Center for Frontiers in Nuclear Science

Electron Ion Collider

Abhay Deshpande

Lecture 1 of 3

NNPSS 2023 at UC Riverside

Stony Brook University

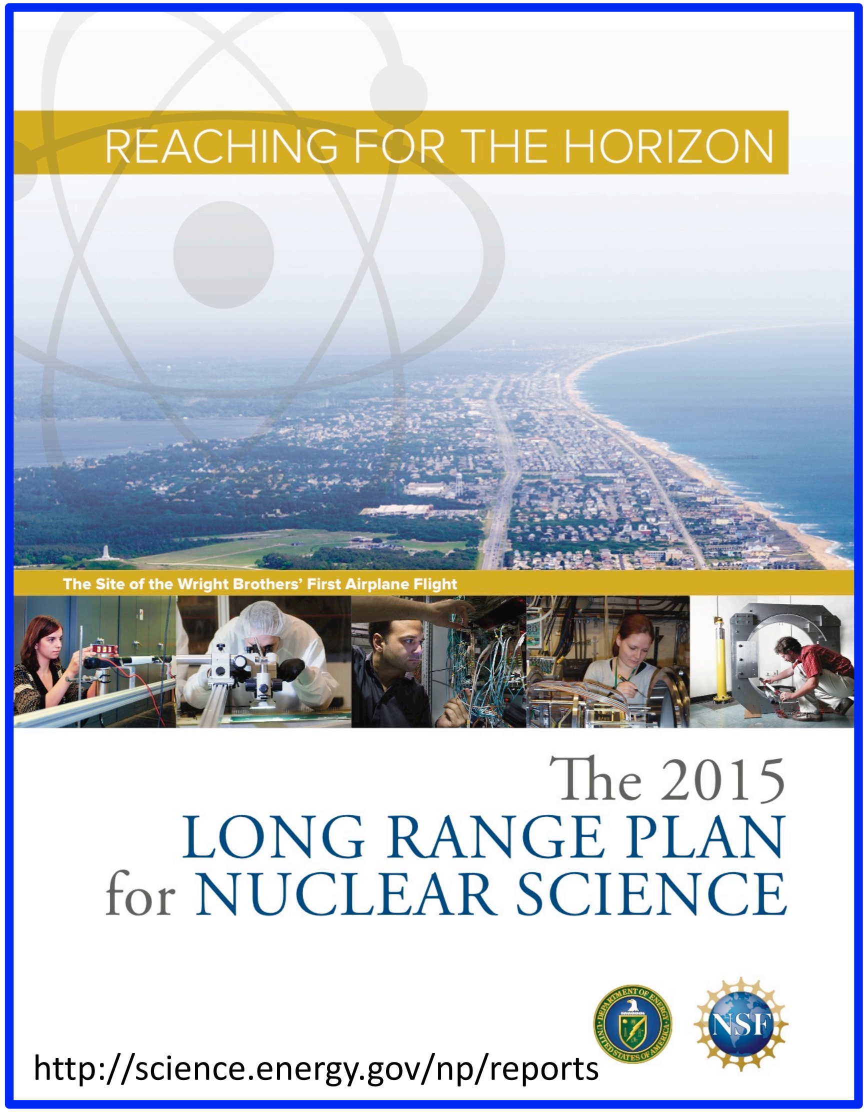
Brookhaven National Laboratory

Introduction to EIC – three lectures

- Hour 1: What is EIC?
  Introduction to EIC, historical motivation

- Hour 2: Why a polarized collider? Why nuclei?
  Limitations of past & current experiments, why nuclei?

- Hour 3: EIC: (modern) Why?
  What, how and when the EIC could deliver



Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

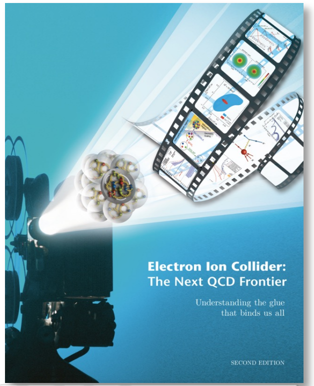
RECOMMENDATION:

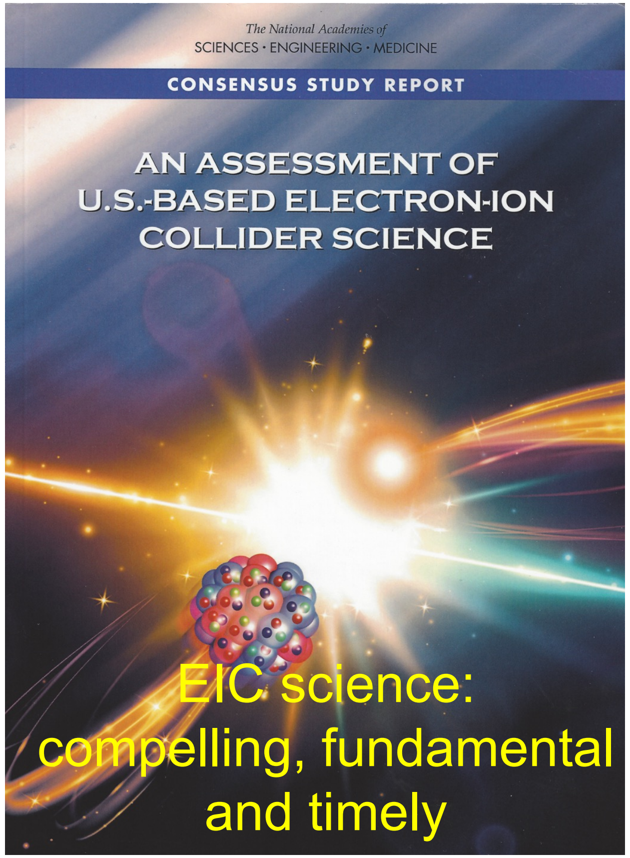
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Facilities for Radioactive Isotope Beams (FRIB) construction completed & Physics started May 9, 2022.

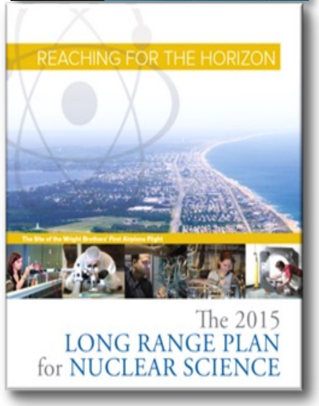
➔ ***DOE has kept its promise. EIC construction plan is well on the way.***

National Academy of Science, Engineering and Medicine
Assessment July 2018





EIC science: compelling, fundamental and timely

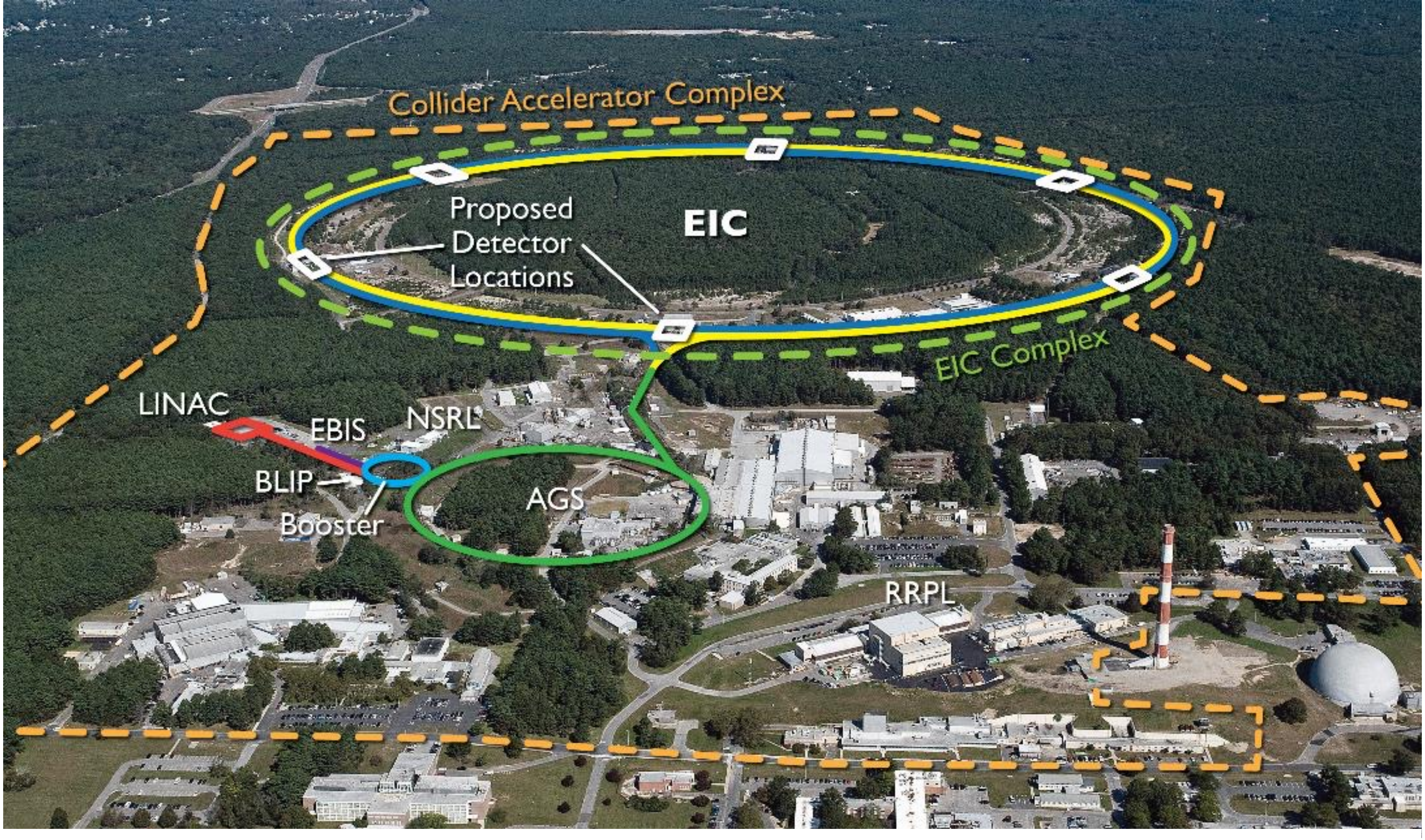


Physics of EIC

- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

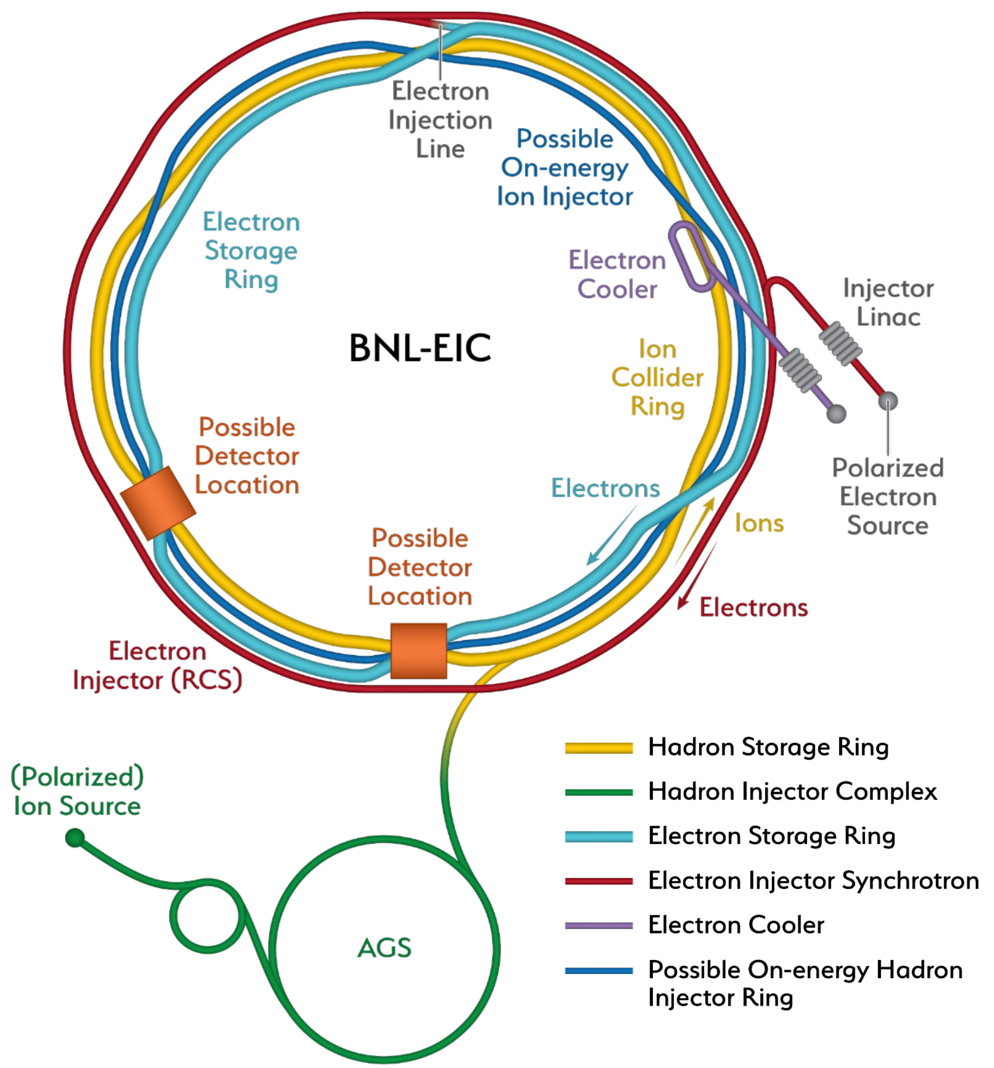
Machine Design Parameters:

- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice

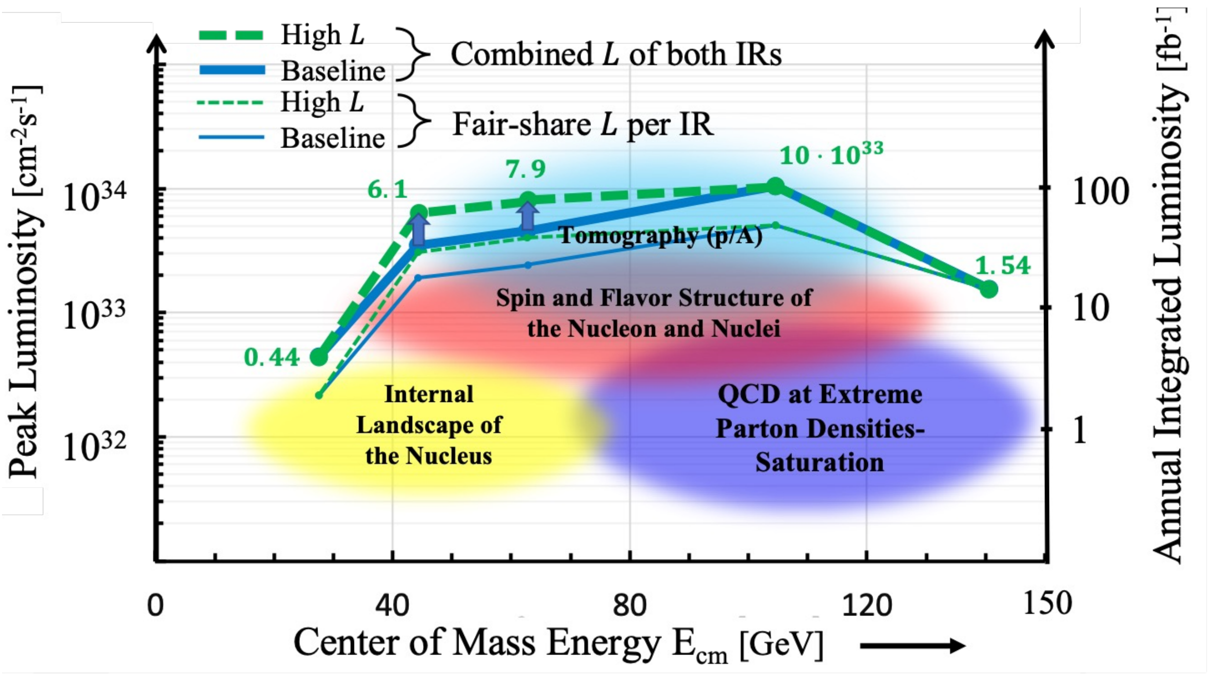


- EIC benefits from $B class investments at BNL and the highly successful RHIC program.
- RHIC will conclude operations in 2025. EIC installation will begin after RHIC ops concludes.

EIC Accelerator



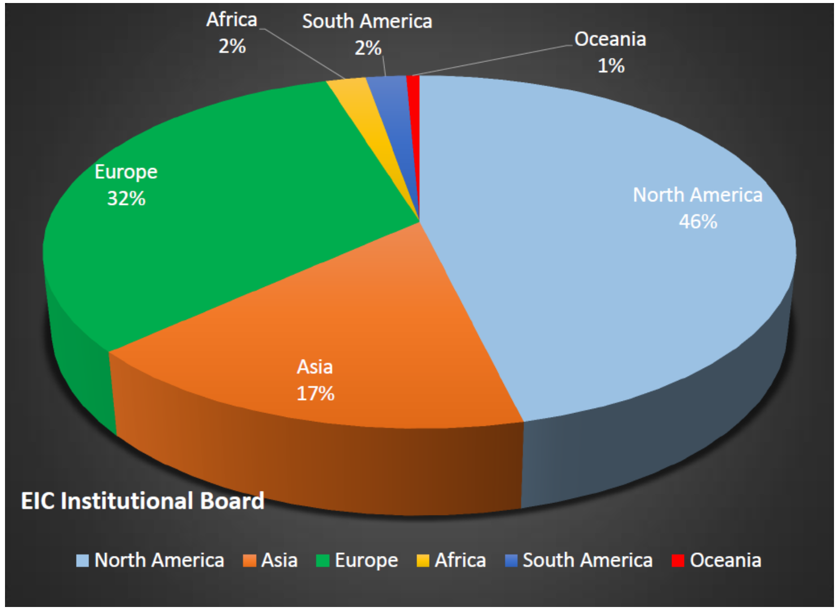
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



The EIC Users Group: [EICUG.ORG]

Formally established in 2016, now we have:
~1350 Ph.D. Members from 36 countries, 270 institutions
New members welcome

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory



EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker’s Committee, Election & Nominations Committee

Year long workshops: Yellow Reports for detector design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Remote (2021)**, **Stony Brook (2022)**, **Warsaw (2023)**

Electron Ion Collider…

What is so special about this new collider being planned in the US?

Why so much excitement?

These lectures will try to explain….

Study of internal structure of a watermelon:

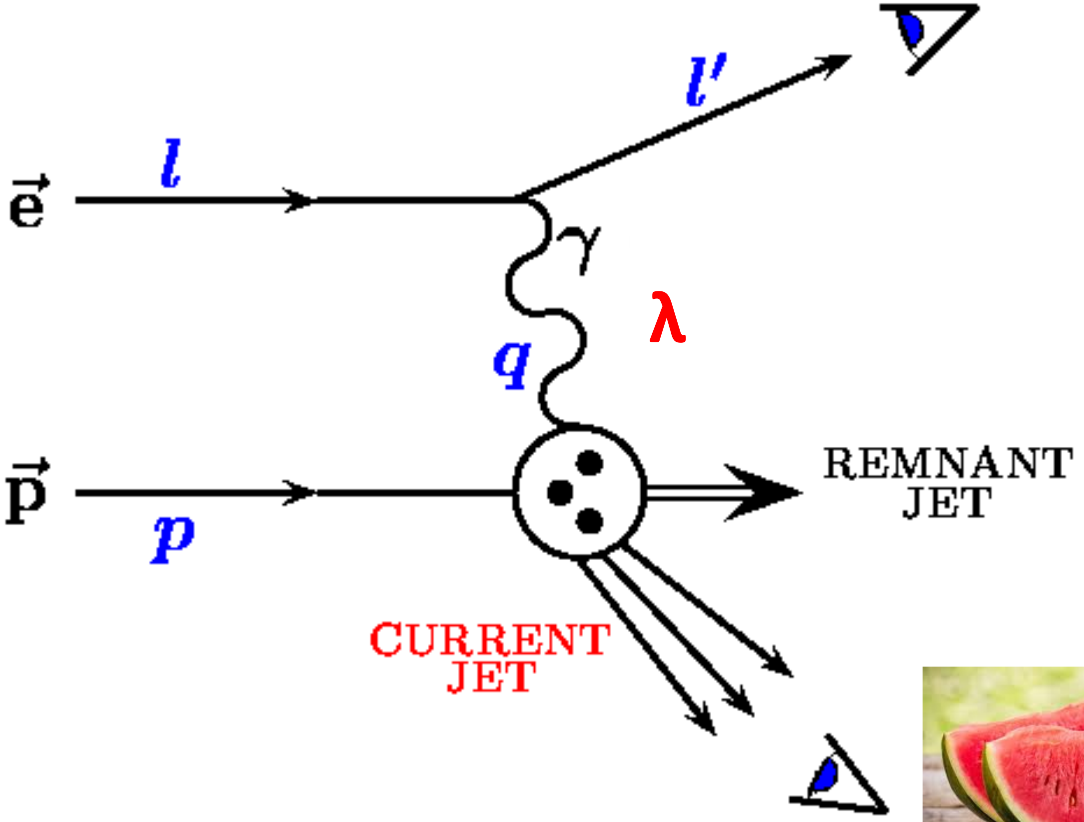
A-A (RHIC/LHC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (Deep Inelastic Scattering -- DIS)

Deep Inelastic Scattering



q = h/λ

h = constant

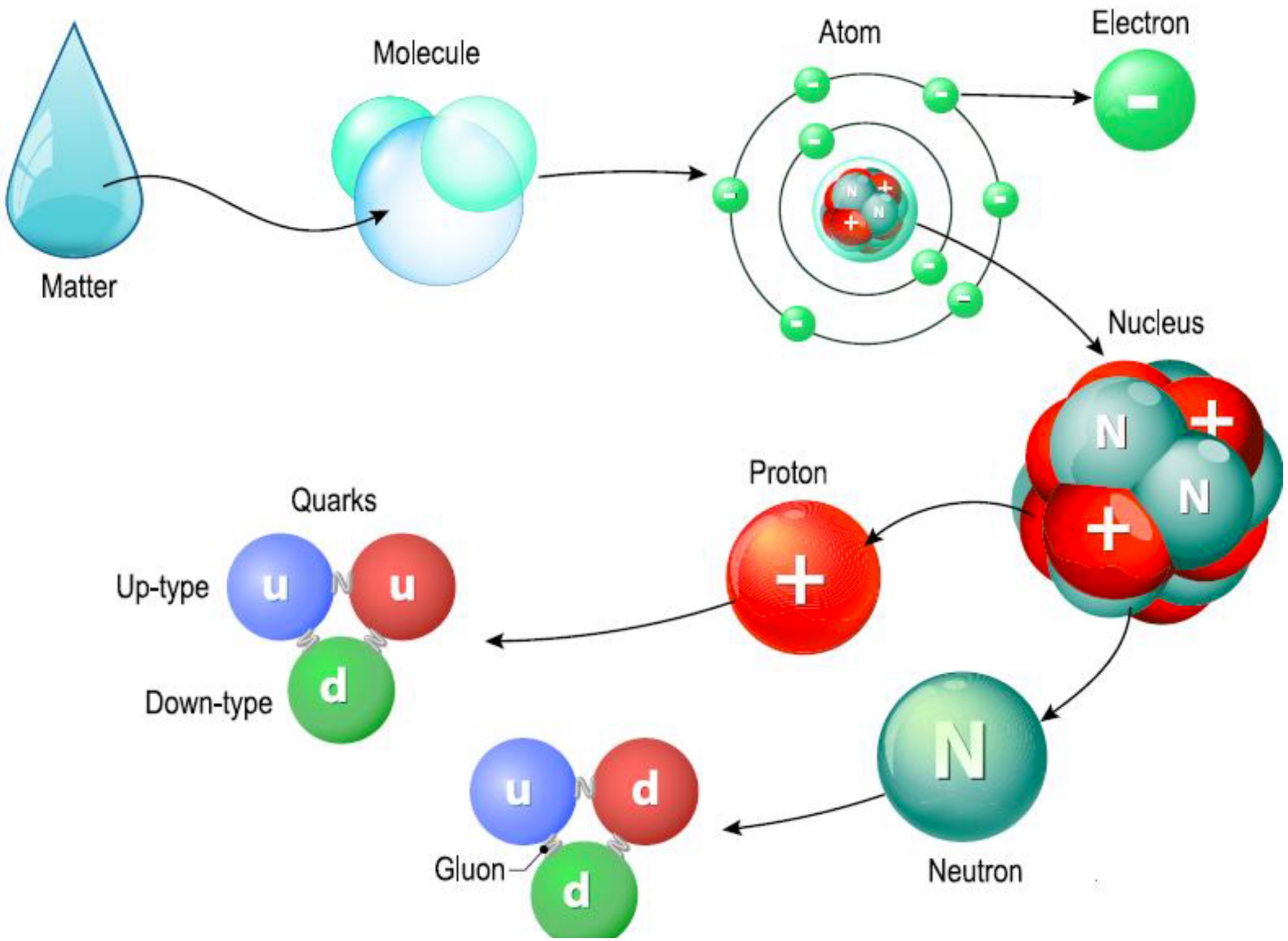
λ = wavelength

q = momentum transferred

Deep Inelastic: (**λ** << Proton Size)

Our curious minds…

Quest for the fundamental structure of matter



What's in there?

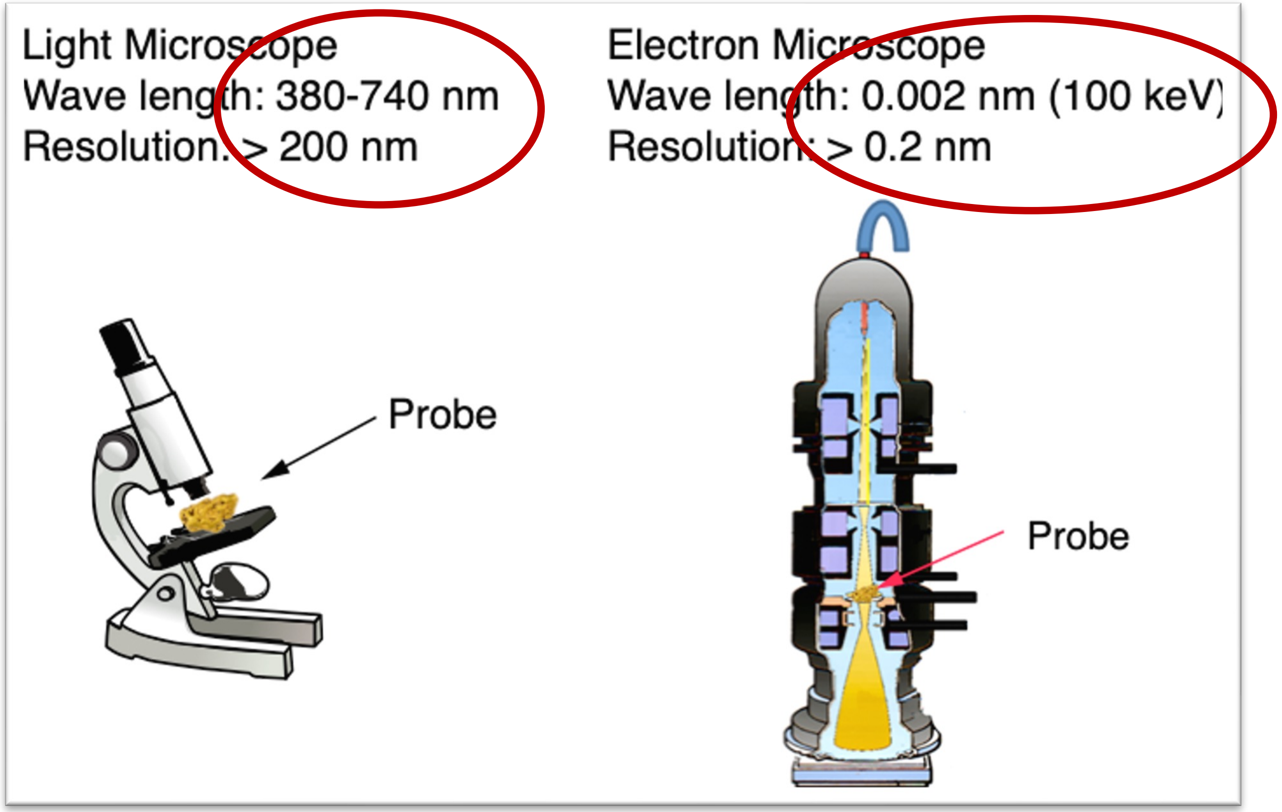
What are we made up of?

What is the "smallest"?

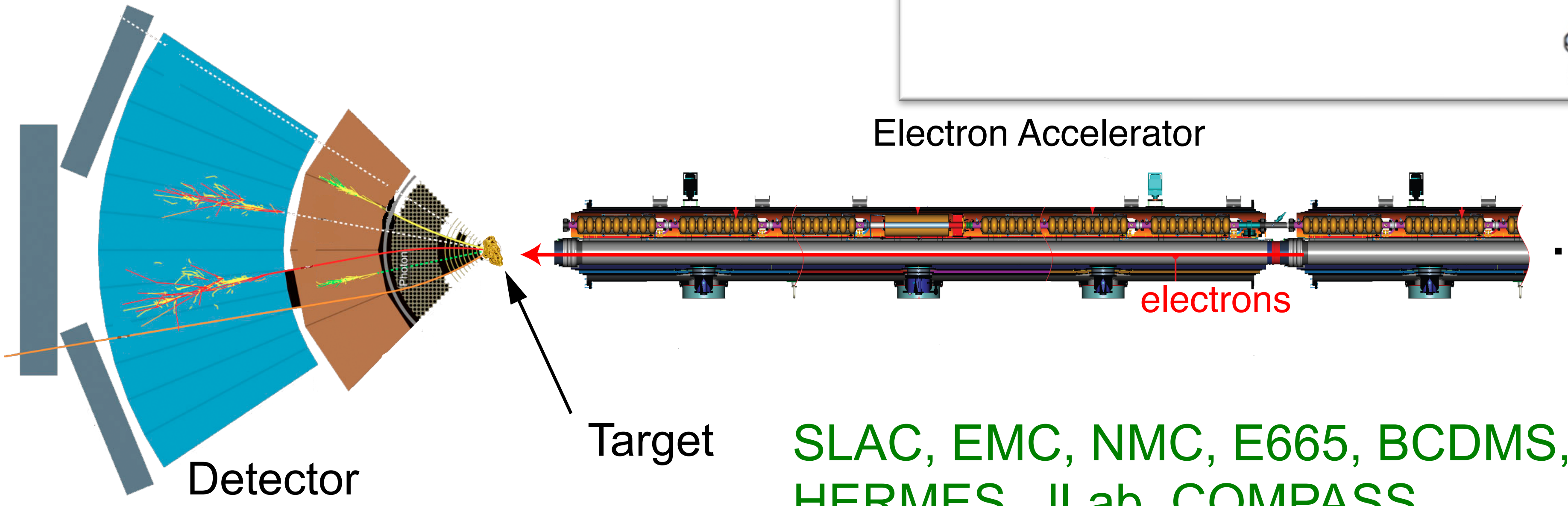
What is "fundamental" that can't be divided further?

National Academy of Sciences, Consensus Report on the US EIC

Studying smaller and smaller things…

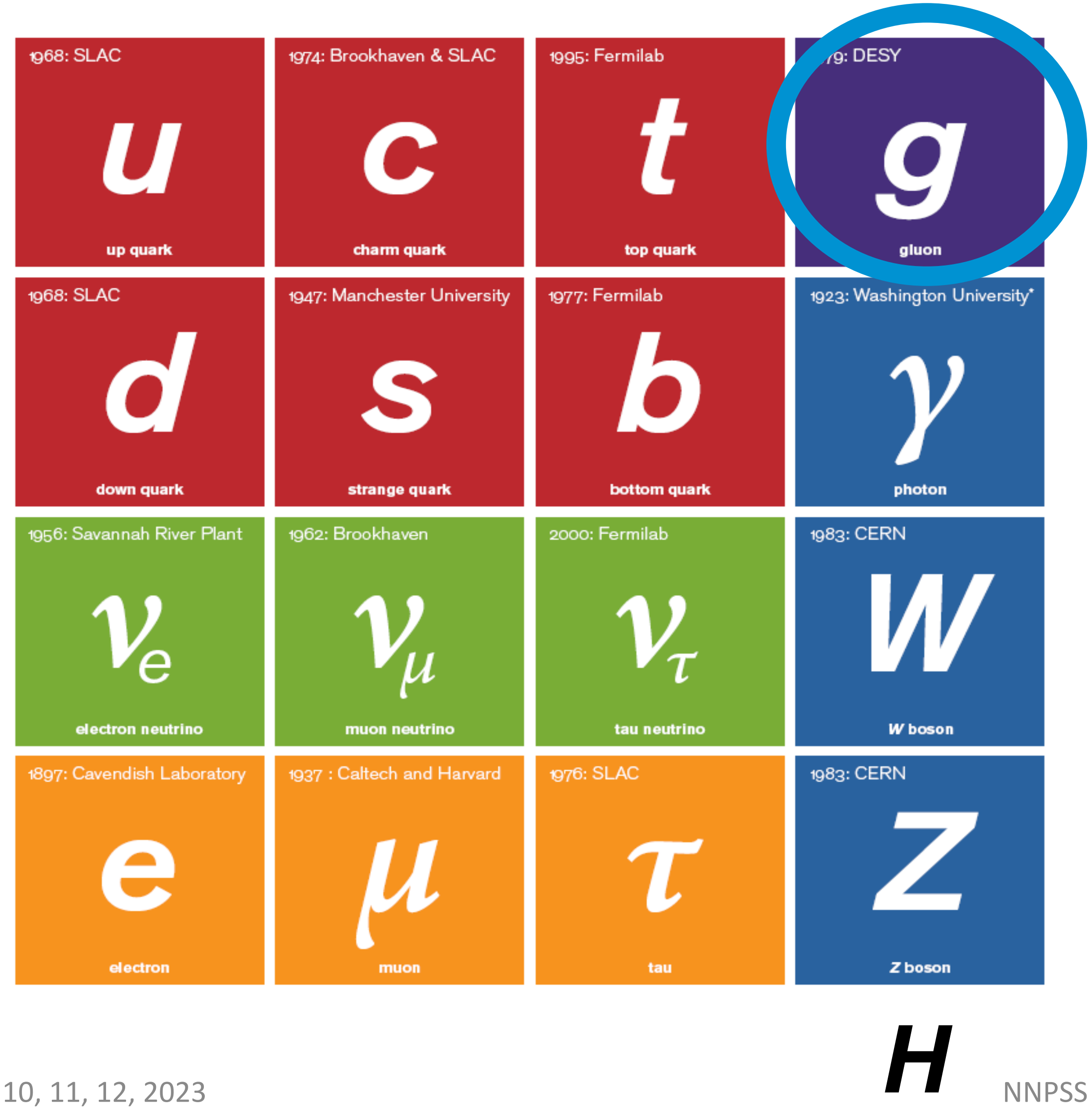


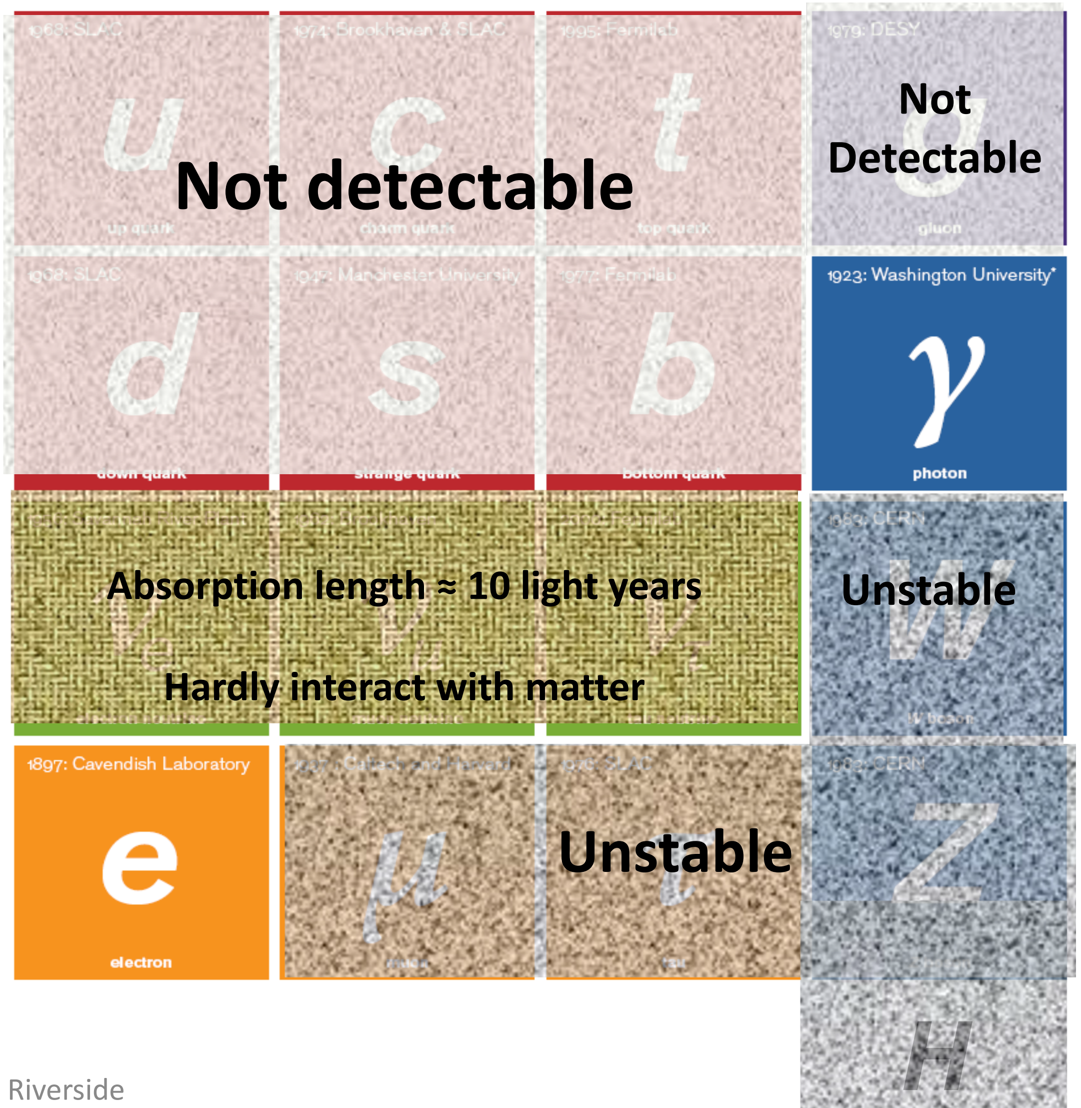
Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm



SLAC, EMC, NMC, E665, BCDMS, HERMES, JLab, COMPASS, …

Many 

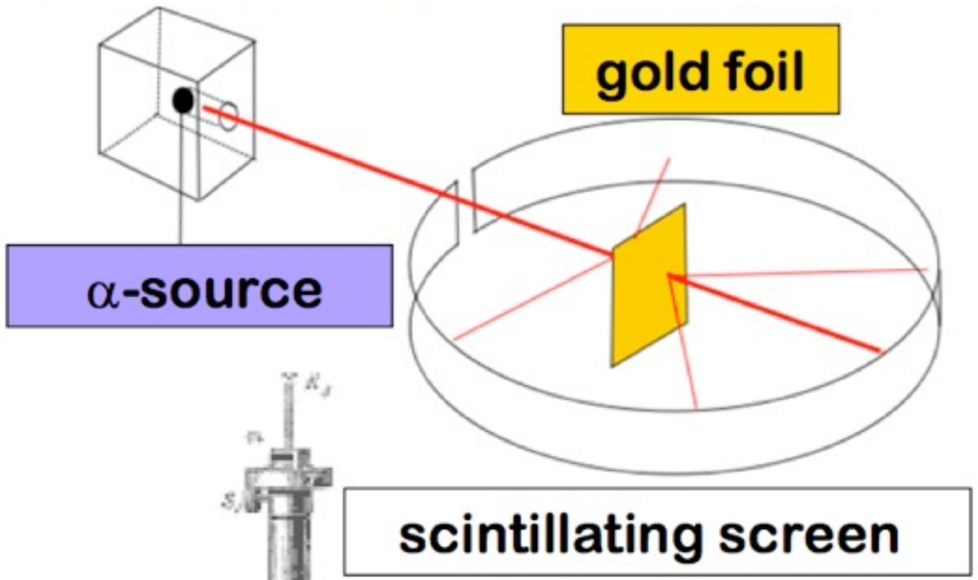

1968: SLAC
u
up quark
1974: Brookhaven & SLAC
c
charm quark
1995: Fermilab
t
top quark
79: DESY
g
gluon
1968: SLAC
d
down quark
1947: Manchester University
s
strange quark
1977: Fermilab
b
bottom quark
1923: Washington University*
γ
photon
1956: Savannah River Plant
ν_e
electron neutrino
1962: Brookhaven
ν_μ
muon neutrino
2000: Fermilab
ν_τ
tau neutrino
1983: CERN
W
W boson
1897: Cavendish Laboratory
e
electron
1937 : Caltech and Harvard
μ
muon
1976: SLAC
τ
tau
1983: CERN
Z
Z boson
H

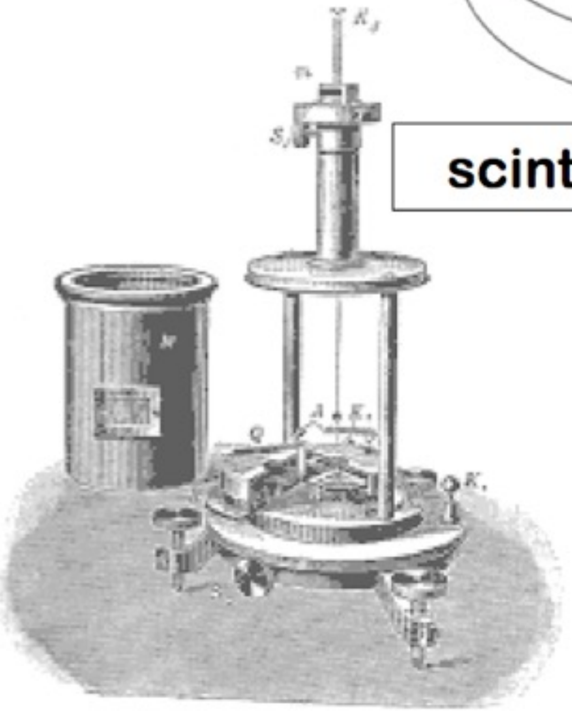

Not detectable
Not Detectable
1923: Washington University*
γ
photon
Absorption length ≈ 10 light years
Hardly interact with matter
Unstable
1897: Cavendish Laboratory
e
electron
Unstable

It all began with….

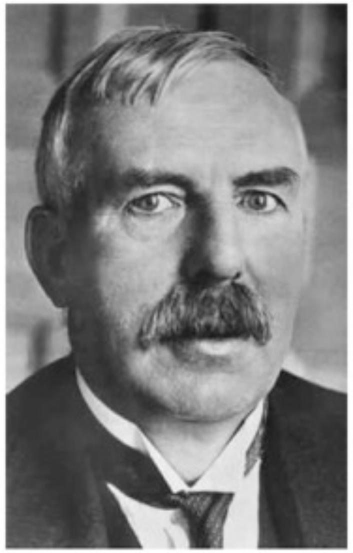
Rutherford Scattering

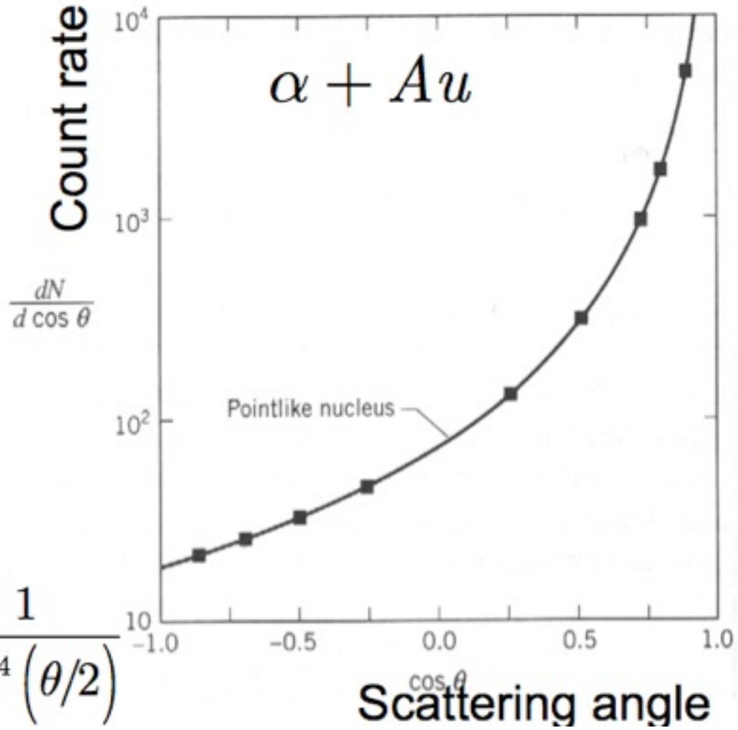
~5 MeV





Ernest Rutherford,
Nobel Prize 1908



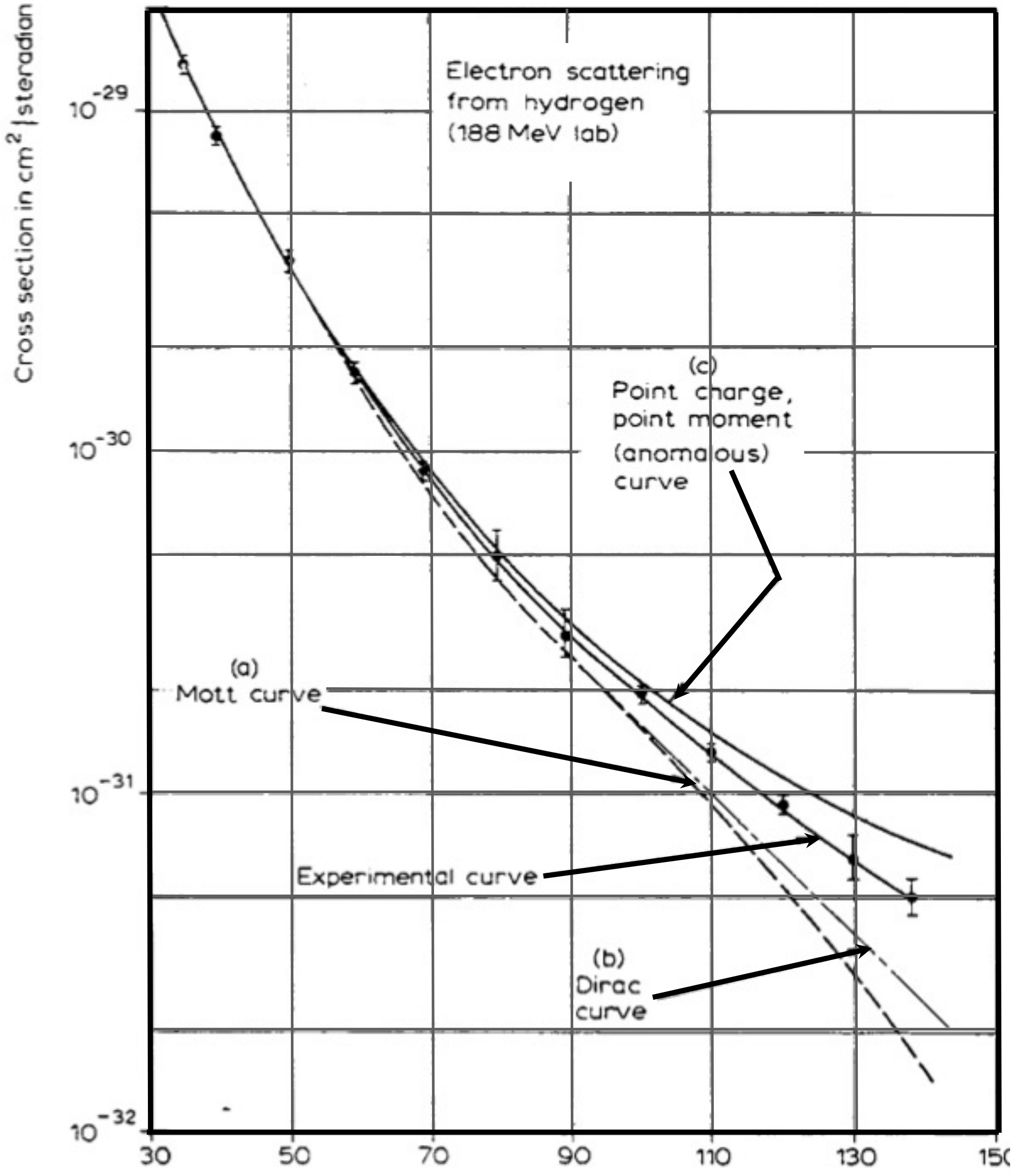


$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\mathrm{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

Scattering off a hard sphere; $r_{\mathrm{nucleus}} \sim (10^{-4}\,.r_{\mathrm{atom}}) \sim 10^{-14}$ m

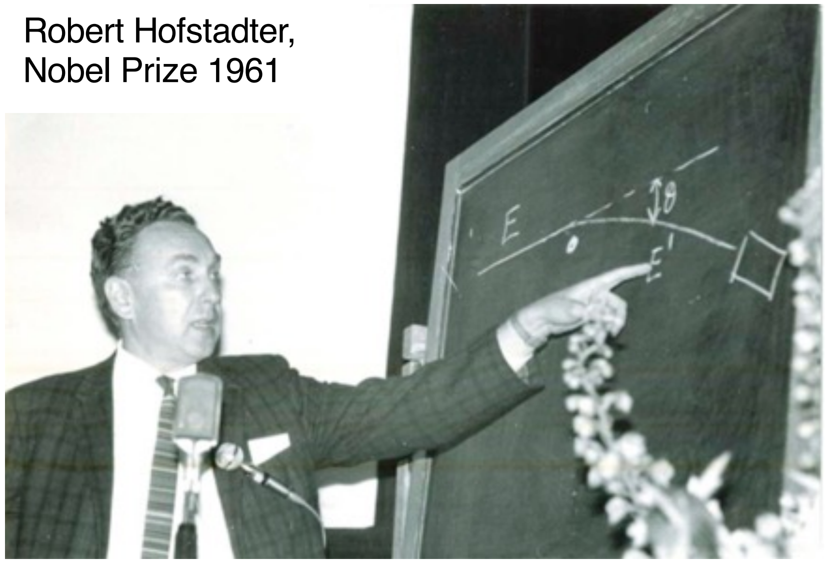
Elastic Electron Scattering

~200 MeV



$r_{\text{nucleon}} \sim 0.7$ fm

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,

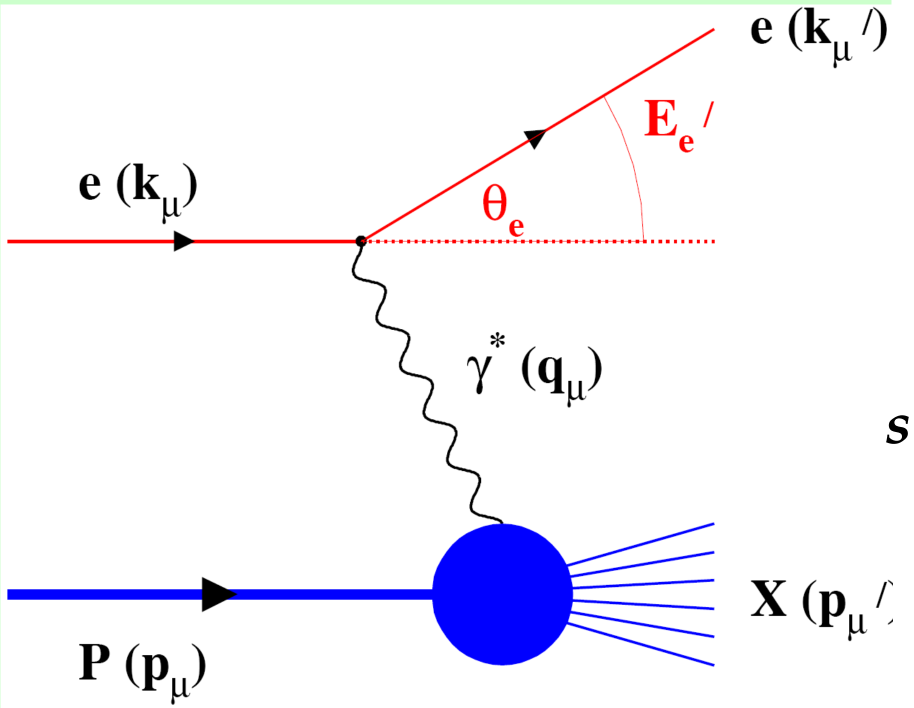
$$g_p \neq 2, \quad g_p \simeq 5.6$$

and, hence, internal (spin) structure.

How to explain this in modern language? Let us see…

Deep Inelastic Scattering: Precision & Control

Kinematics:



$$s = 4\, E_e\, E_p$$

Inclusive events: e+p/A → e'+X

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

The only dimension considered comes in through "x".

Fraction of momentum carried by the quark/parton.

It is obviously moving in the direction of the proton. – Only one-dimensional information is explored & hence revealed….

All transverse motion was ignored. However, now we have more precision…

Unpolarized e-p/A DIS

DIS without Spin:

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

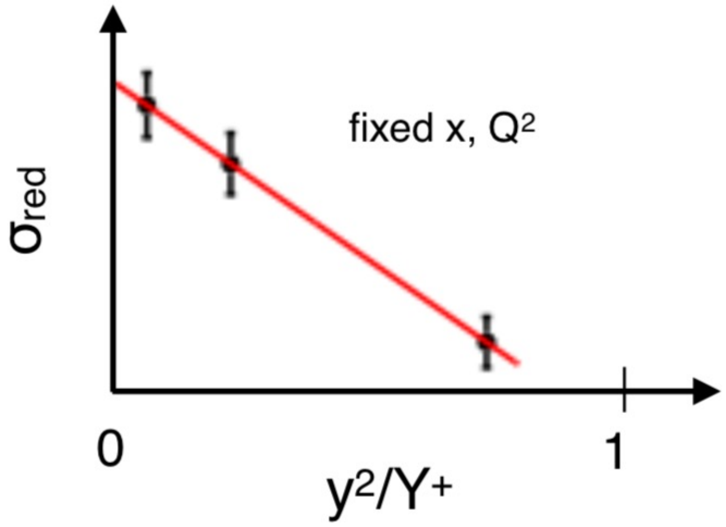
Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

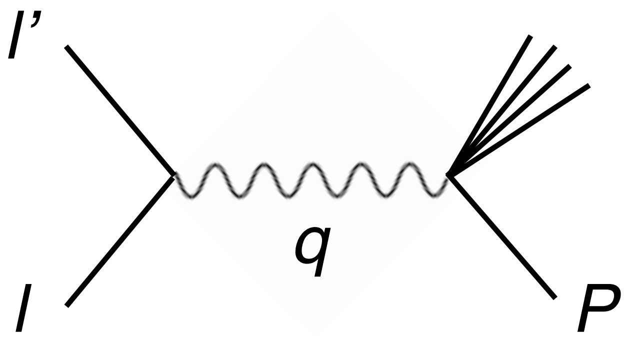
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

Rosenbluth Separation:

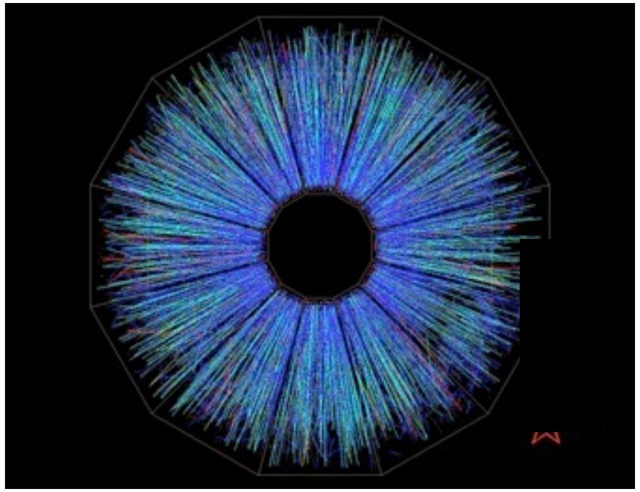
- Recall $Q^2 = x\, y\, s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$



Inelastic Scattering



Not convinced of additional complexity?



Then forget this talk, and calculate this!

Simplify - consider *inclusive* inelastic scattering,

$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\mathrm{lepton}} W_{\mu\nu\,\mathrm{nucleon}}, \qquad W_{\mu\nu\,\mathrm{nucleon}}(p,q)$$

Again, <u>two</u> (parity-conserving, spin-averaged) structure functions:

$$W_1, W_2 \ \ \text{or, alternatively expressed,} \ \ F_1, F_2$$

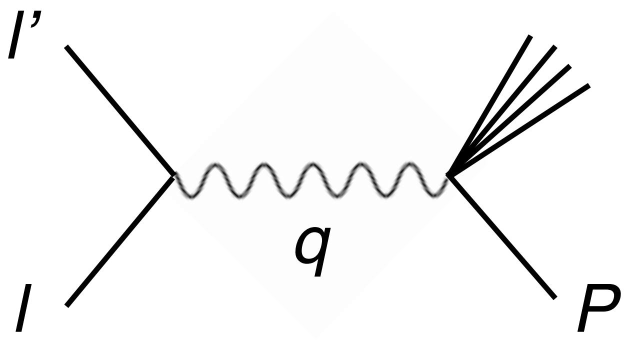
which may depend on <u>two</u> invariants,

$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \ \ 0 < x < 1$$

So much for the structure, the physics is in the structure functions.

Courtsey E. Sichtermann

Inelastic Scattering



Considerably more complex, indeed!

Simplify - consider *inclusive* inelastic scattering,

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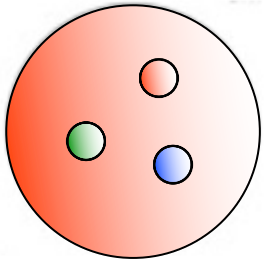
Courtsey E. Sichtermann

Elastic scattering off Dirac Protons



Imagine *incoherent* scattering off *Dirac* Partons (quarks) *q* :

$$W_1^q = \frac{e_q^2}{2m_q} [\ldots]_q - 1), \quad W_2^q = -\frac{2m_q e_q^2}{q^2}\delta(x_q - 1) \text{ and } x_q = -\frac{q^2}{2q \cdot p_q}$$

and, furthermore [...]uppose that the quarks carry a fraction, *z*, of the proton momentum

$$p_q = z_q\, p, [\ldots] \text{ that } x_q = \frac{x}{z_q} \quad (\text{also note } m_q = z_q M\,!)$$

which uses the r[...]tions between $K_{1,2}$ and $K_{4,5}$

Now,

$$MW_1 = [\ldots] \sum_q \int_0^1 \frac{e_q^2}{2M}\delta(x - z_q)\, f_q(z_q)\, dz_q = \frac{1}{2}\sum_q e_q^2 f_q(x) \equiv F_1(x)$$

$$-\frac{q^2}{2Mx}W_2 = [\ldots] \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

Two important *observable* consequences,

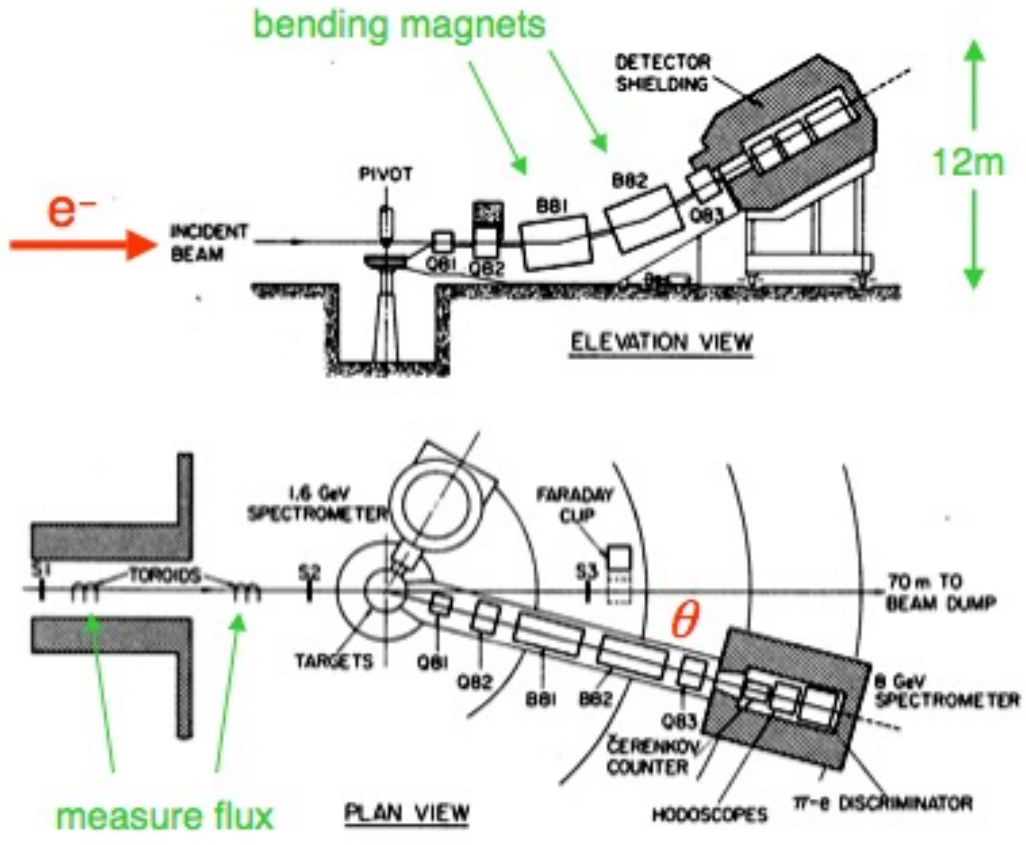
Bjorken scaling: $F_{1,2}(x), \quad \text{not } F_{1,2}(x, Q^2)$

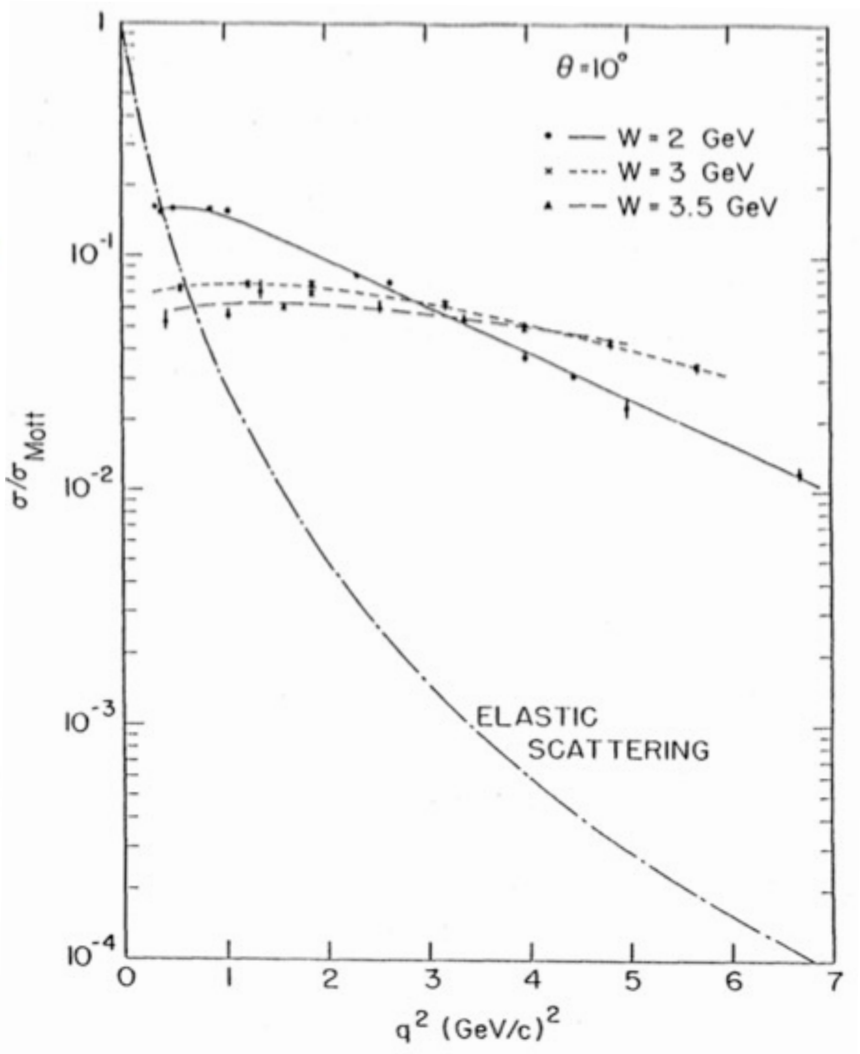
Callan-Gross relation: $F_2 = 2xF_1(x)$

Courtsey E. Sichtermann

~10 GeV

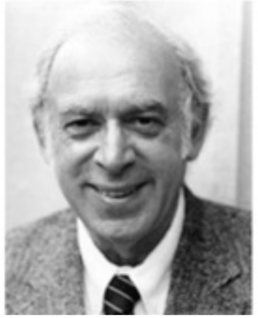
Deep-Inelastic Electron Scattering





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

Deep-Inelastic Electron Scattering

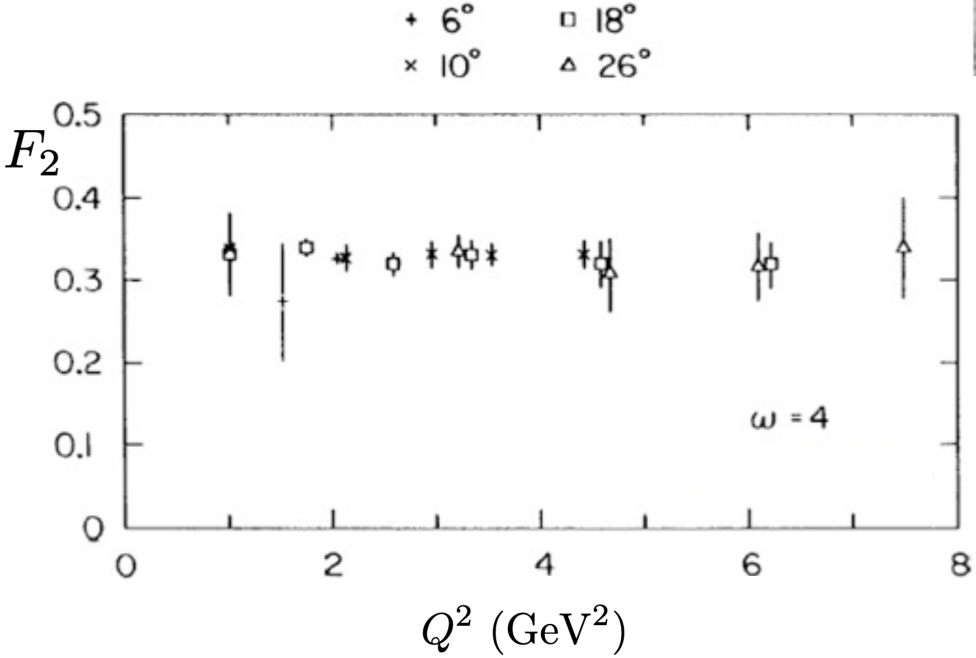


J.T. Friedman

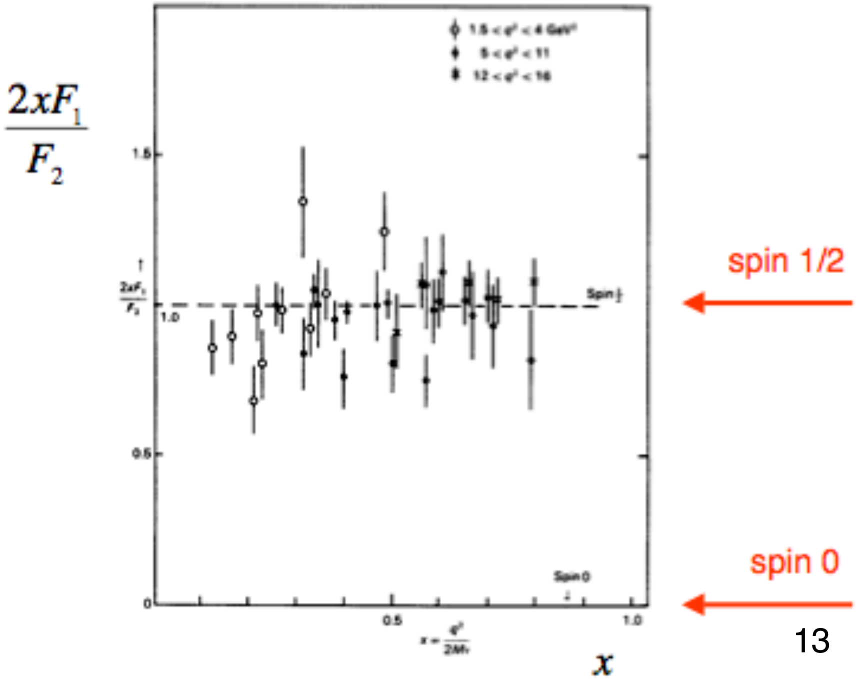
R. Taylor
Nobel Prize 1990

H.W. Kendall

Bjorken scaling:



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.

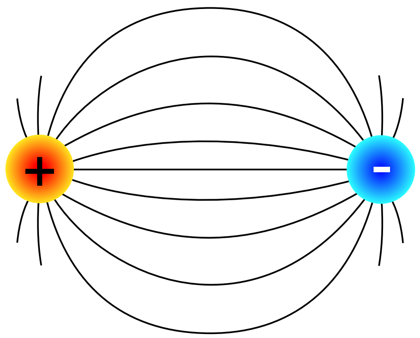
Homework:
Find out how we know quarks carry fractional charge.

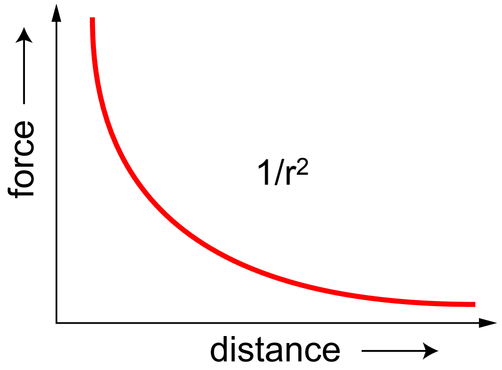
Hint: Neutrino Scattering… Gargamell Experiment at CERN.

Quantum Electrodynamics (QED)

Theory of electromagnetic interactions

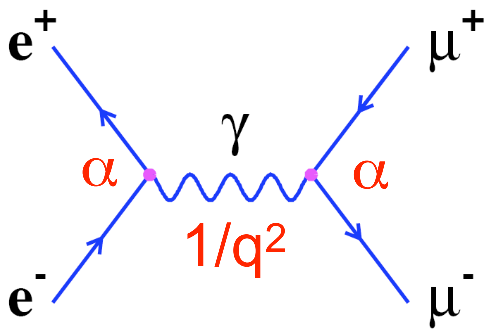
- Exchange particles (photons) do not carry electric charge
- Flux is not confined: $V(r) \sim 1/r$, $F(r) \sim 1/r^2$





$$V(r) = -\frac{q_1\ q_2}{4\pi\varepsilon_0\ r} = -\frac{\alpha_{em}}{r}$$

Example Feynman Diagram:
e^+e^- annihilation



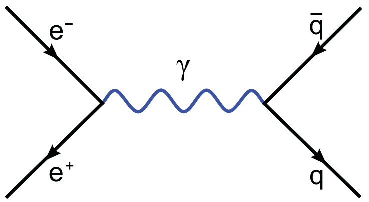
Coupling constant (α): Interaction Strength

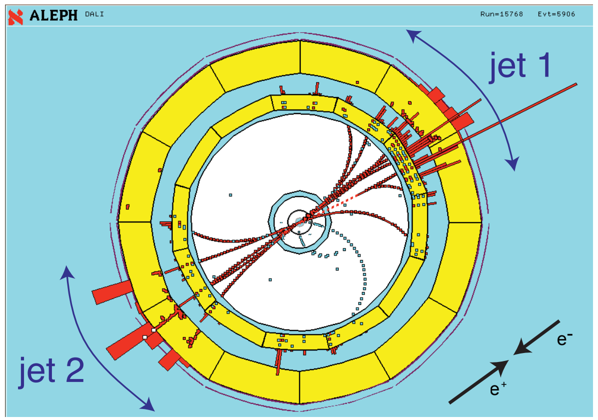
In QED: $\alpha_{em} = 1/137$

Gluons!

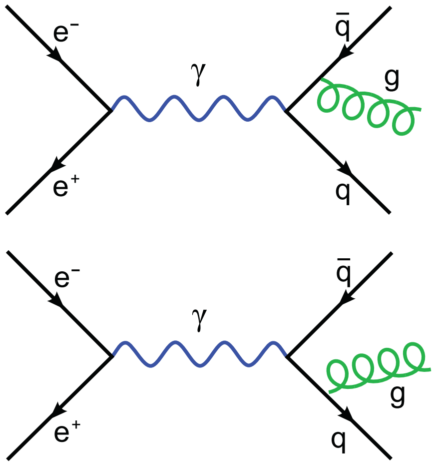
Discovery of gluons: Mark-J, Tasso, Pluto, Jade experiments at PETRA (e+e- collider) at DESY (CM energy 13-32 GeV)

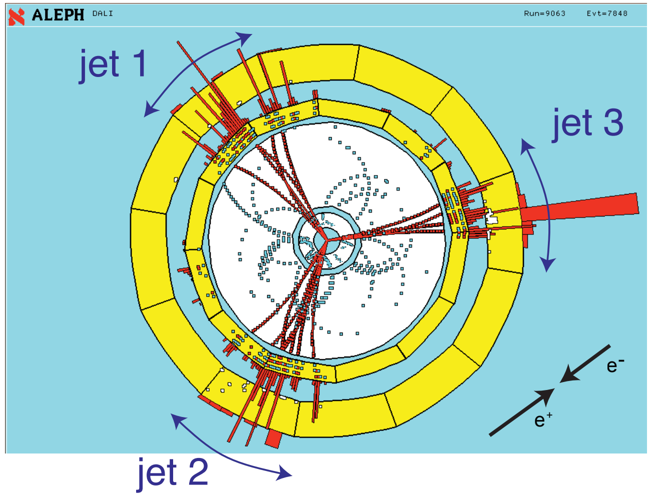
- $e^+ e^- \rightarrow q\ \bar{q} \rightarrow$ 2-jets





- $e^+ e^- \rightarrow q\ \bar{q}\ g \rightarrow$ 3-jets



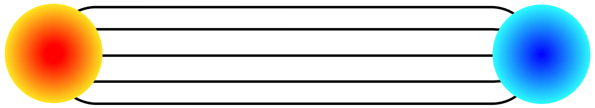


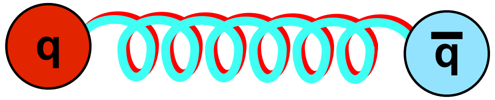
Quantum Chromodynamics (QCD)

Quantum Chromo Dynamics is the "nearly perfect" fundamental theory of the strong interactions

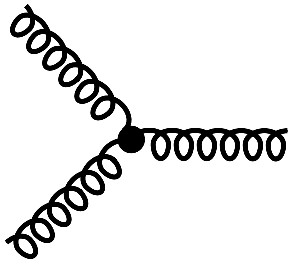
F. Wilczek, hep-ph/9907340

- Three color charges: red, green and blue





- Exchange particles (gluons) carry color charge and can self-interact



Self-interaction: QCD significantly harder to analyze than QED

- Flux is *confined*: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$

~1/r at short range

long range ~ r

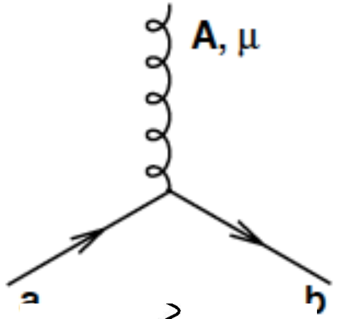
Long range aspect ⇒ quark confinement and existence of nucleons

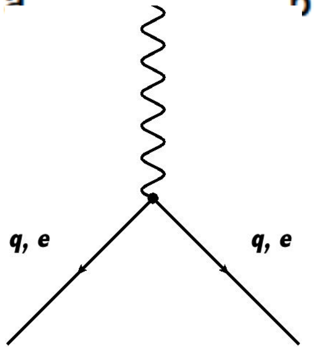
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less (and couple to charged particles)

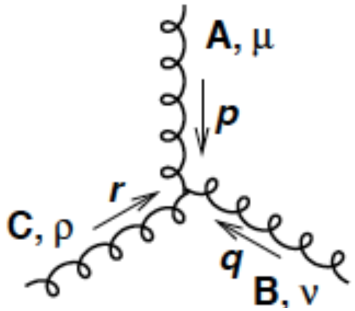
QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

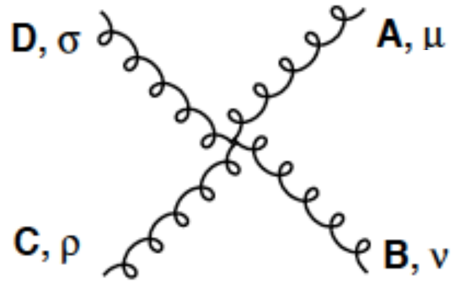
In QCD &
g → γ in QED





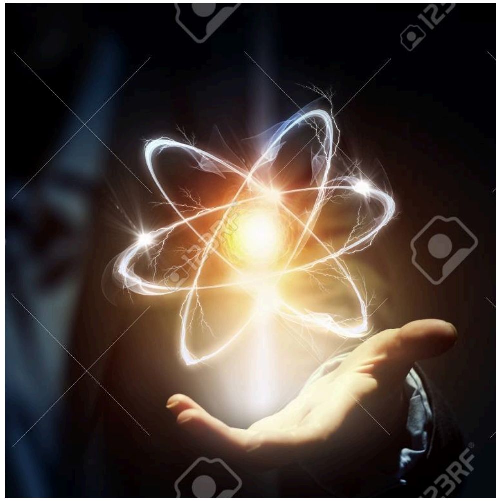
Only in QCD

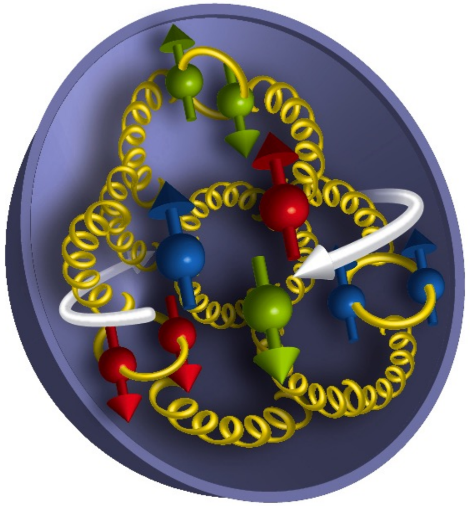




Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

About 100 years after the discovery of the atom and the proton





We know atomic structure so well, that we *define* “time” using electronic transitions:
Current accuracy
~1 sec in 220 Million years

However, the internal structure of the proton is
known to only about 20-30%
~20 minutes in an hour…!

WHY? Because of the gluons

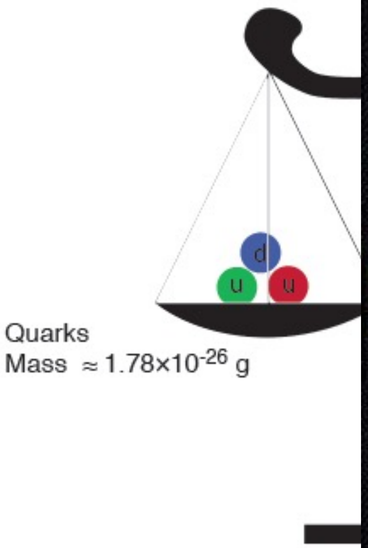
Proton mass puzzle

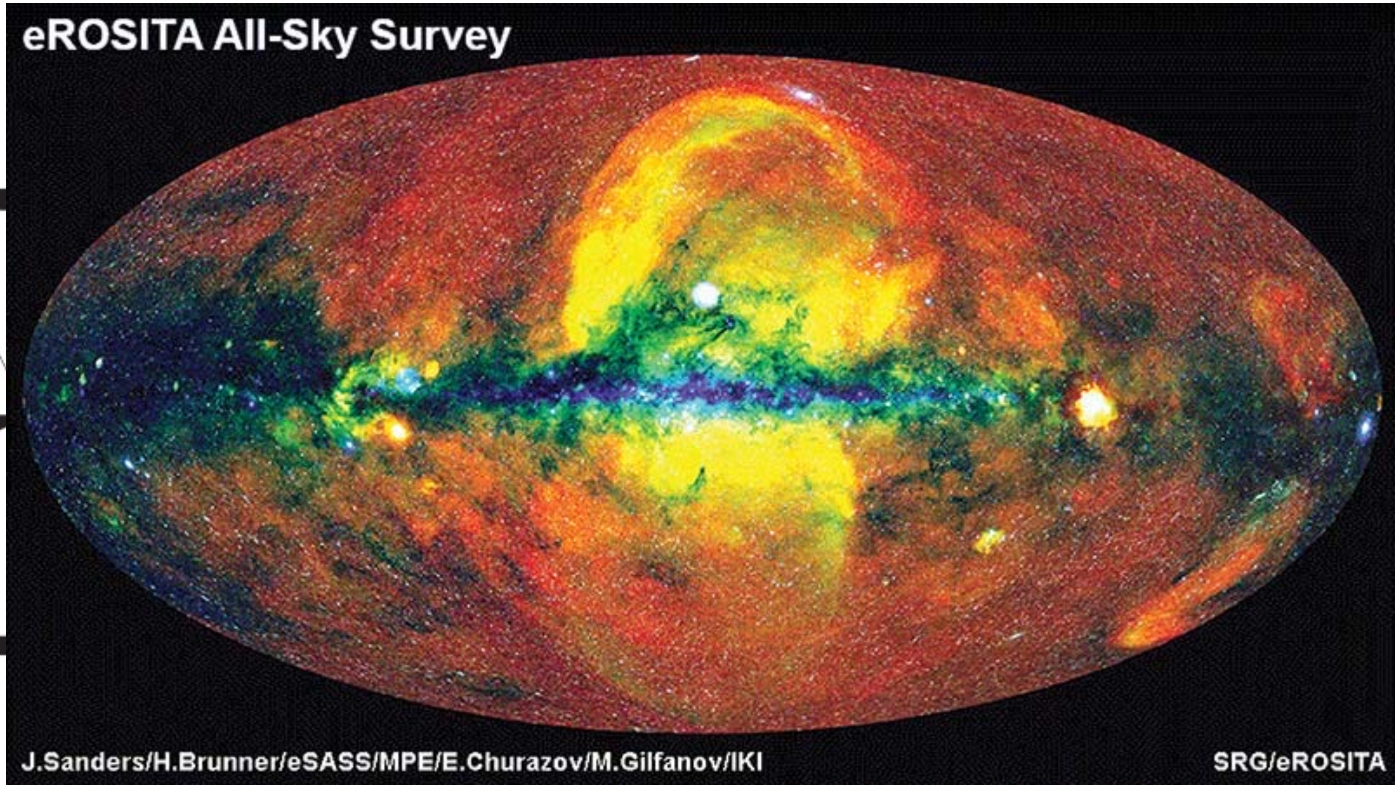
© Nobel Media AB. Photo: A. Mahmoud
François Englert

© Nobel Media AB. Photo: A. Mahmoud
Peter W. Higgs

Nobel 2013 With Francois Englert

“Higgs Boson” that gives mass to quarks, electrons,….





Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

But the proton’s mass is 168 x 10^{-26} grams

→**only 1% of the mass of the protons (neutrons)** → Hence the Universe

→Where does the rest of the mass come from?

HERA - Electron Proton Collider

Unpolarized e-p/A DIS

DIS without Spin:

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

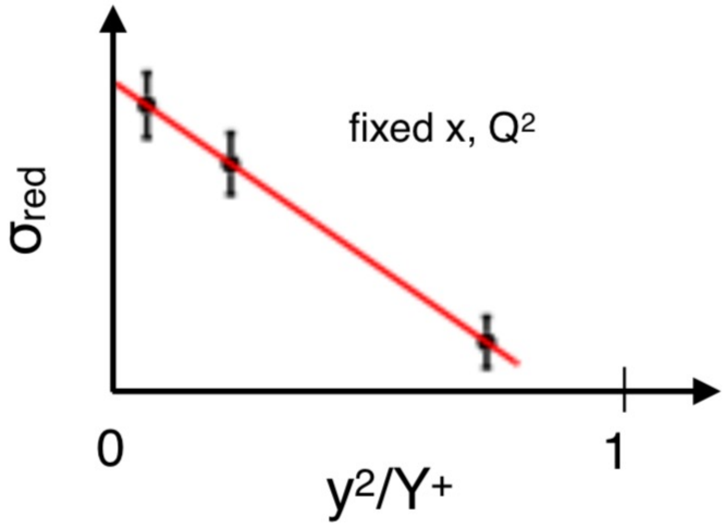
Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dx dQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

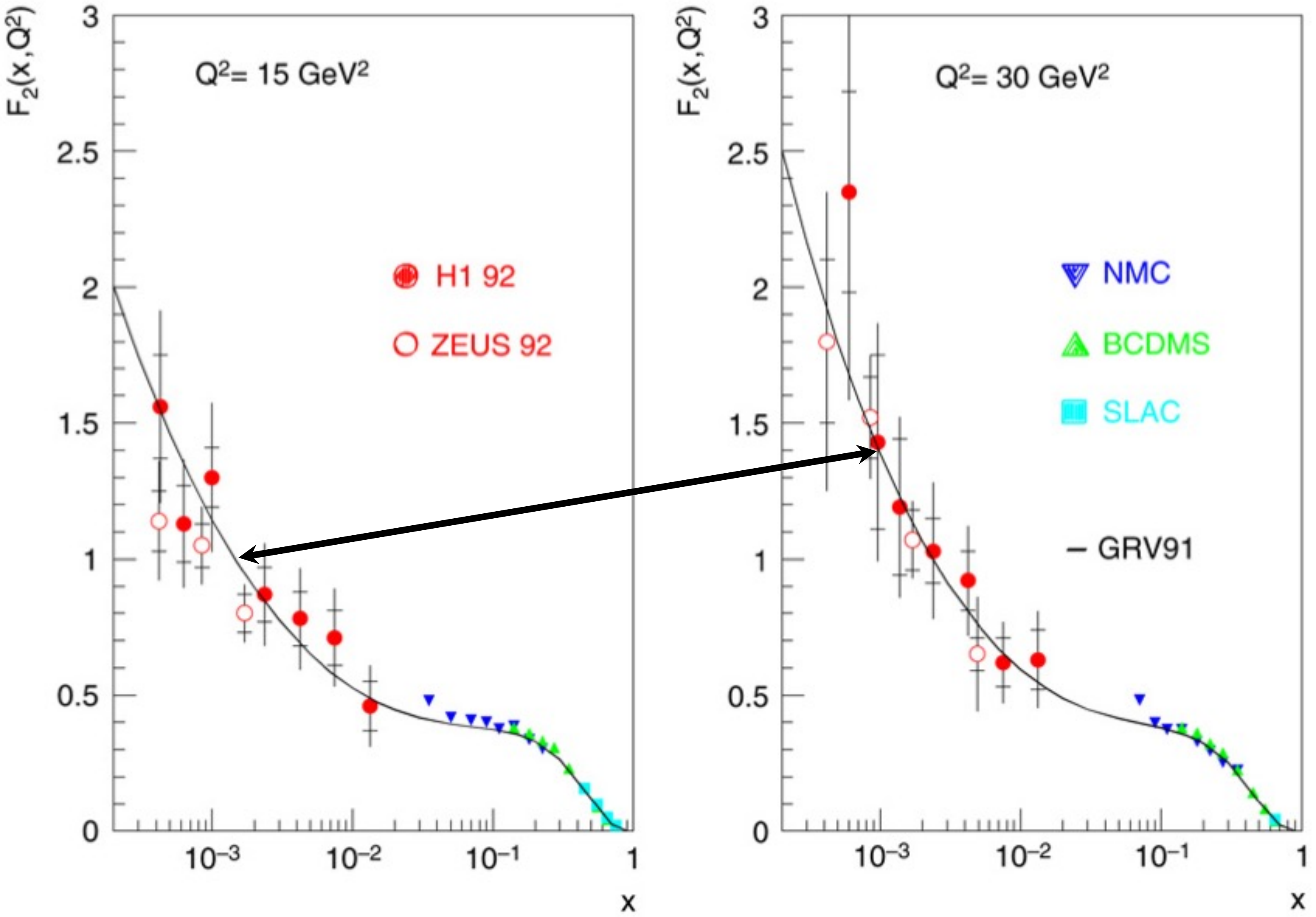
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

Rosenbluth Separation:

- Recall $Q^2 = x\,y\,s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$



HERA - Early Measurements



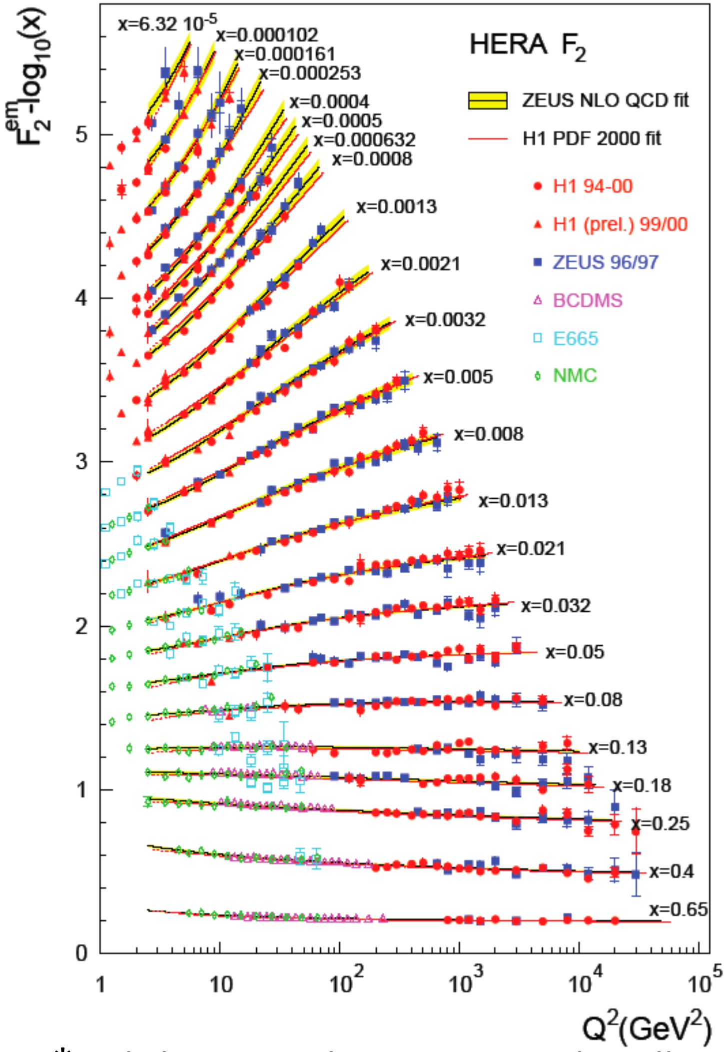
Can these observations be related?

Measurement of unpolarized glue at HERA

F$_2$ Structure Function

Vs.

Q^2 mom. exchanged

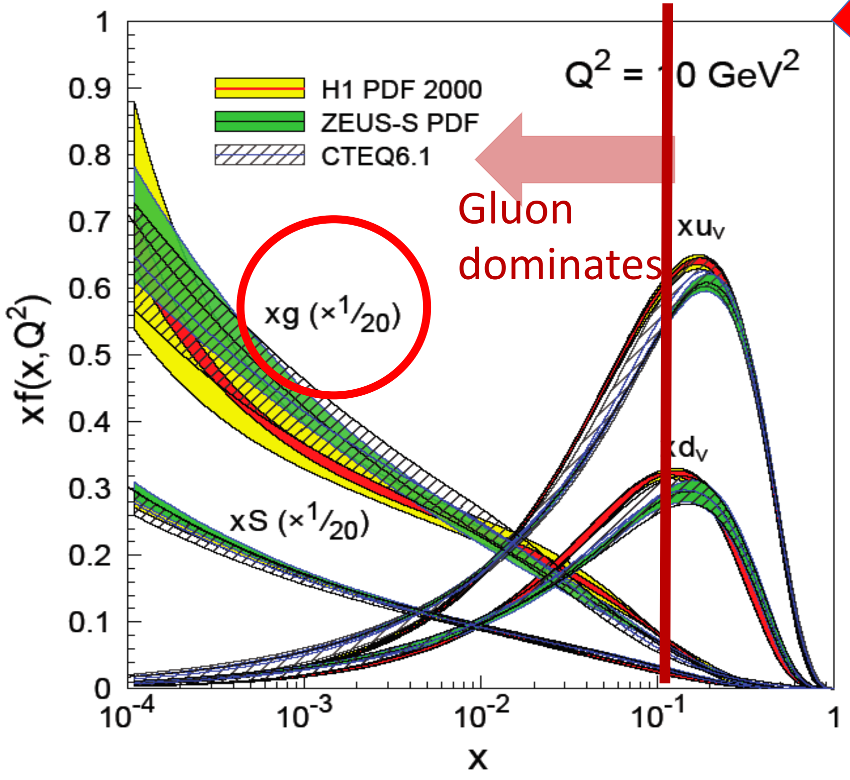


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

- Scaling violations of F$_2$(x,Q^2)

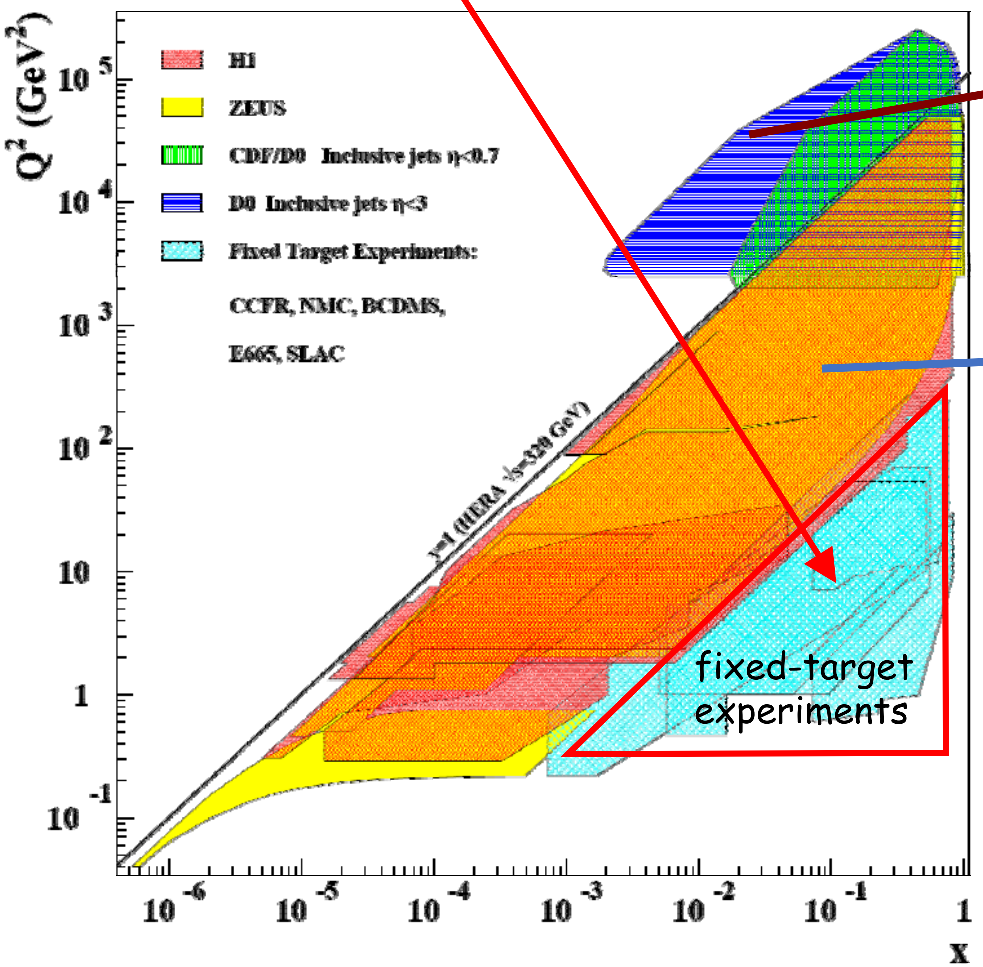
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

- NLO pQCD analyses: fits with **linear** DGLAP* equations



Perspective on x,Q^2, Center of Mass

Fixed target e-N experiments
(center of mass < 30 GeV)



Hadron-Hadron Collider: CM ~2 TeV

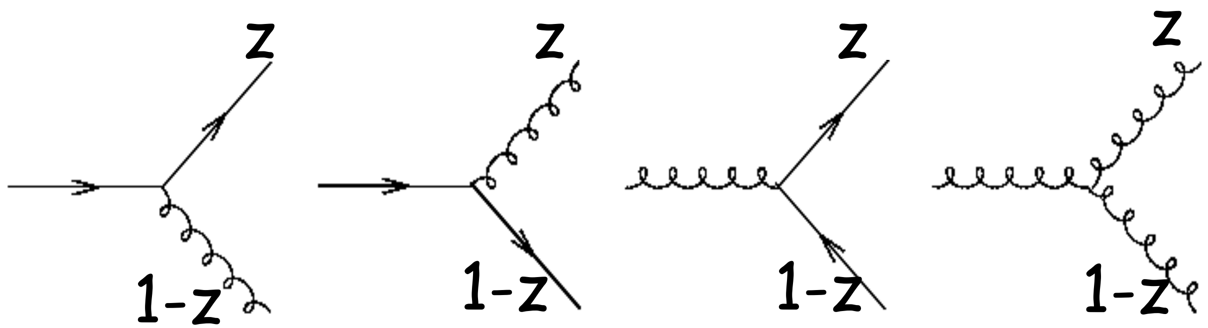
Typically accessible
By e-N collider experiments
CM ~ 300 GeV

$$Q^2 = S\ x\ y$$

Remember:
Meaning of x, Q^2, and y?

QCD Radiation

DGLAP equations are easy to “understand” intuitively, in terms of four “splitting functions”,



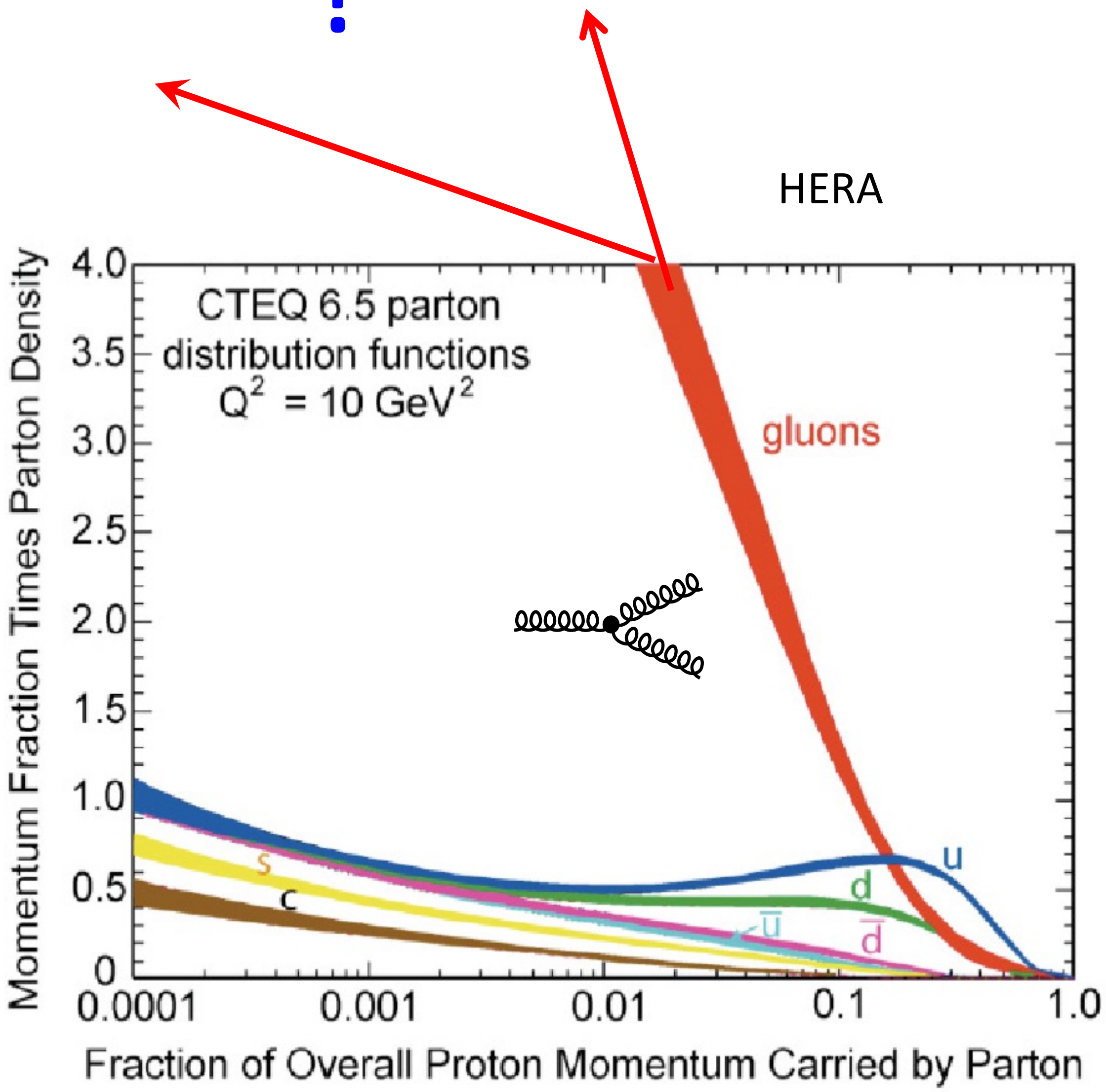
$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

Yu.L. Dokshitzer, Sov.Phys. JETP **46** (1977) 641,
V.N. Gribov and L.N.Lipatov, Sov. Journ. Nucl. Phys. **15** (1972) 438; ibid **15** (1972) 675
G.Altarelli and G.Parisi, Nucl.Phys. **B126** (1977) 298

Low x rise of the gluon distribution

?

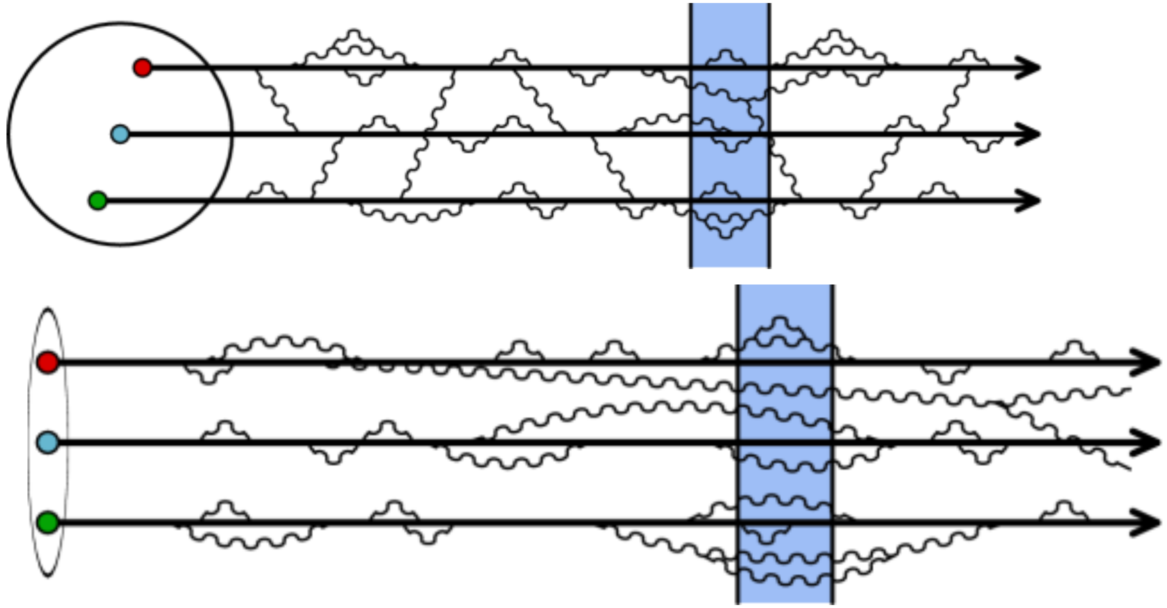
HERA



What could tame the low-x rise?

How does a Proton look at low and very high energy?

Time →



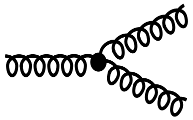
Cartoon of boosted proton

Low energy: High x
Regime of fixed target exp.

High energy: Low- x
Regime of a Collider

At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate smaller x gluons ➔ which in turn radiate more… a chain reaction leading to a **runaway growth?**



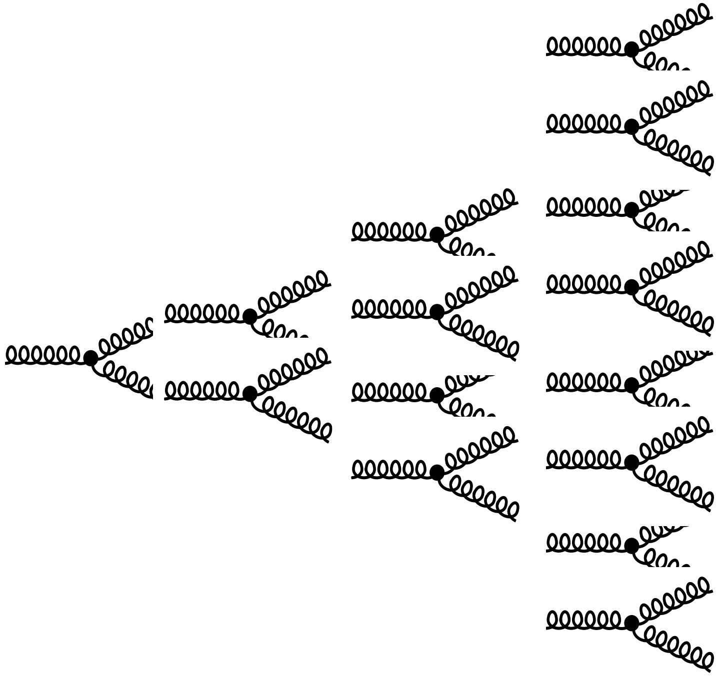
Gluon splitting

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004



? Infinity?

No!

“*spin* has killed more theories in physics than any other single observables”
-- Elliot Leader

“If theorists had their way, they would ban all experiments with Spin”
-- James D. Bjorken (jokingly)

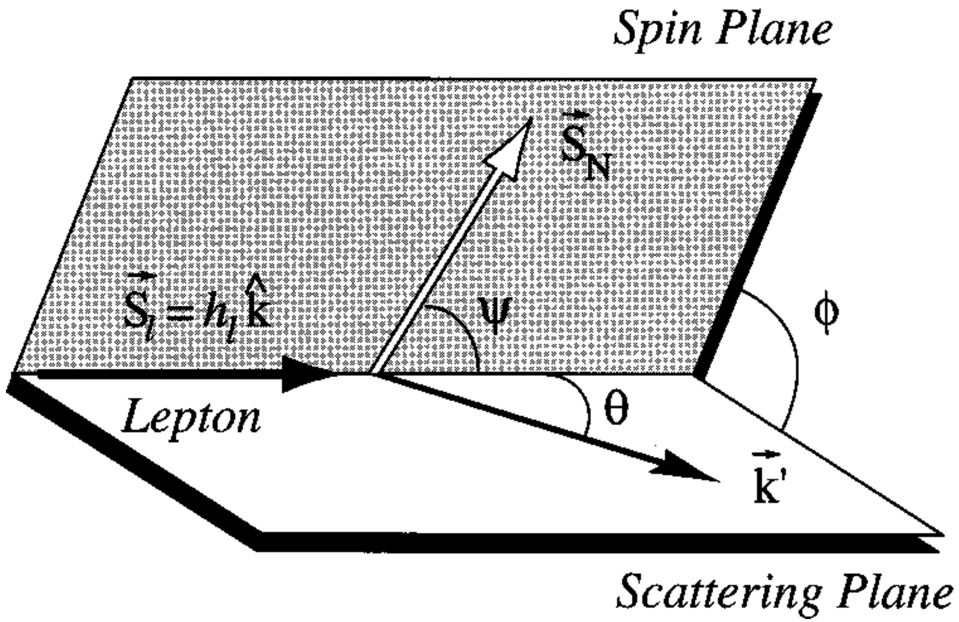
What happens when we add “spin” to the electron-Nucleon scattering?

Levitating top

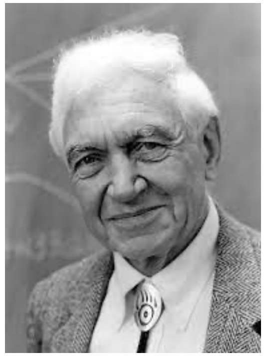
Despite understanding gravity, and rotational motion individually, when combined it produces unexpected, unusual and interesting results.

In nature, we observe such things and try to understand the physics behind it.

Lepton-nucleon cross section…*with spin*



$$\Delta\sigma = \cos\,\psi\Delta\sigma_{\parallel} + \sin\,\psi\,\cos\,\phi\Delta\sigma_{\perp}$$



V. W. Hughes
1922-2003

$$\gamma = \frac{2Mx}{\sqrt{Q^2}} = \frac{\sqrt{Q^2}}{\nu}.$$

For high energy scattering γ is small

$$\frac{d^2\Delta\sigma_{\parallel}}{dx\,dQ^2} = \frac{16\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{\gamma^2 y^2}{4}\right)g_1 - \frac{\gamma^2 y}{2}\,g_2\right]$$

$$\frac{d^3\Delta\sigma_T}{dx\,dQ^2\,d\phi} = -\cos\,\phi\,\frac{8\alpha^2 y}{Q^4}\,\gamma\sqrt{1-y-\frac{\gamma^2 y^2}{4}}\left(\frac{y}{2}\,g_1 + g_2\right)$$

Cross section asymmetries….

- $\Delta\sigma_{||} =$ anti-parallel – parallel spin cross sections
- $\Delta\sigma_{perp}$= lepton-nucleon spins orthogonal
- Instead of measuring cross sections, it is prudent to measure the differences: Asymmetries in which many measurement imperfections might cancel:

$$A_{||} = \frac{\Delta\sigma_{||}}{2\bar{\sigma}}, \quad A_{\perp} = \frac{\Delta\sigma_{\perp}}{2\bar{\sigma}},$$

which are related to virtual photon-proton asymmetries A_1,A_2:

$$A_{||} = D(A_1 + \eta A_2), \quad A_{\perp} = d(A_2 - \xi A_1)$$

$$\boxed{A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}}$$

$$A_2 = \frac{2\sigma^{TL}}{\sigma_{1/2} + \sigma_{3/2}} = \gamma\,\frac{g_1 + g_2}{F_1}$$

First Moments of SPIN SFs

$$\Delta q = \int_0^1 \Delta q(x)\,dx \qquad g_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right] = \frac{1}{12}(\underbrace{\Delta u - \Delta d}_{a_3 = g_a}) + \frac{1}{36}(\underbrace{\Delta u + \Delta d - 2\Delta s}_{a_8}) + \frac{1}{9}(\underbrace{\Delta u + \Delta d + \Delta s}_{a_0})$$

Neutron decay

(3F-D)/3
Hyperon Decay

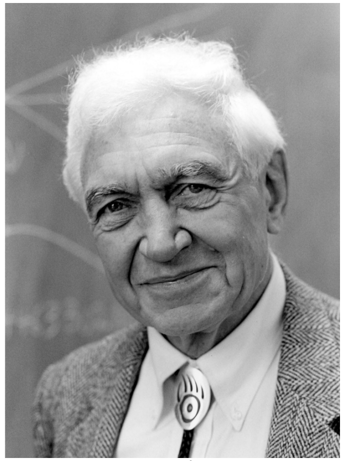
$\Delta\Sigma$

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

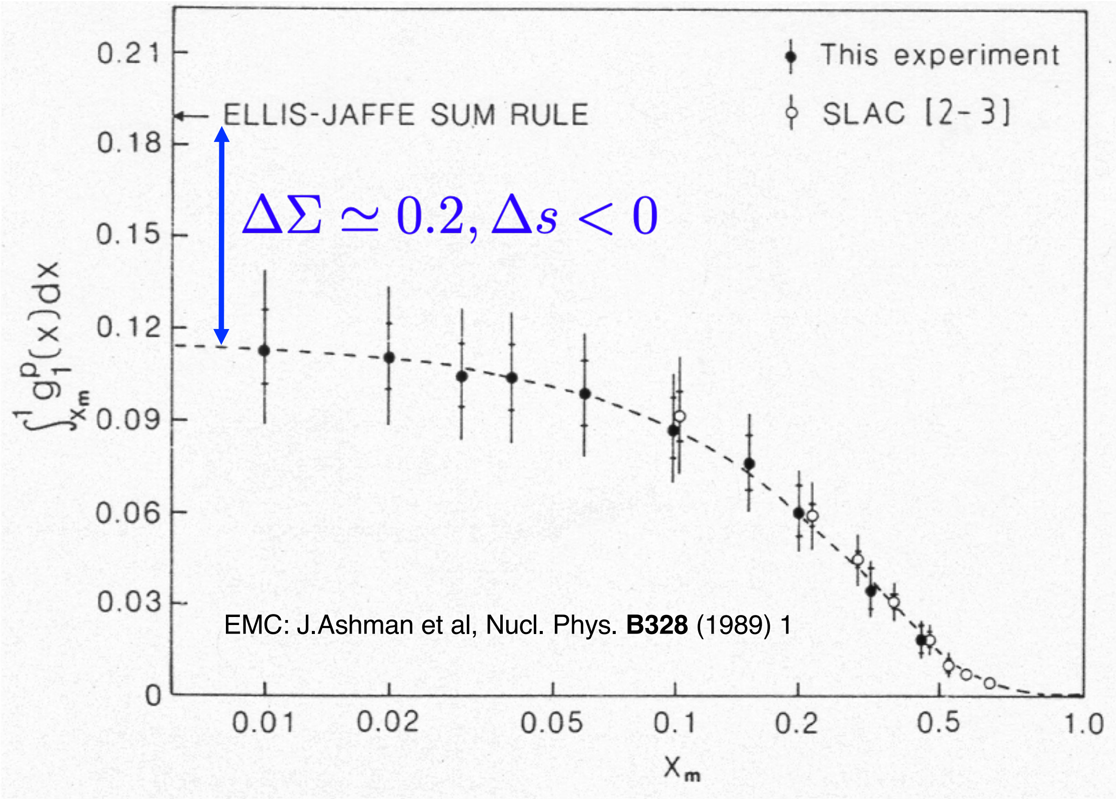
Spin Crisis

Life was easy in the Quark Parton Model until first spin experiments were done!

Polarized Deep-Inelastic Scattering



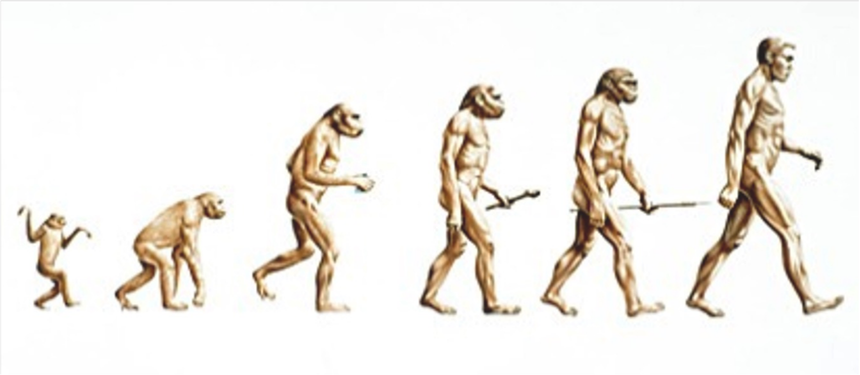
V.W. Hughes (1921-2003)

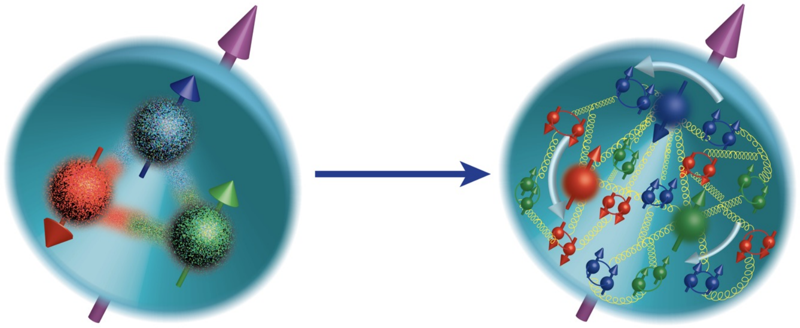


“ The sum of quark and anti-quark spins contribute little to the proton spin, and strange quarks are negatively polarized. ”

Spin "Crisis" → Spin Puzzle

Discovered by EMC experiment at CERN
Confirmed by SMC, SLAC, HERMES
Gluon's contribution measured by RHIC





$$\frac{1}{2} = [\underbrace{\mathrm{Q_{spin}}}^{\sim 25\%}_{} + \overbrace{\mathrm{Q_{ang.mom.}}}^{\text{Lecture 3}}_{?}] + [\overbrace{\mathrm{G_{spin}}}^{\text{Lecture 2} \atop \sim 25\%} + \overbrace{\mathrm{G_{ang.mom.}}}^{\text{Lecture 3}}_{?}]$$

Transverse motion and finite size of the proton must create the orbital motion.

Connected to the mass?

Homework

-- How do we know quarks have fractional charges? – neutrino scattering

-- Calculate the Center of Mass energy

1. What is it for a Collider with 10 GeV e beam colliding on 250 GeV proton
2. What energy of the electron would be needed to achieve the same CME in a fixed target experiment? (make simple reasonable assumptions where needed)

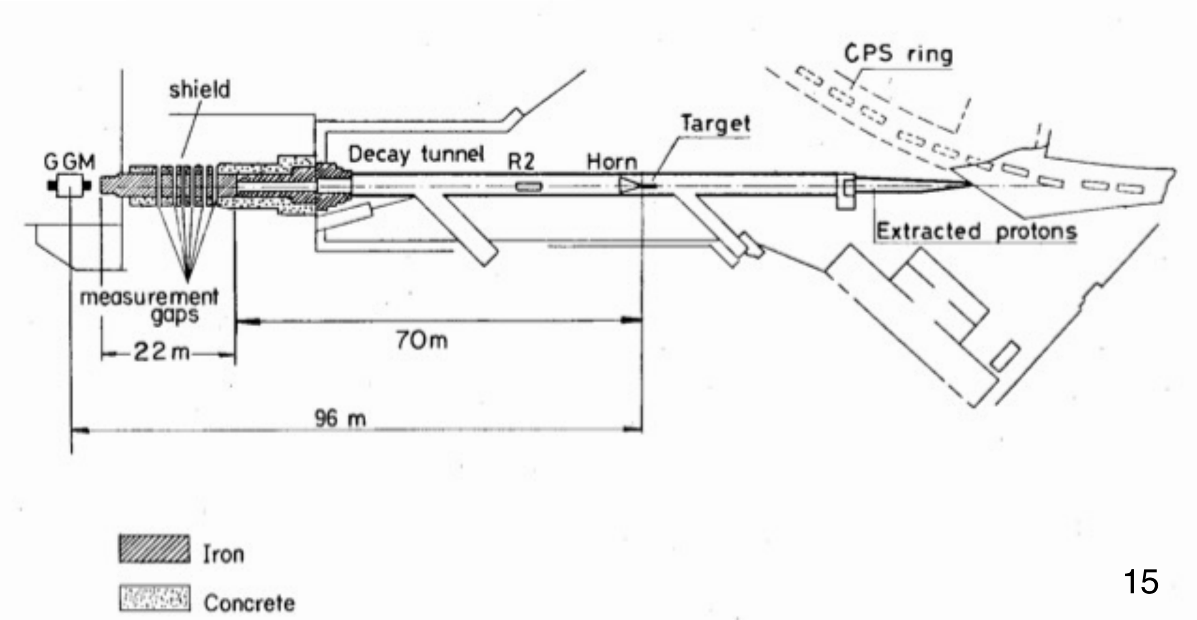
Deep-Inelastic *Neutrino* Scattering

Recognize this from CERN?

Gargamelle bubble chamber, observation of weak neutral current (1973).

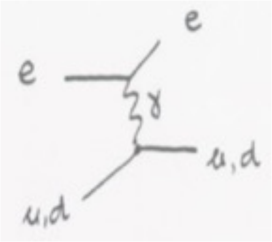
Charged-current DIS!

Nucl.Phys. **B73** (1974) 1
Nucl.Phys. **B85** (1975) 269
Nucl.Phys. **B118** (1977) 218
Phys.Lett. **B74** (1978) 134



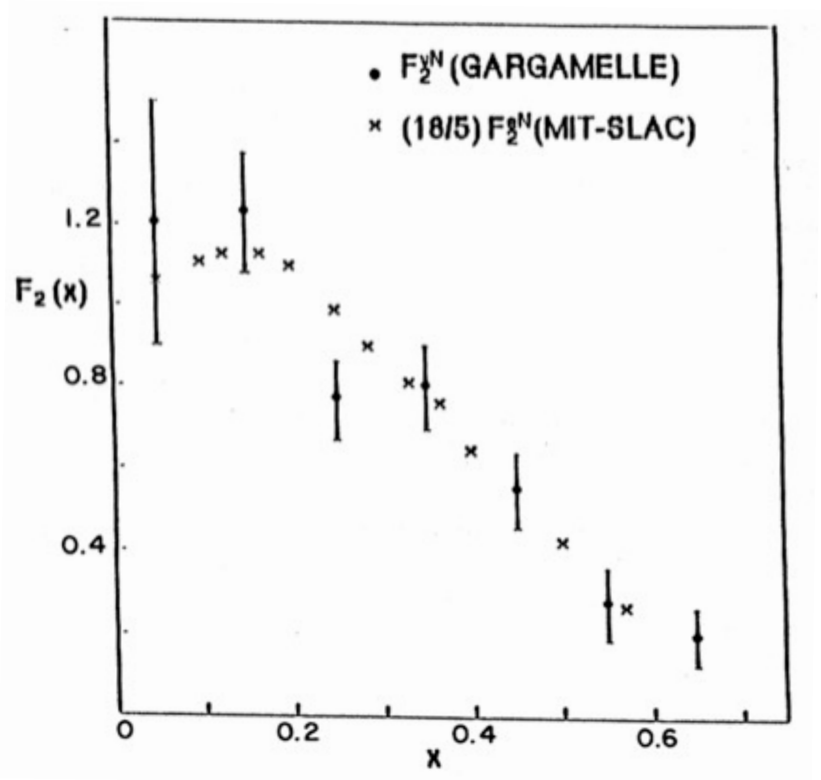
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:

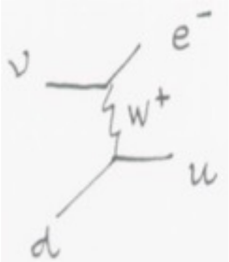


$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p : uud, \quad n : ddu$$

$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$



Charged-current DIS:

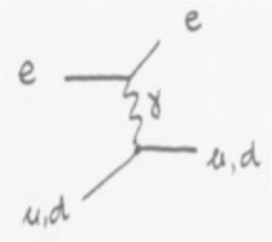


$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:



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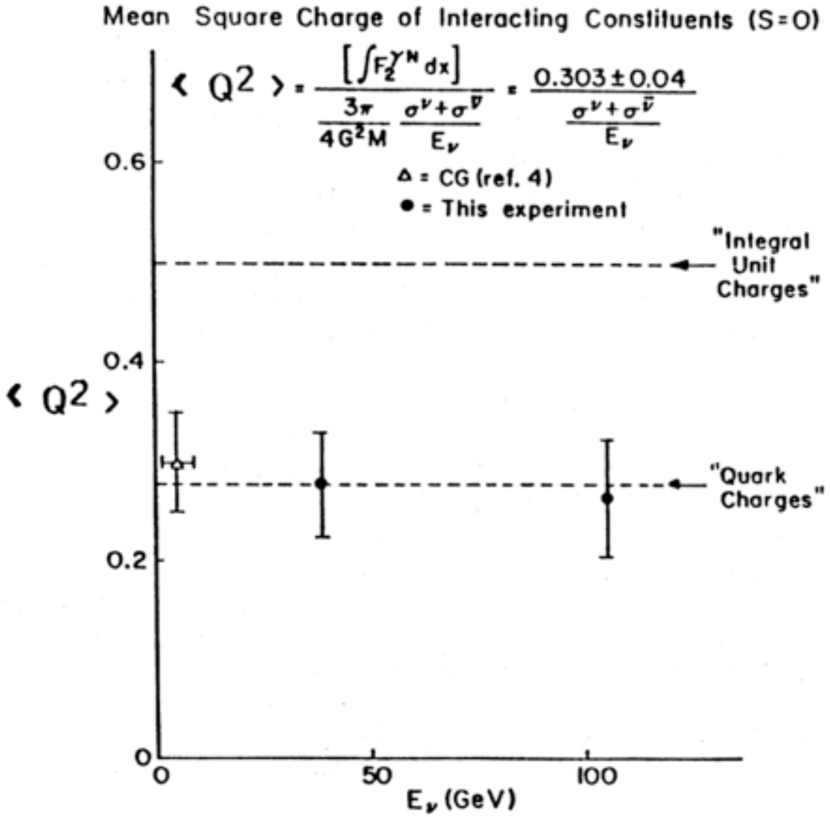
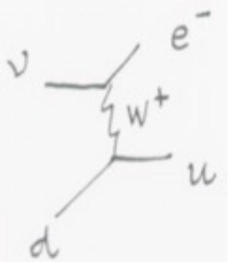


Charged-current DIS:



$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

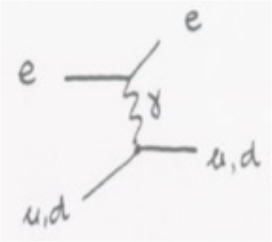
$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Ratio:

$$\frac{F_2^N}{F_2^{\nu N}} = \frac{1}{2}(e_u^2 + e_d^2) = \frac{5}{18} \simeq 0.28$$

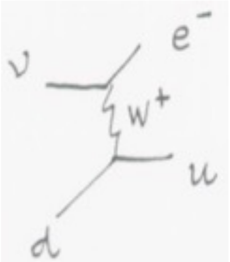
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:



$$F_2^N = x\,\frac{e_u^2 + e_d^2}{2}\,(u + \bar{u} + d + \bar{d})$$

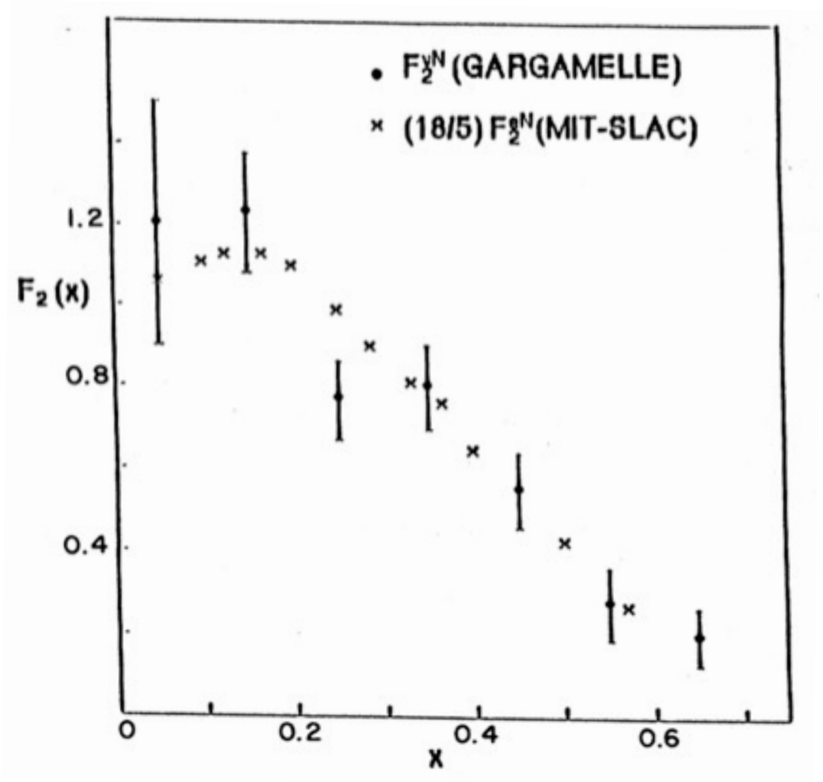
Charged-current DIS:



$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Momentum fraction:

$$\int_0^1 F_2^N\,dx = \frac{e_u^2 + e_d^2}{2}\int_0^1 x(u + \bar{u} + d + \bar{d})$$

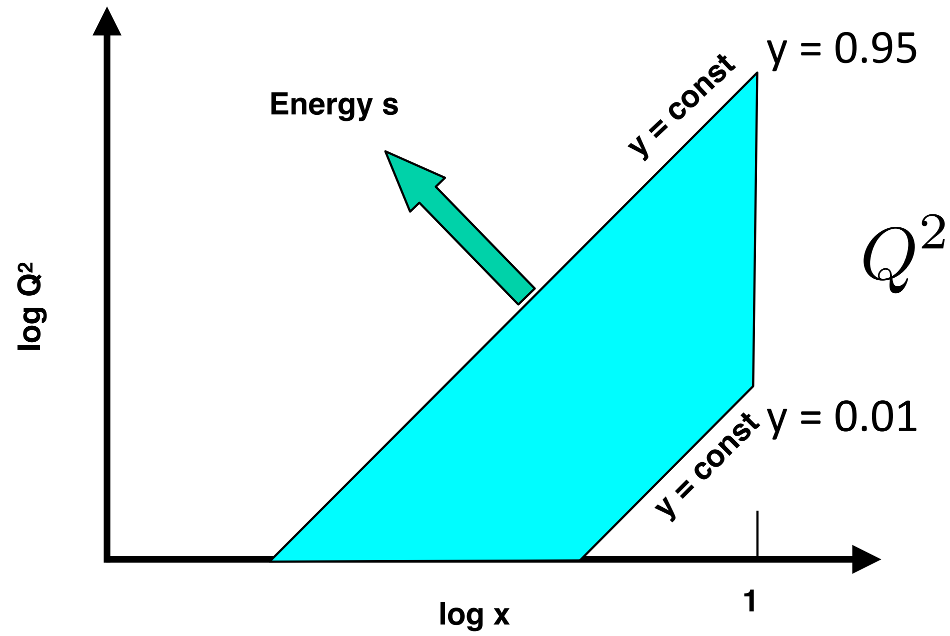


Gargamelle: 0.49 +/- 0.07

SLAC: 0.14 +/- 0.05

Quarks carry half of the nucleon momentum!

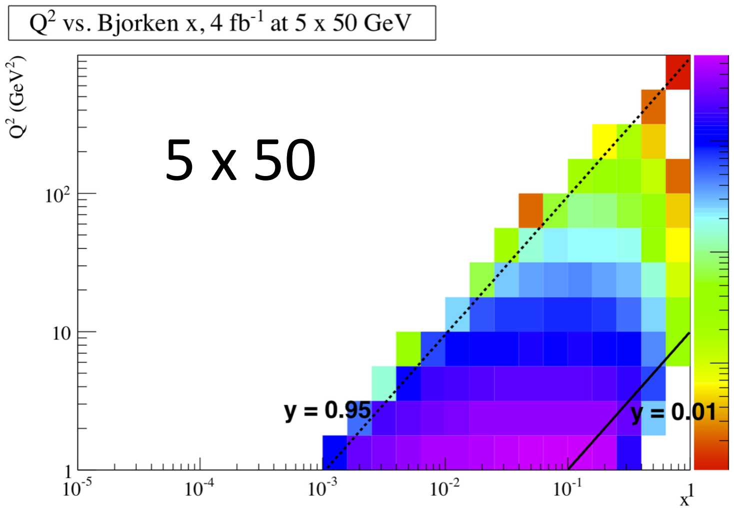
The x-Q² plane…

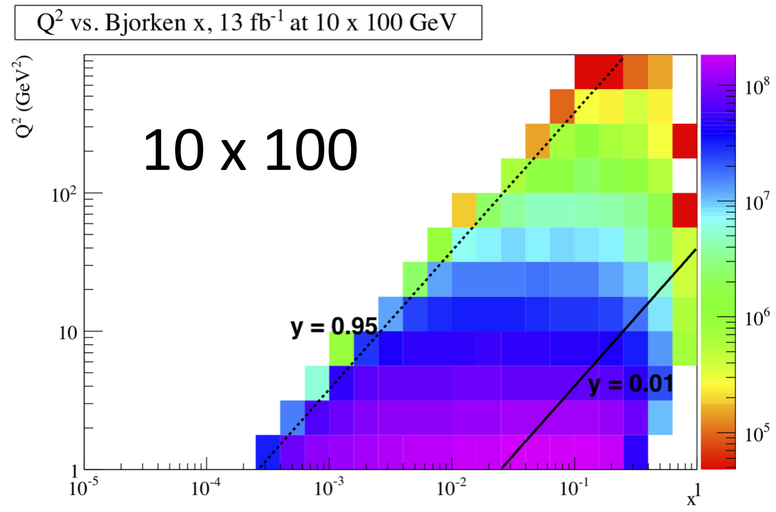


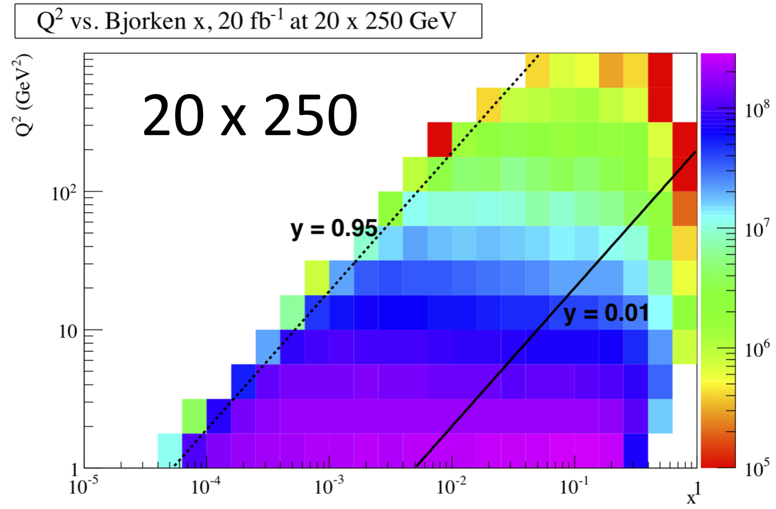
$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to 0.95 < y < 0.01

Kinematic coverage as a function of energy of collisions



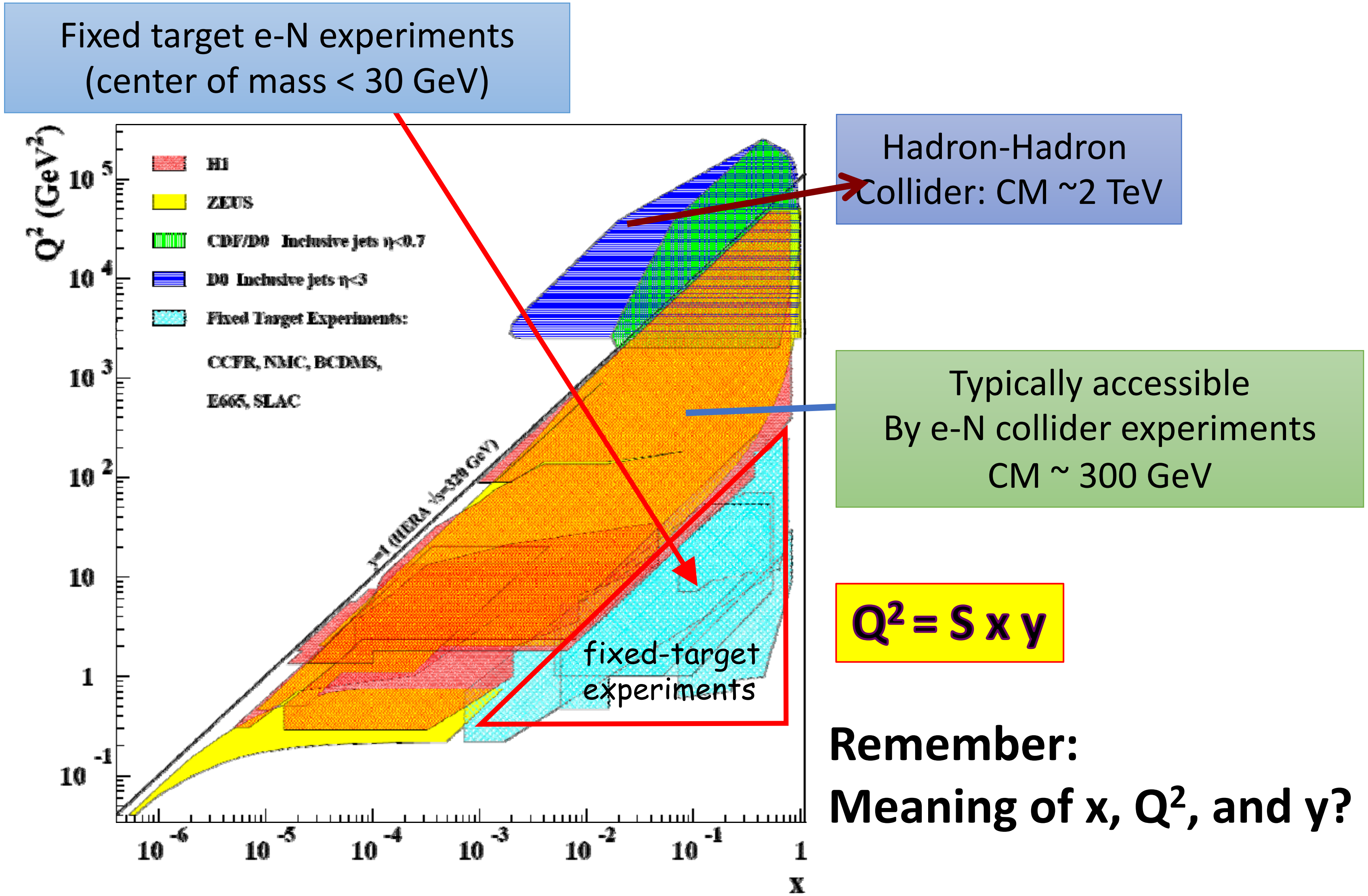




As beam energies increase, so does the x, Q^2 coverage of the collider: 5, 10 and 20 GeV electrons colliding with 50, 100 and 250 GeV protons

y = 0.95 and 0.01 are shown on all plots (they too shift as function of energy of collisions)

Perspective on x,Q^2, Center of Mass



$Q^2 = S\ x\ y$

Remember:
Meaning of x, Q^2, and y?