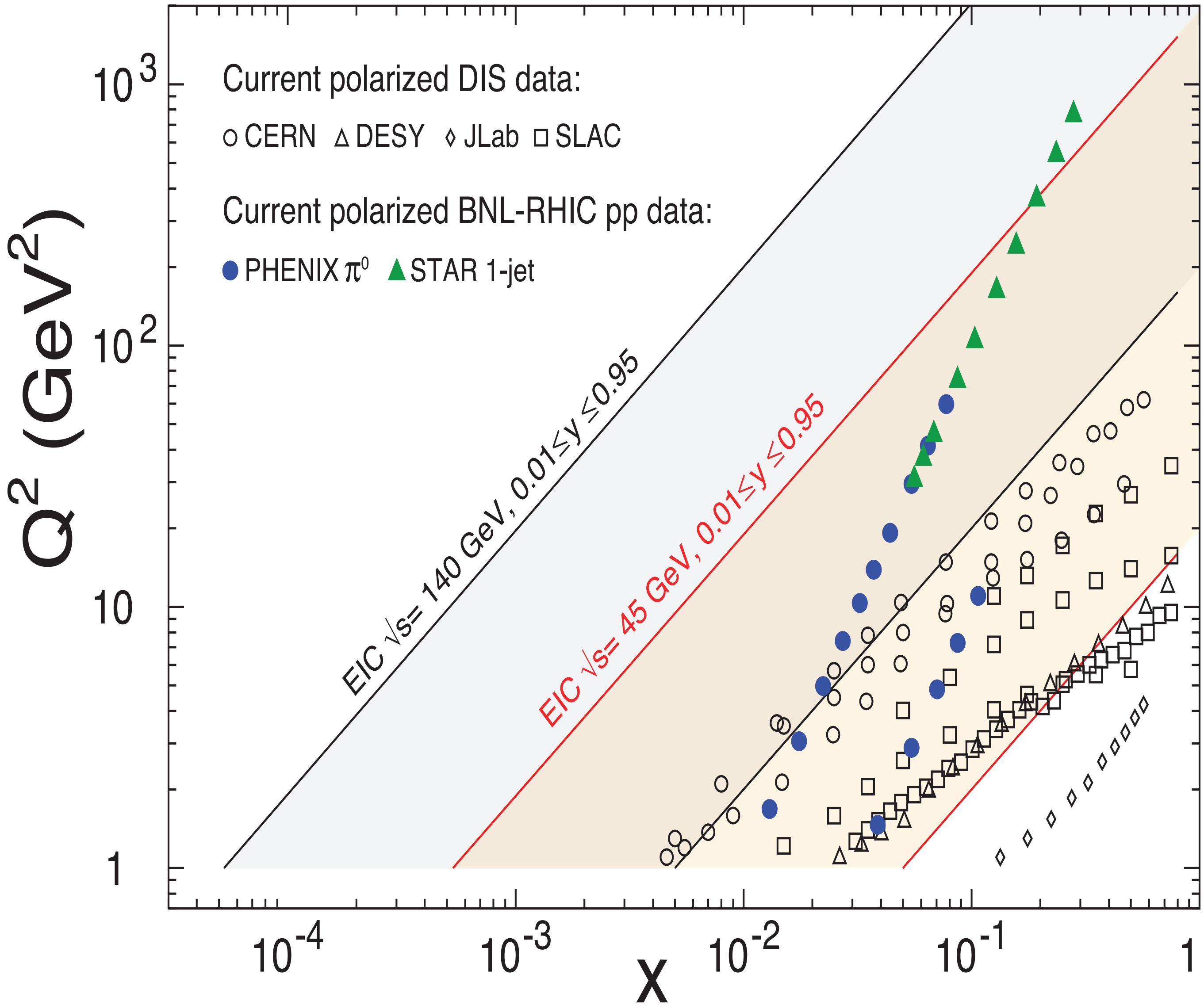
Beamline functions as spectrometer: $dp/p < 3\times10^{-4}$

EIC Detectors & IR

Field-free electron pass thru hadron triplet magnets ⇒ minimize Sync Rad

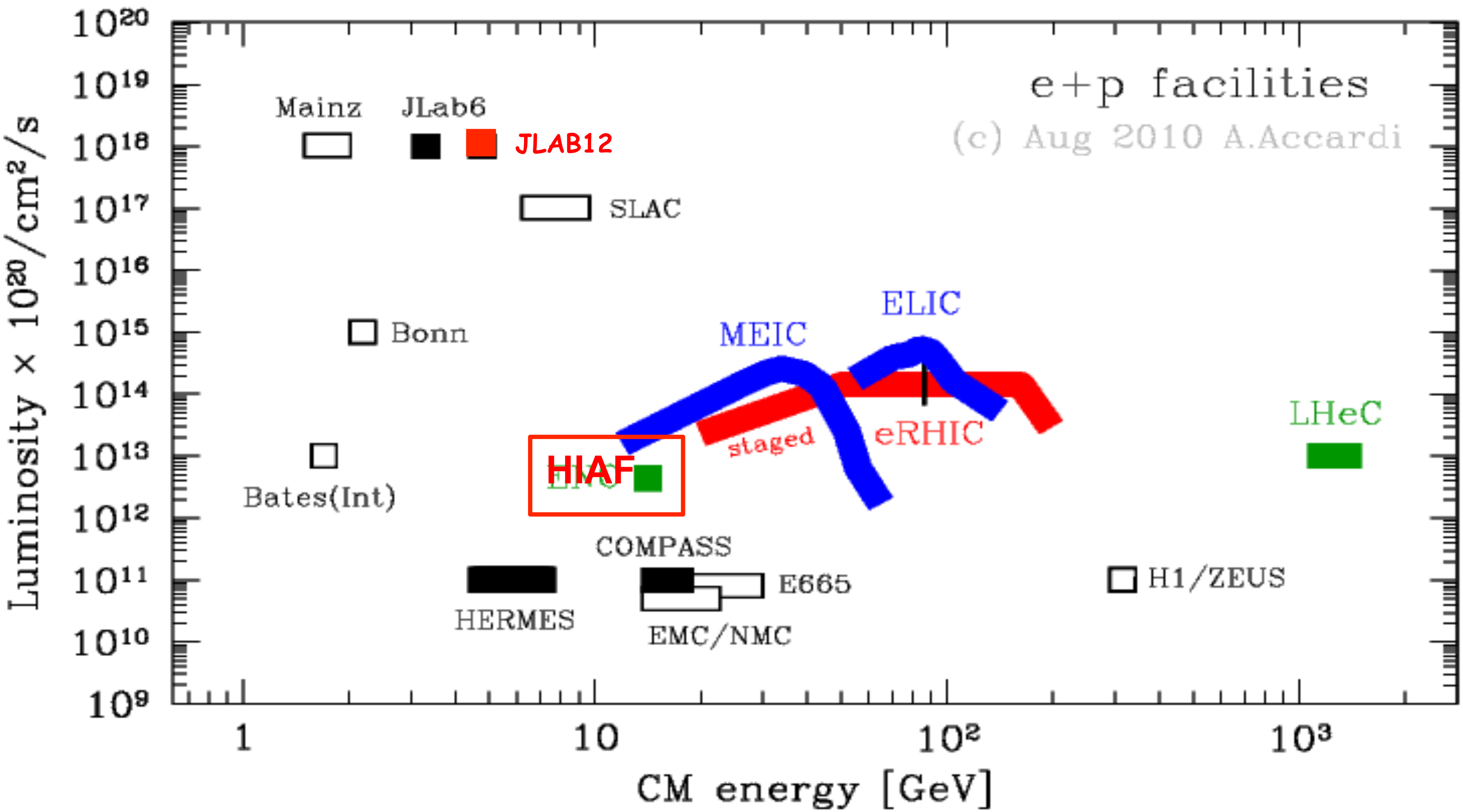


EIC Kinematic Coverage



Lepton-Nucleon Facilities

HIAF: e(3GeV) +p(12GeV), both polarized, L(max)=4*10^{32}cm^2/s



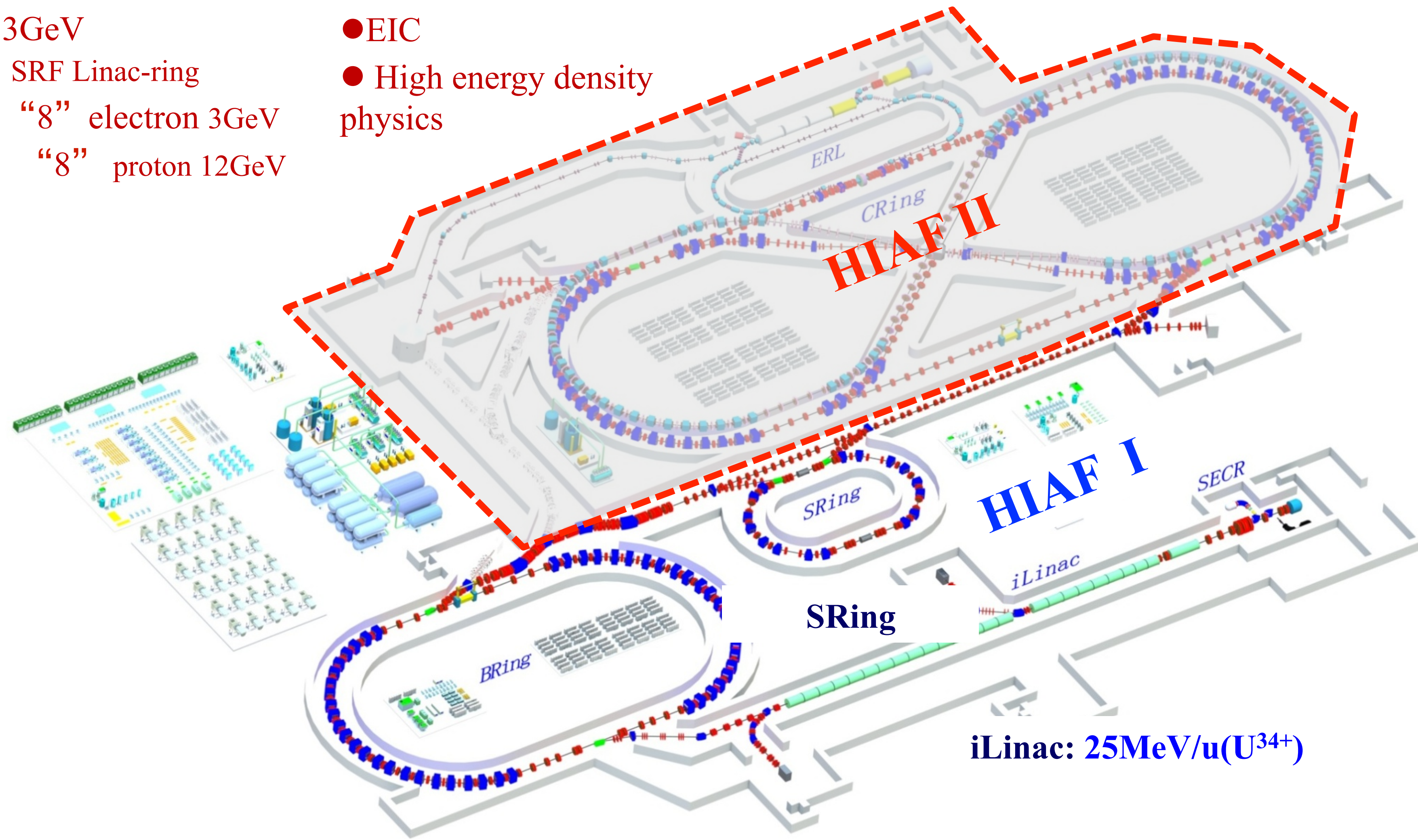
Overview of the HIAF Complex

EIC@HIAF
Xurong Chen, Hadron2015

HIAF II

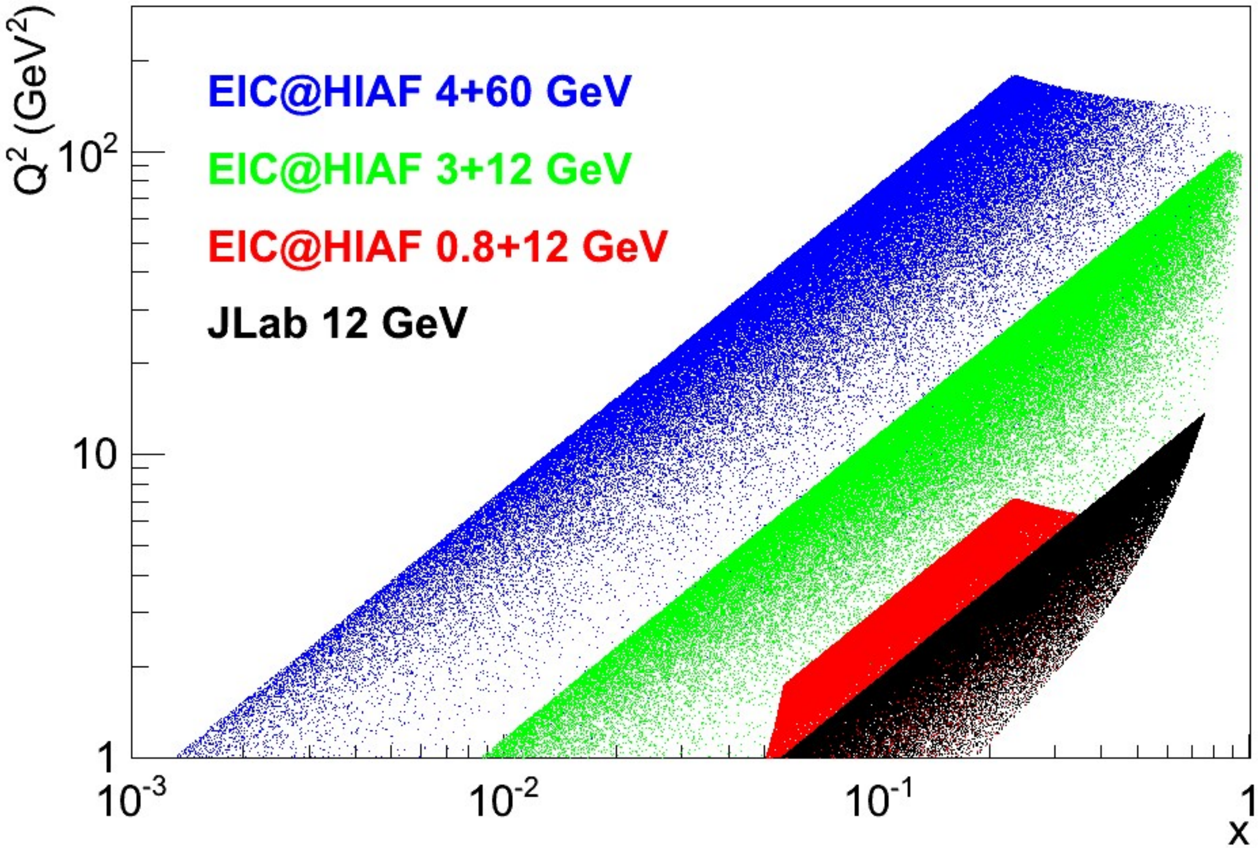
- 3GeV SRF Linac-ring
- "8" electron 3GeV
- "8" proton 12GeV
-

- EIC
- High energy density physics



EIC@HIAF Kinematic Coverage Comparison with JLab 12 GeV

e(3GeV) +p(12GeV), both polarized, L(max)=4*10^{32}cm^2/s



EIC@HIAF:

- study sea quarks (x > 0.01)
- deep exclusive scattering at Q^2 > 5-10
- higher Q^2 in valance region
- range in Q^2 allows some study gluons

plot courtesy of Xurong Chen

Figure of Merit

- **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: $L=4*10^{32}$, D=1

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

  Unpolarized:

  FOM(1)/FOM(2) = L(1)/L(2) ~ 4

  Polarized:

  $FOM(1)/FOM(2) = L(1)/L(2) * [D(1)^2 /D(2)^2] \sim 200$

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