Center for Frontiers in Nuclear Science

The Electron Ion Collider

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Lecture 1 of 3

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Overview of these lectures: Understanding the structure of matter

- **Lecture 1:** Past studies in hadron structure… Quantum Chromodynamics (~1970-2000)
- **Lecture 2:** Introduction to a Collider (~2000-2025) as an example I will consider the polarized Relativistic Heavy Ion Collider (RHIC). (*Heavy ion physics in another lecture set*)
- **Lecture 3:** The US Electron Ion Collider: Frontiers QCD (~2030+)

Overview of these lectures:
Understanding the structure of matter

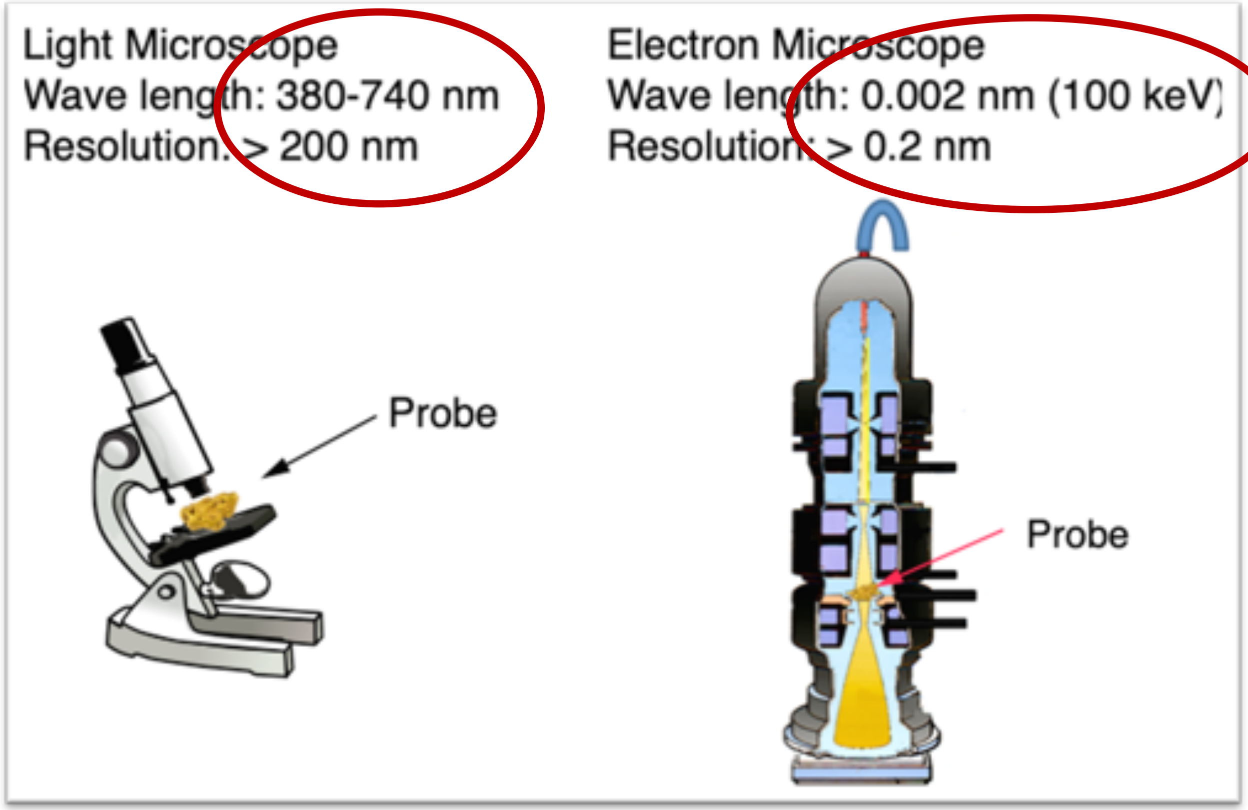
Lecture 1: Past studies of hadron structure (Quantum Chromodynamics)

- Brief History
- The Standard Model (SM) & experimental method, kinematics etc.

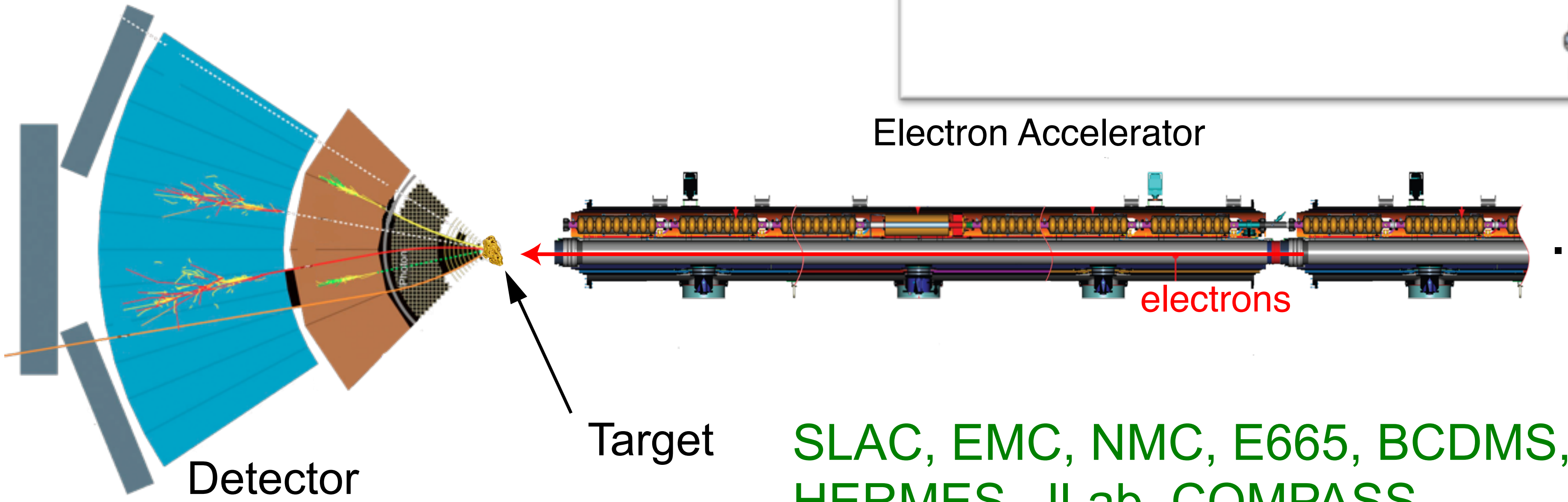
- QCD: Some early surprises
  - Spin: **EMC spin crisis**: inclusive and semi-inclusive DIS and current status
  - Nuclei: EMC effect in nuclei: what we know, what we don't know…

- Need for a **collider**

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, …

$$\lambda = \frac{h}{2\pi} \cdot \frac{1}{p} \longrightarrow resolution = \frac{h}{2\pi} \frac{1}{momentum}$$

Resolution and momentum….

Probing matter with electrons…

- In the 1960s Experiments at Stanford Linear Accelerator Center (SLAC) established the quark model and our modern view of particle physics "the Standard Model"

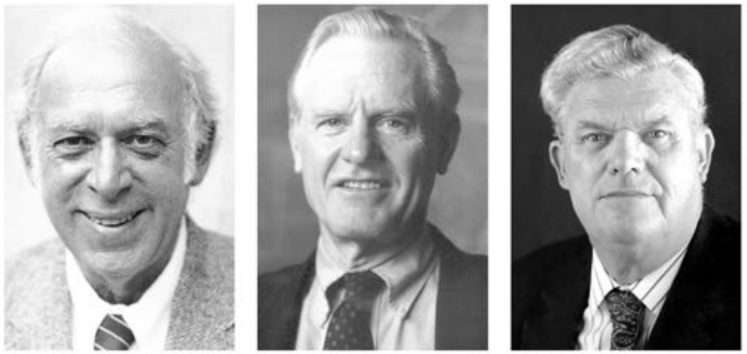


Photo from the Nobel Foundation archive.
Jerome I. Friedman
Prize share: 1/3

Photo from the Nobel Foundation archive.
Henry W. Kendall
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Richard E. Taylor
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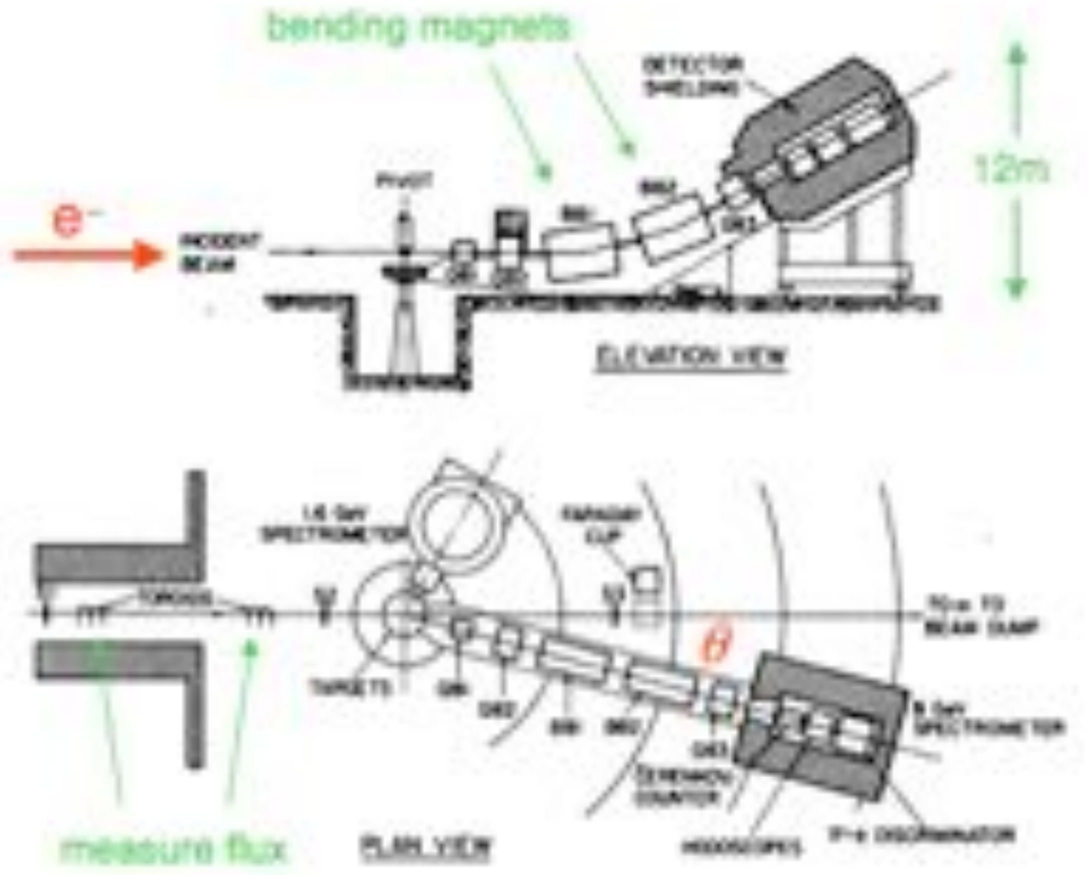
Nobel Prize in Physics 1990



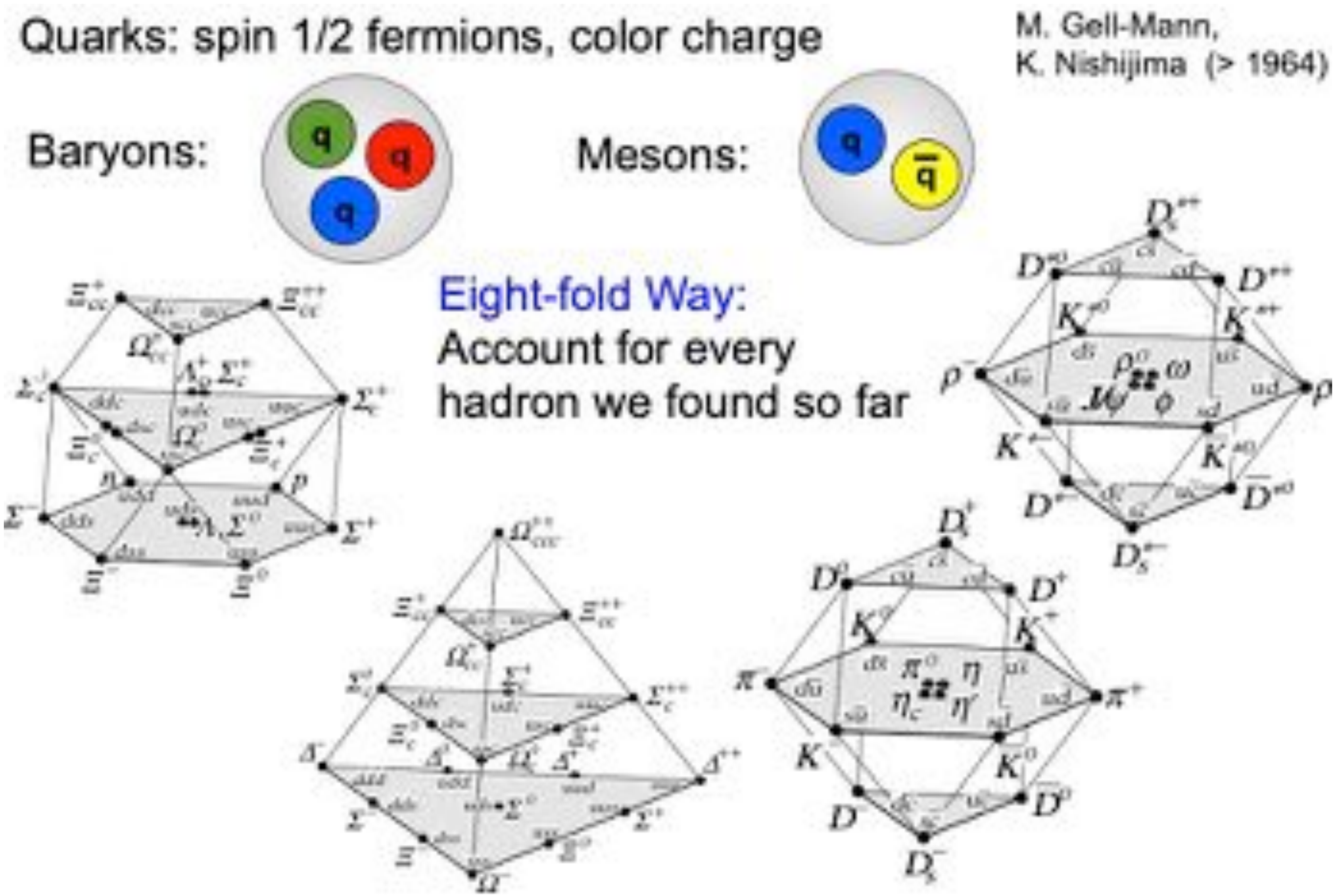
Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

determine *E'*

Spectrometer can rotate in the horizontal plane,

vary θ

The Static (Constituent) Quark Model



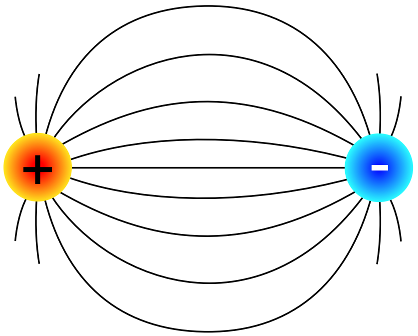
For detailed properties of the multiquark systems the model failed

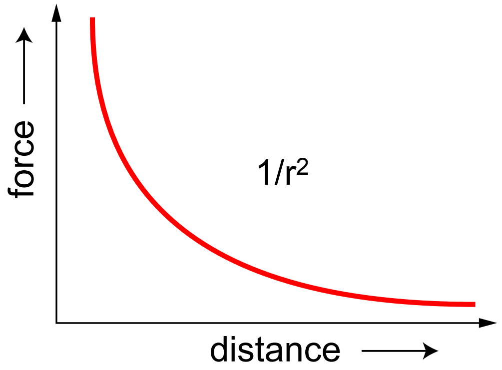
How come? What was missing?

Quantum Electrodynamics (QED)

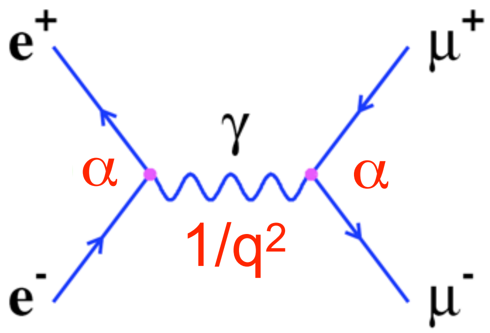
Theory of electromagnetic interactions

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





Example Feynman Diagram:
e^+e^- annihilation



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

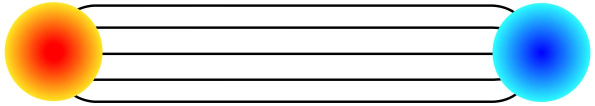
Coupling constant (α): Interaction Strength
In QED: $\alpha_{em} = 1/137$

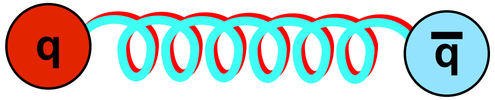
Quantum Chromodynamics (QCD)

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

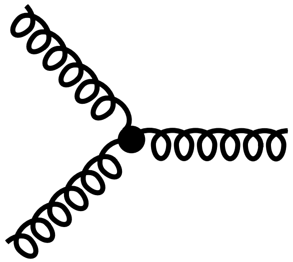
F. Wilczek, hep-ph/9907340

- 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

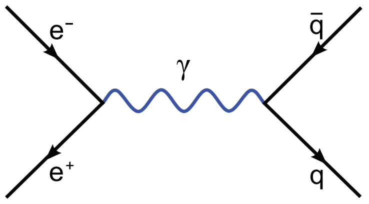
long range ~ r

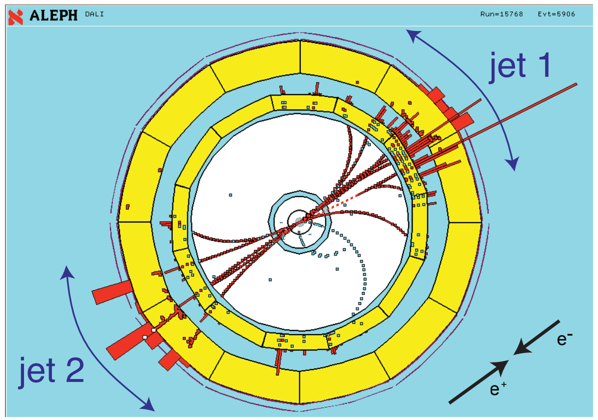
Long range aspect ⇒ quark confinement and existence of nucleons

Gluons!

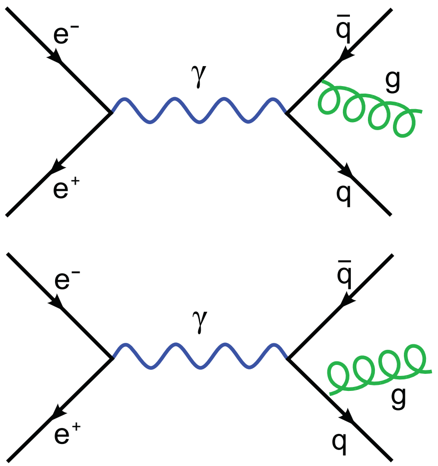
Discovery of gluons: Mark-J, Tasso, Pluto, Jade experiments at PETRA (e+e- collider) at DESY (CM energy 13-32 GeV)

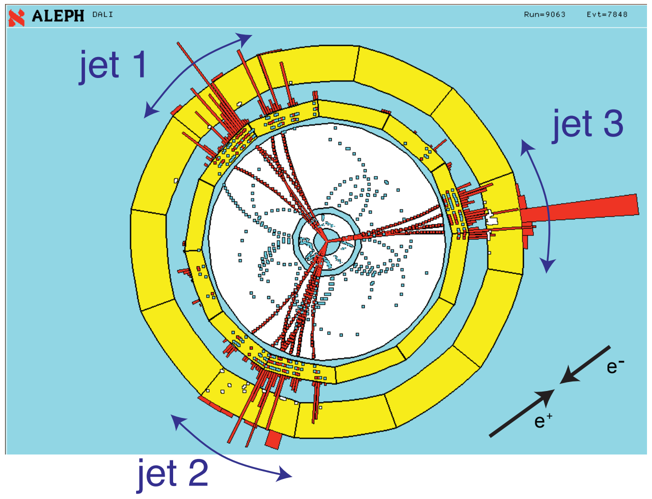
- $e^+ e^- \rightarrow q\ \bar{q} \rightarrow$ 2-jets





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





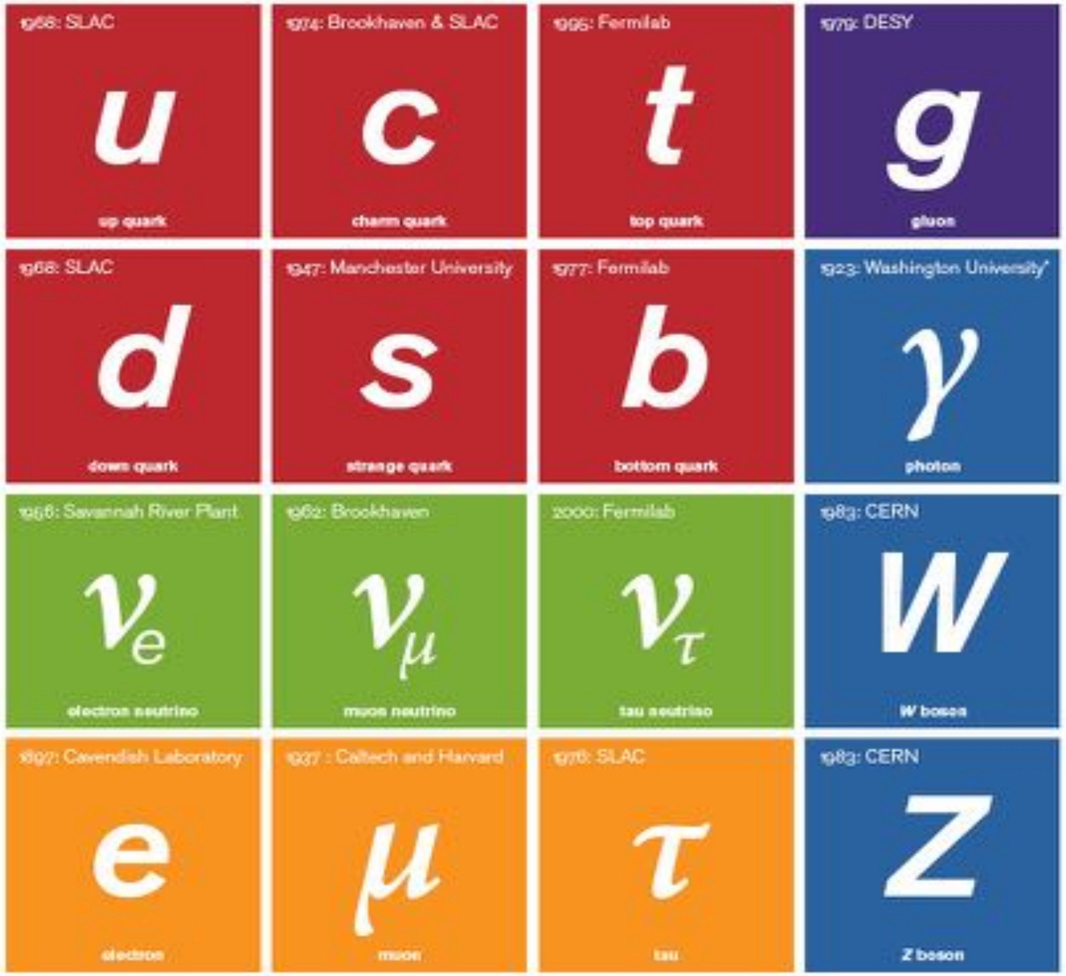
Standard Model (SM) of physics: Fundamental building blocks

+2/3

-1/3

0

-1



18 Nobel Prizes since 1950

2012: CERN

H

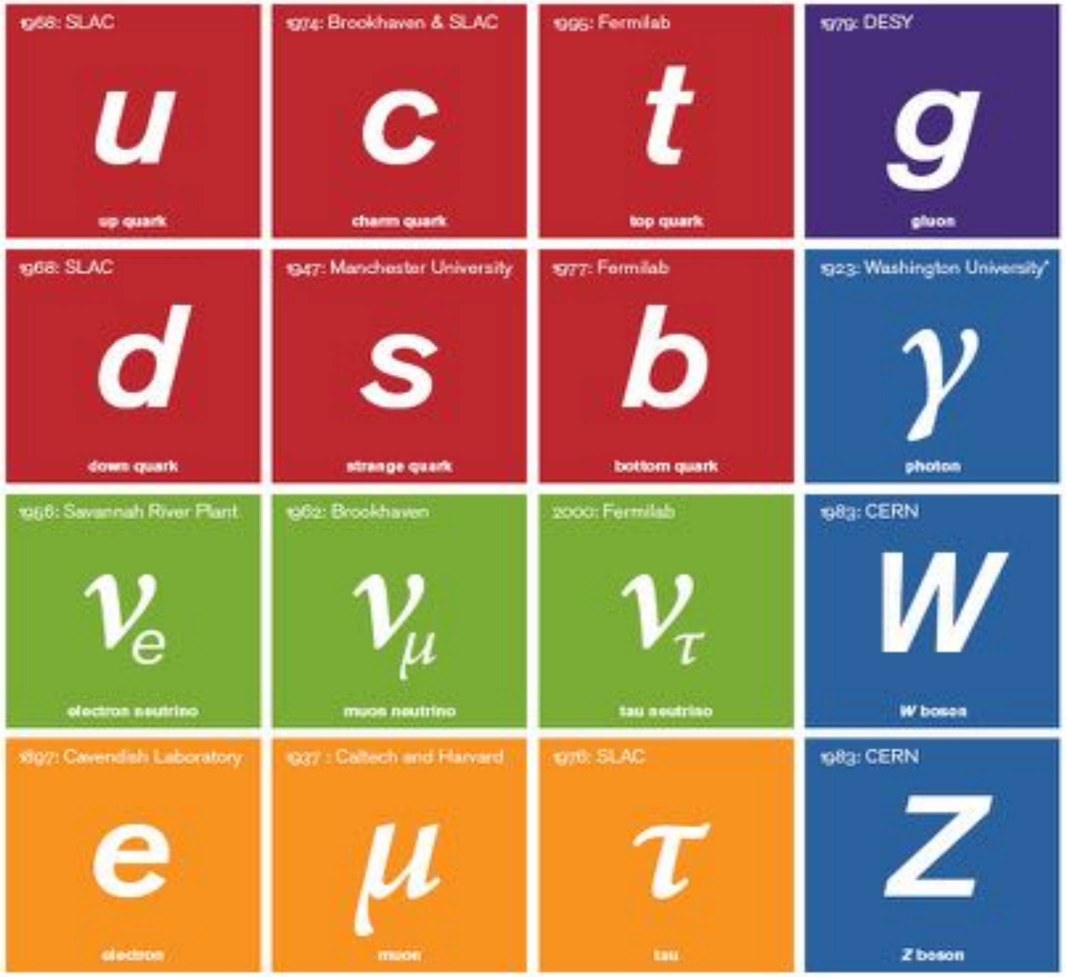
- H BOSON

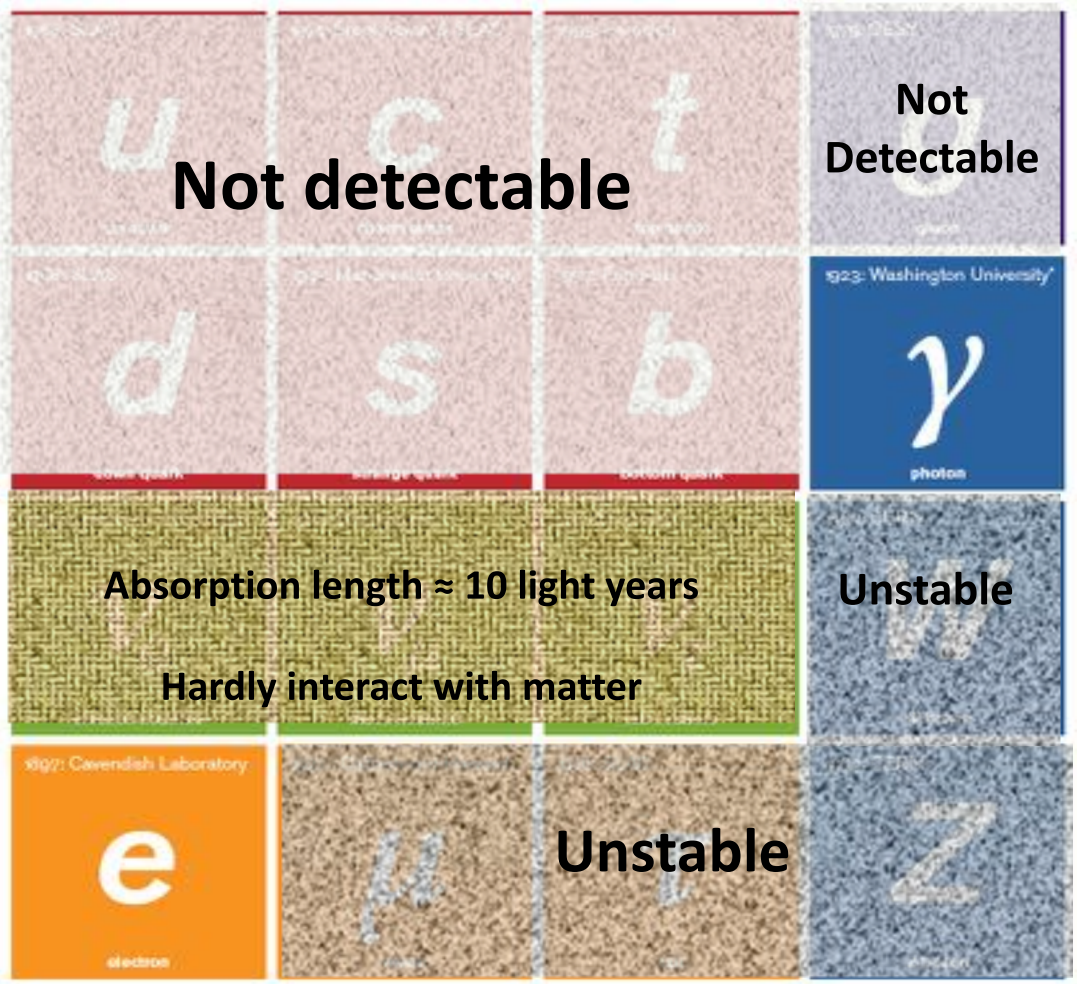
+

2015 Gravitational waves

Einstein gravity

Difficulties in understanding our universe





Deep Inelastic Scattering (DIS)

Scattering of protons on protons is like colliding Swiss watches to find out how they are build.

R. Feynman

We can ask : What is in there, but not how they are built or how they work!

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

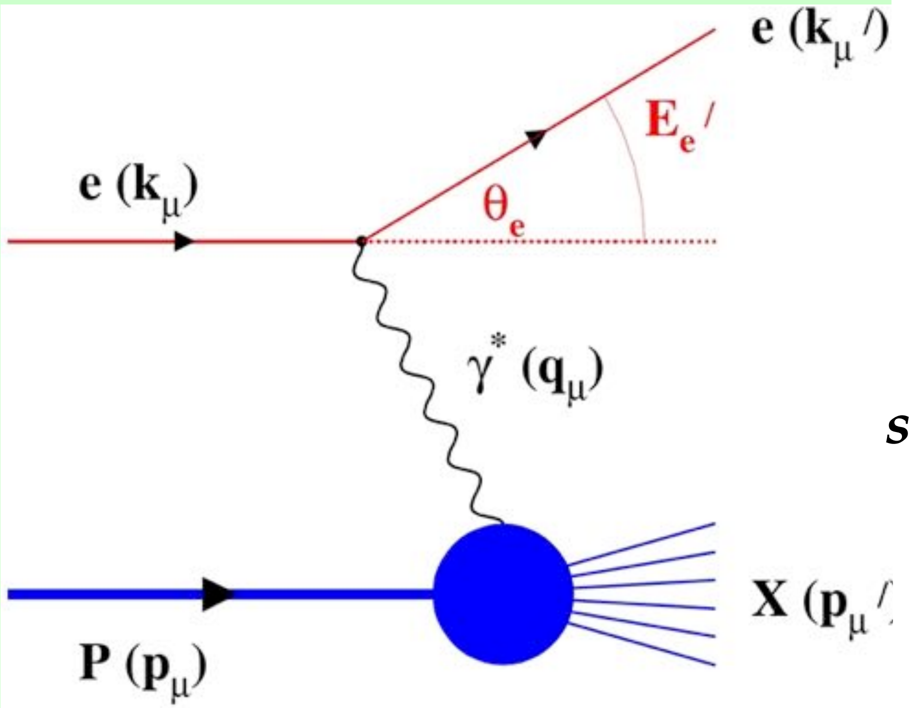
1) Violent collision of melons

2) Cutting the watermelon with a knife

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

Deep Inelastic Scattering: 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)

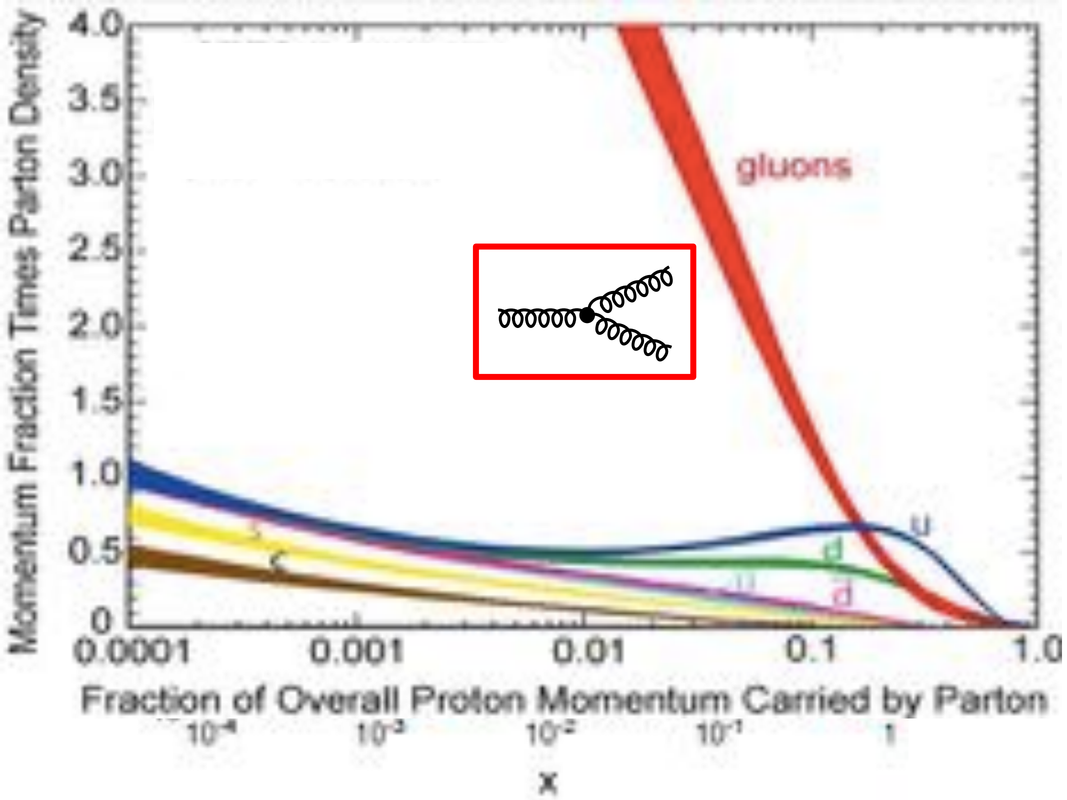
The only dimension considered comes in through "x".

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….

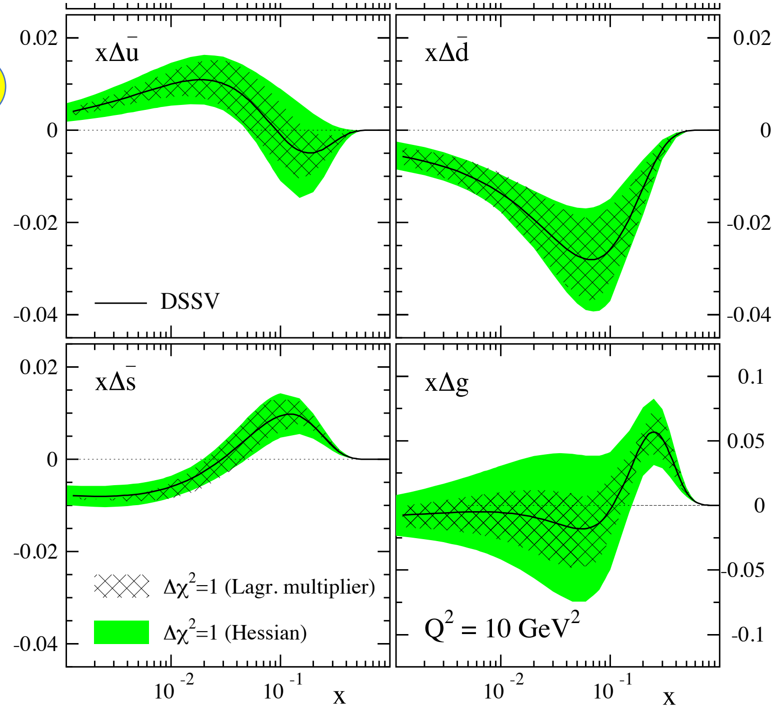
All transverse motion was ignored. However, now we have more precision…

What do ***gluons*** in protons look like?
Unpolarized & polarized parton distribution functions



QCD
Terra-incognita!

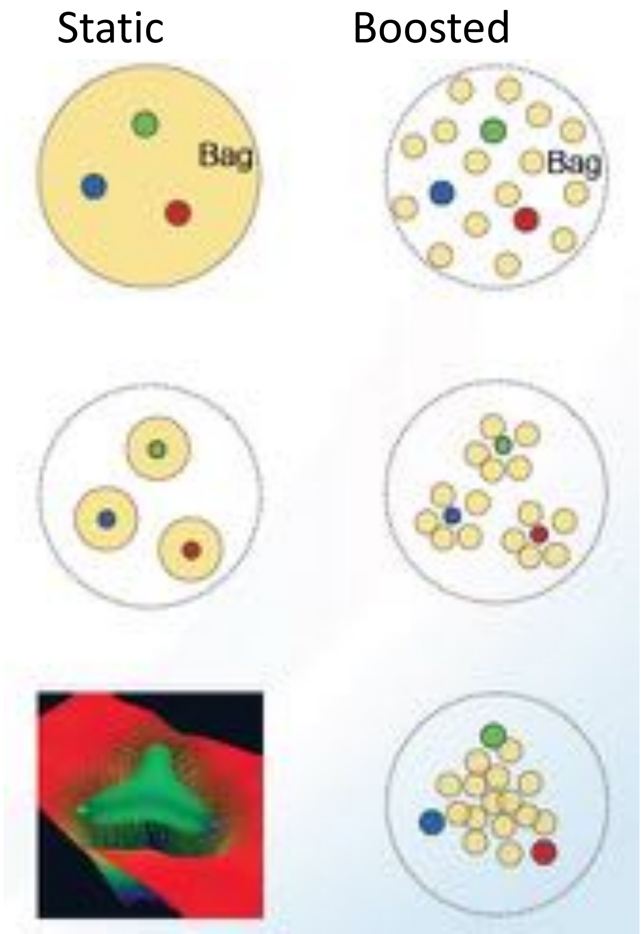
High Potential
for Discovery



Need to go beyond 1-dimension!

Need (2+1)D image of gluons in a nucleon in position & momentum space

What does a proton look like in transverse dimension?



Bag Model: Gluon field distribution is wider than the fast moving quarks. Color (Gluon) radius > Charge (quark) Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks. Color (Gluon) radius ~ Charge (quark) Radius

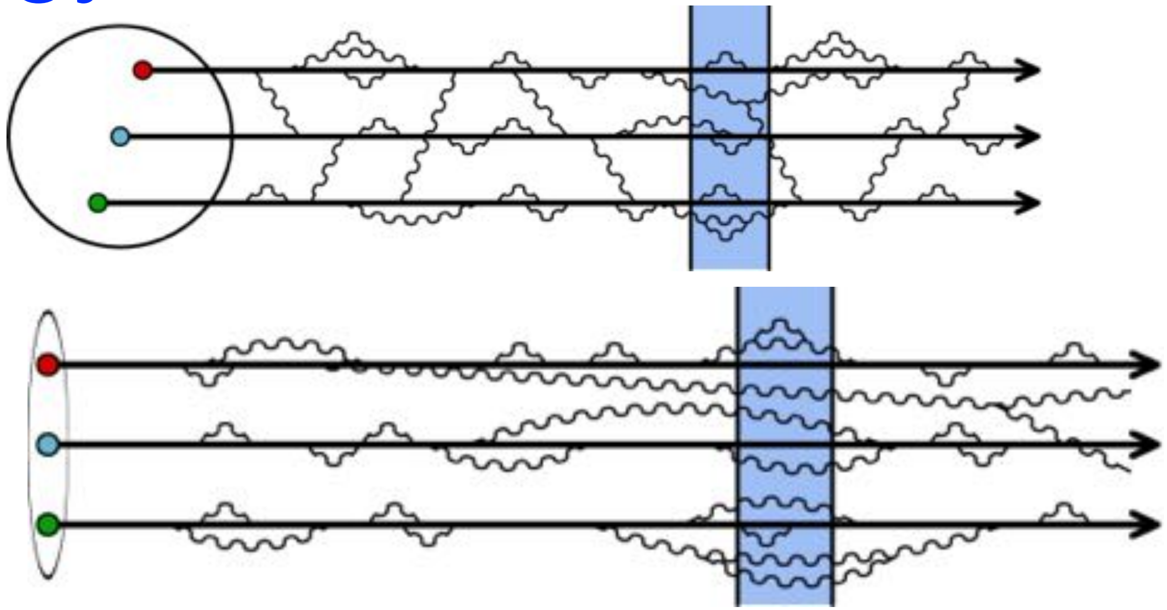
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks: Color (Gluon) radius < Charge (quark) Radius

Need *transverse* images of the quarks *and gluons* in protons

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

Low energy: High x
Regime of fixed target exp.

High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

Gluon and the consequences of its interesting properties:

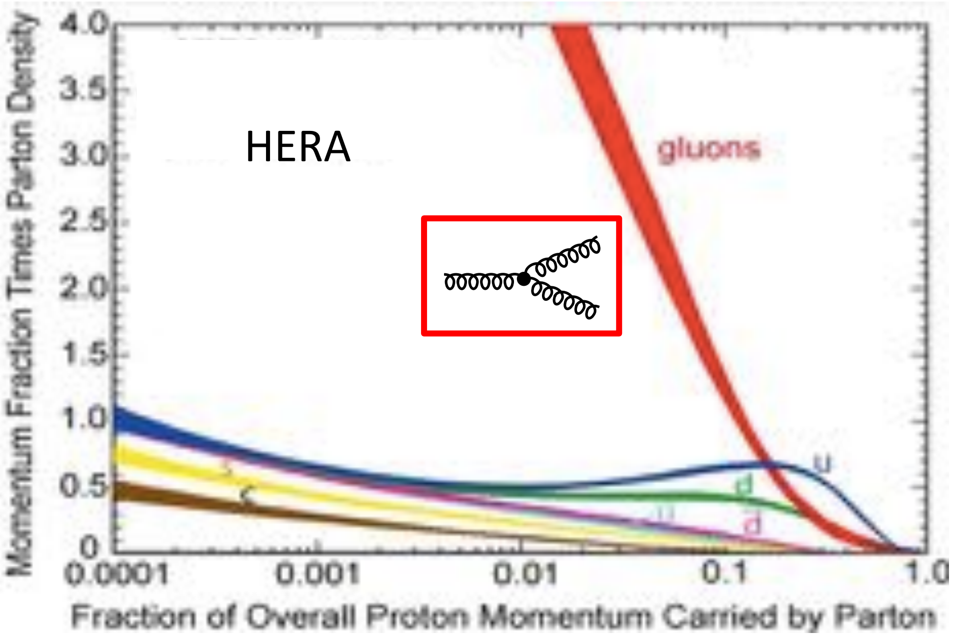
Gluons carry color charge ➔ Can interact with other gluons!

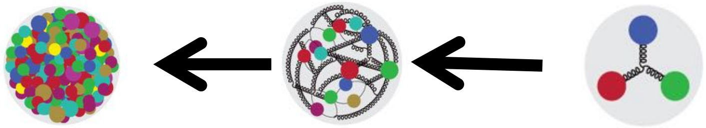
"…The result is a self catalyzing enhancement that leads to a runaway growth.
A small color charge in isolation builds up a big color thundercloud…."

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

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

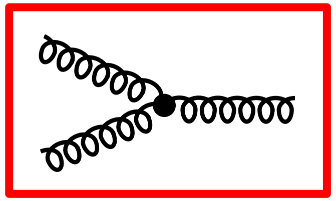




Apparent "indefinite rise" in gluon distribution in proton!

What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination

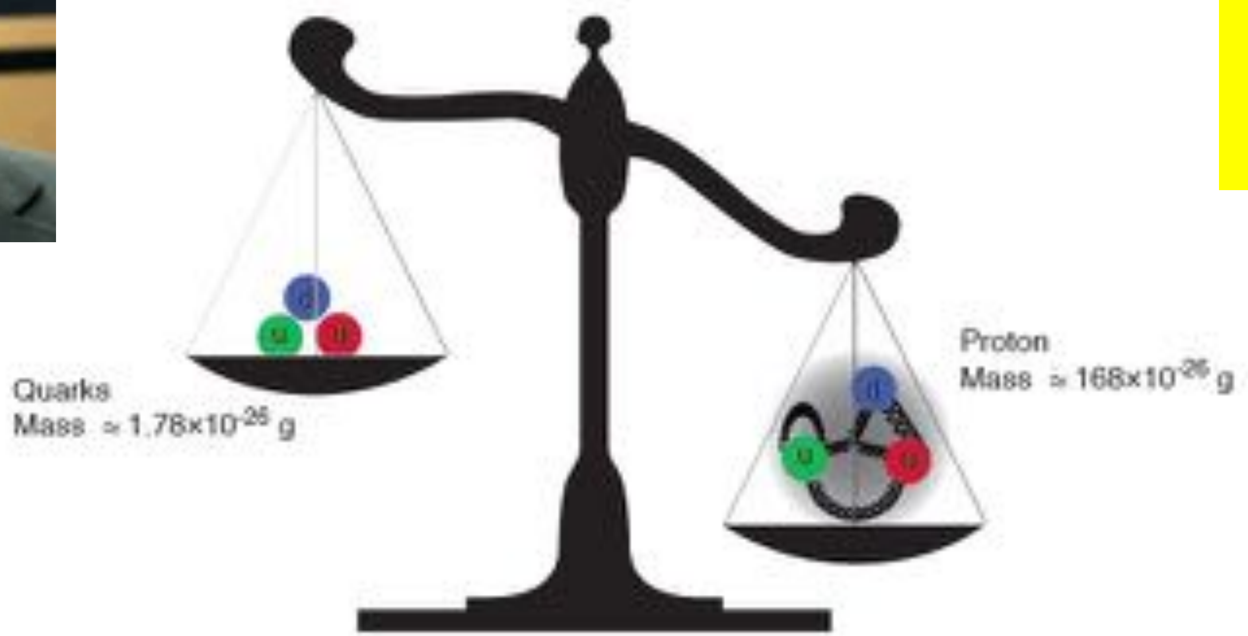


Where? No one has unambiguously seen this before!

If true, effective theory of this →"Color Glass Condensate"

Proton mass puzzle

Peter Higgs



It is like saying:

1 + 1 + 1 = 300

Add the masses of the quarks together 1.78 x 10^{-26} grams ← This mass comes from HIGGS mechanism

But the proton's mass (which is made of 3 dominant quarks and massless gluons) is 168 x 10^{-26} grams

→ only 1% of the mass of the protons (neutrons) and hence the visible universe comes from Higgs

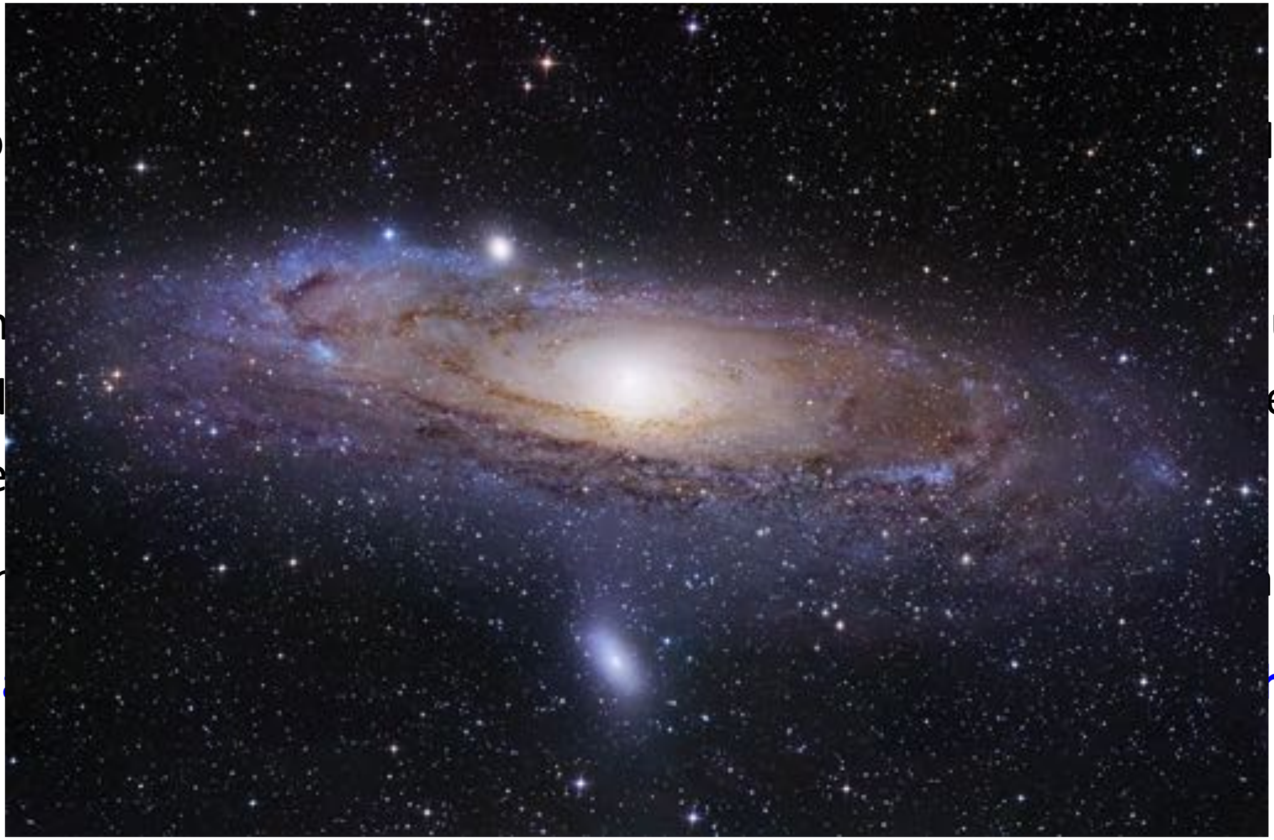
→ Where does the rest of the mass come from?

Emergent Dynamics in QCD

Without gluons,* there would be no nucleons, no atomic nuclei… *no visible world!

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% o … **leon's spin**, and are essential for the dyn…
- Properties of hadron … uation of motion but are also inextricably tied … esides confinement are spontaneous symme…
- The nucleon-nucleon … ppens remains a mystery

Experimental insight … hadrons & nuclei emerge



Spin an important tool to understand nature….

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.

Let's get back to e-p DIS with & without "spin" as an example:

What did we learn?

Unpolarized e-p/A DIS

DIS without Spin:

Inclusive Cross-Section:

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

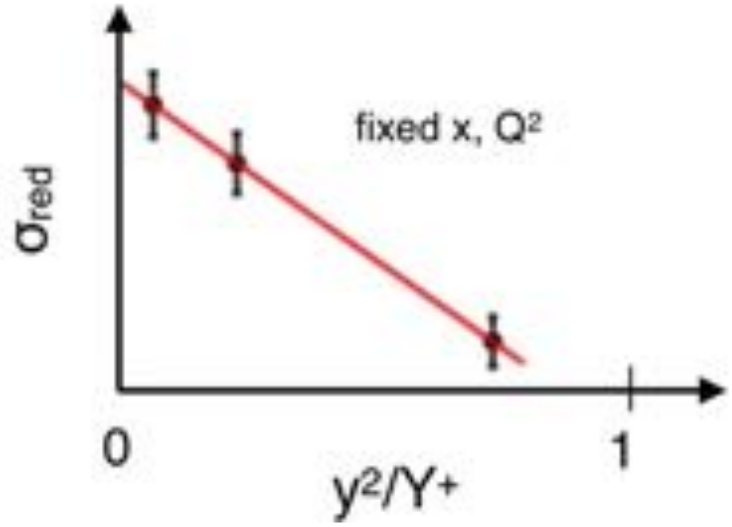
Reduced Cross-Section:

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

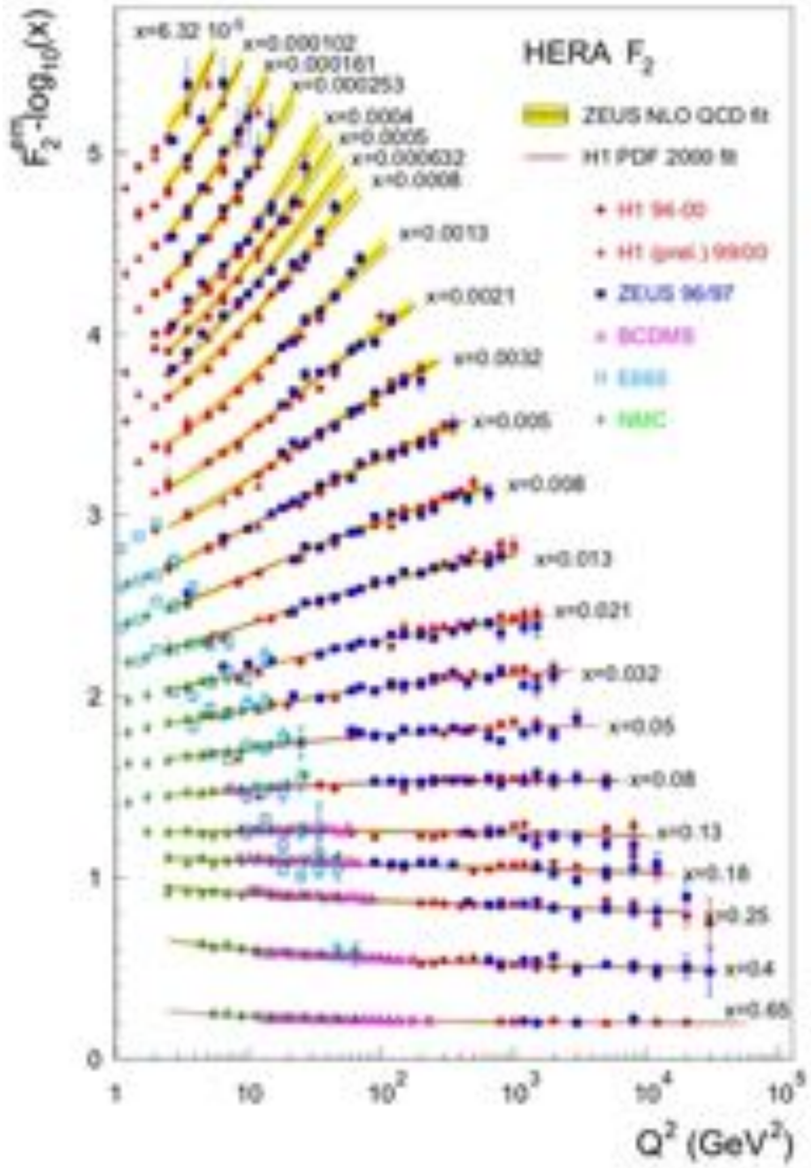
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

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 $y2/Y^+$



- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
- Gluons: $g(x,Q^2)$ through scaling violation: $dF^2/d\ln Q^2$



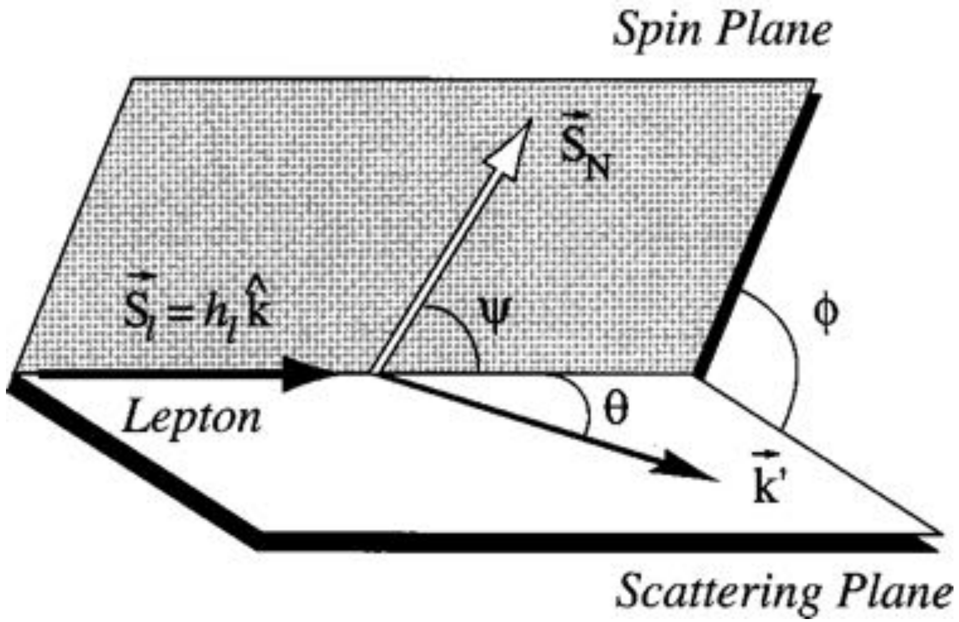
F_2 structure function of the proton measured at DESY (Germany) using the unpolarized HERA (e-p) collider

$\Rightarrow$
- F_2
- $dF_2/d\ln Q^2$

+ pQCD+ DGLAP Evolution

$$f(x, Q_1^2) \rightarrow f(x, Q_2^2)$$

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:

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

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

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

First Moments of SPIN SFs

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

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

$a_3 = g_a$: Neutron decay

a_8: (3F-D)/3 Hyperon Decay

a_0: $\Delta\Sigma$

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

Spin Crisis

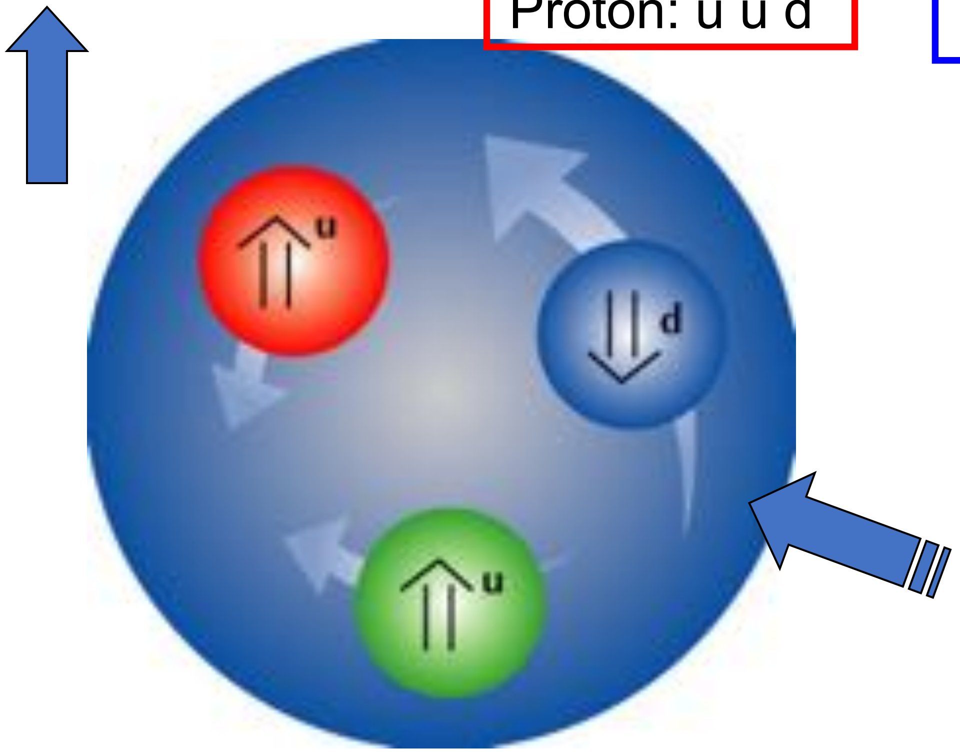
Life was easy in the Quark Parton Model until first spin experiments were done!

Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects… now, illustration only, but historically taken seriously)

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
- And there are three of them in the

Proton: u u d

Neutron: u d d



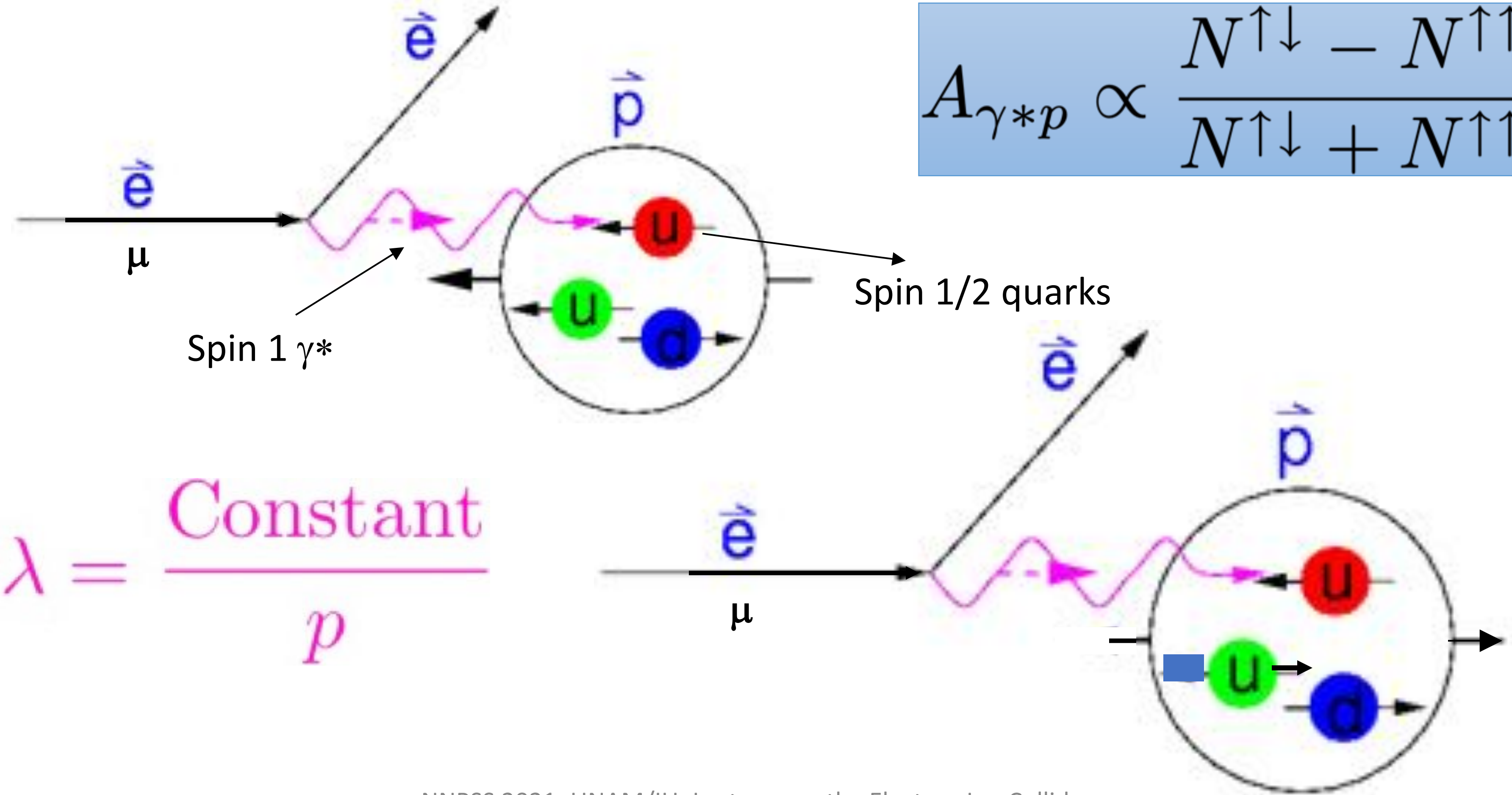
S_{proton} = Sum of all quark spins!

$$1/2 \overset{?}{=} 1/2 + 1/2 + 1/2$$

$$1/2 = 1/2 - 1/2 + 1/2$$

How was the Quark Spin measured?

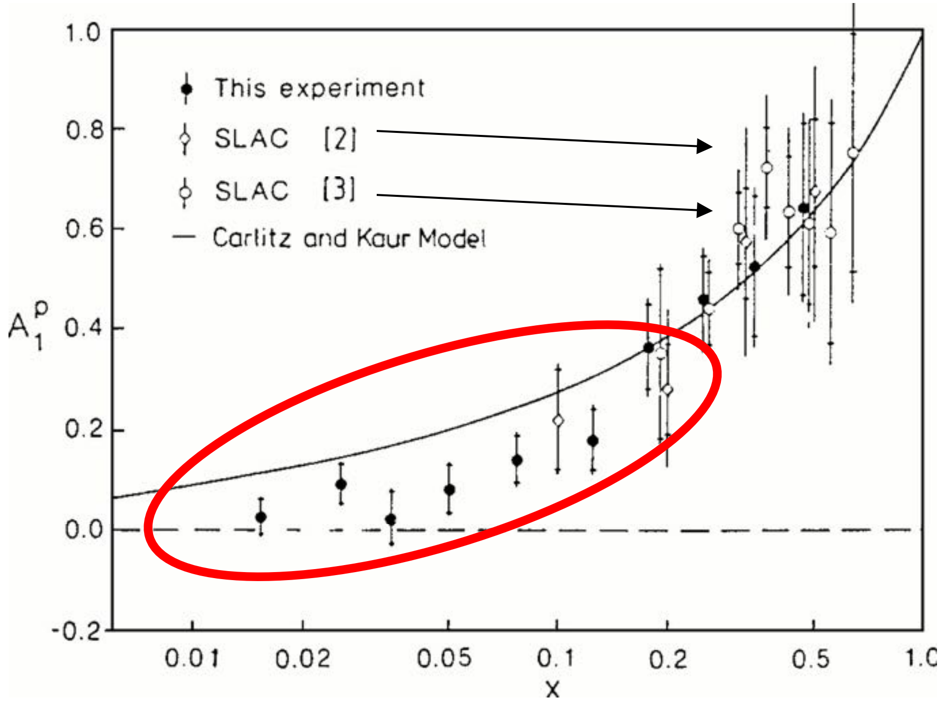
- Deep Inelastic polarized electron or muon scattering

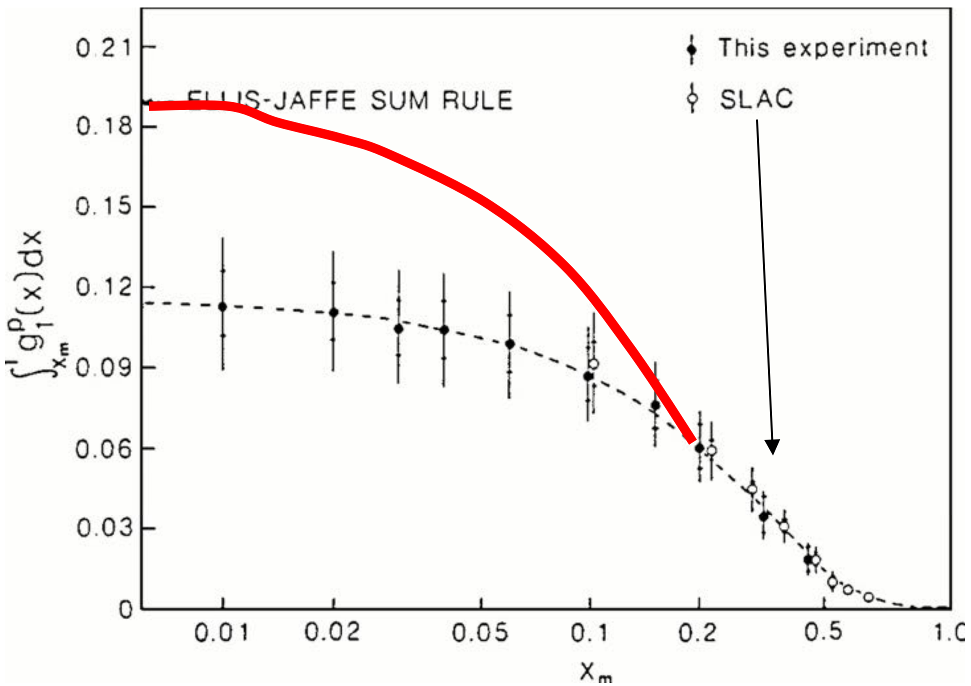


$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$$\lambda = \frac{\text{Constant}}{p}$$

Proton Spin Crisis (1989)!



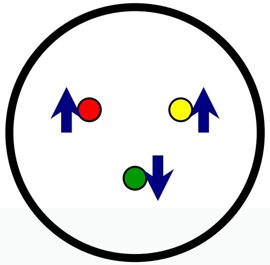


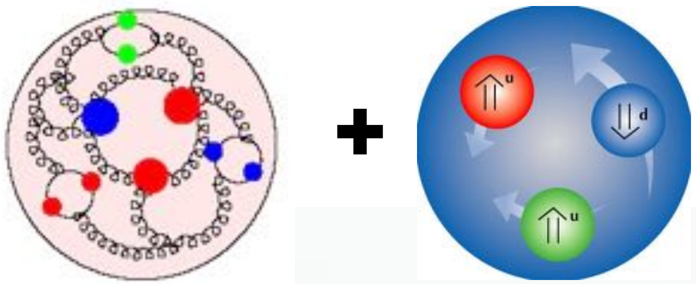
$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)

$\Delta\Sigma$ = 0.58 expected from E-J sum rule....

If the quarks did not carry the nucleon's spin, what did? → Gluons?

Our Understanding of Nucleon Spin Puzzle





1980s

1990/2000s

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

ΔΣ = 0.12 +/- 0.17

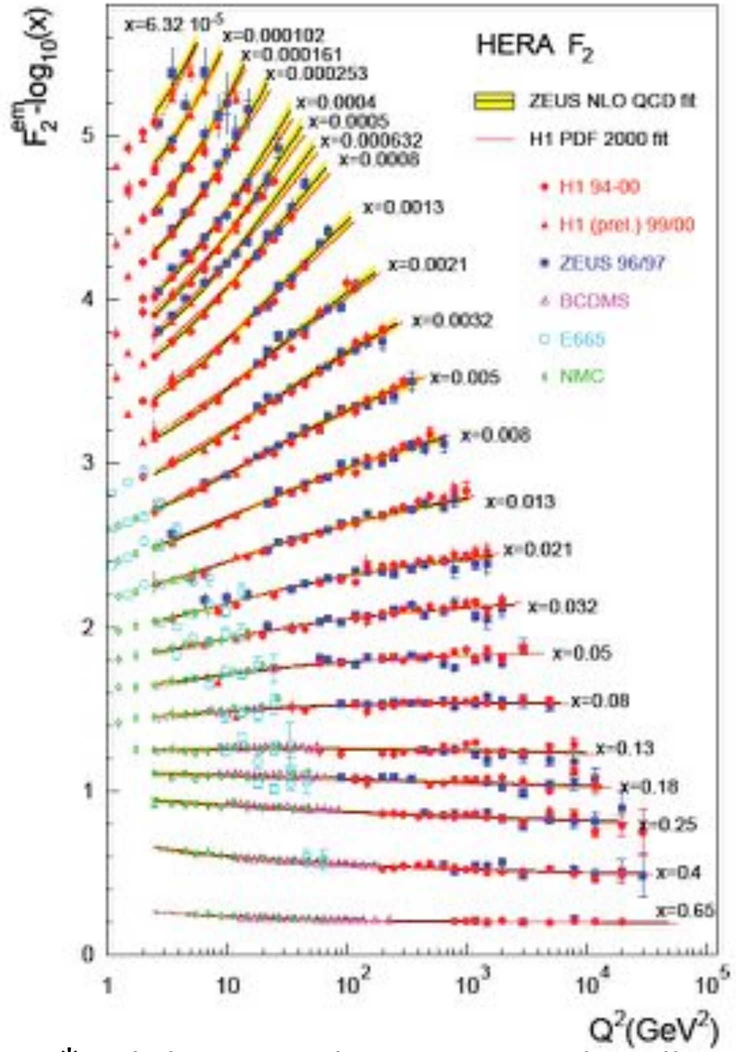
Spin discovered a problem…. What now? Need precision and investigations of gluons….

Measurement of unpolarized glue at HERA

F$_2$ Structure Function

Vs.

Q^2 mom. exchanged

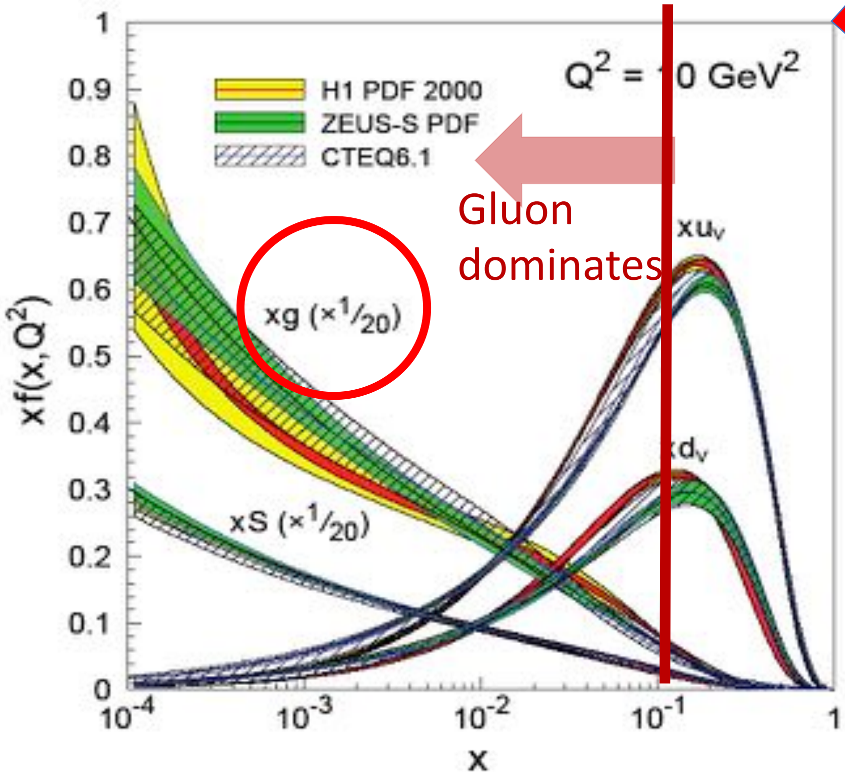


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

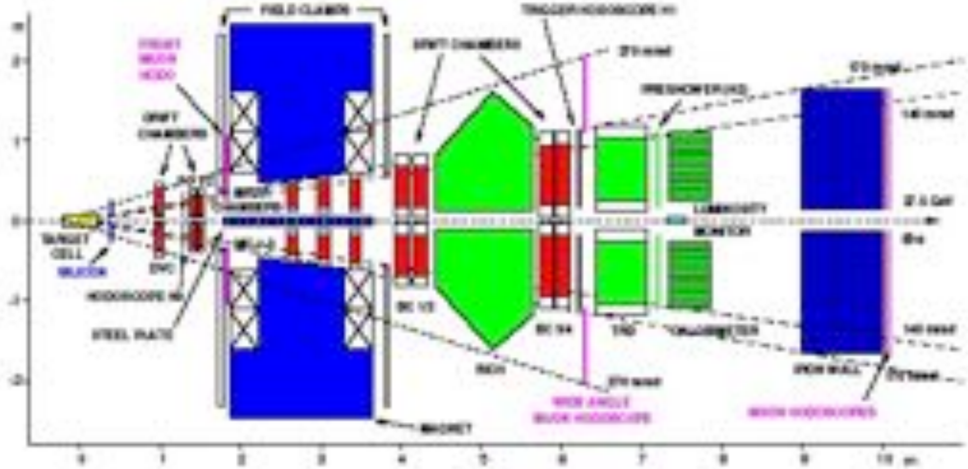
- Scaling violations of $F_2(x,Q^2)$

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

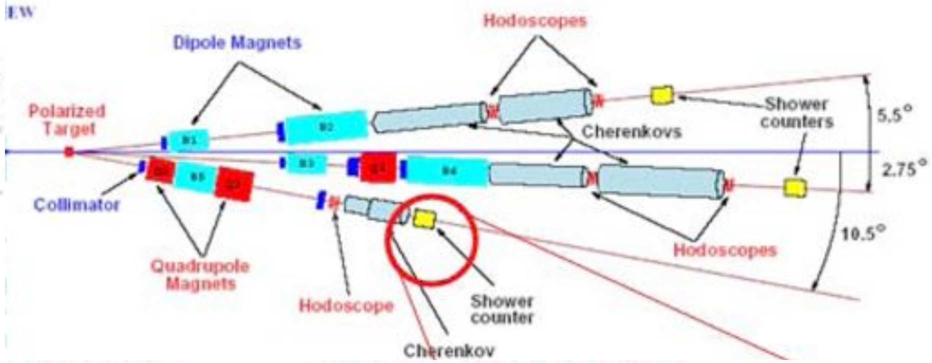
- NLO pQCD analyses: fits with **linear** DGLAP* equations

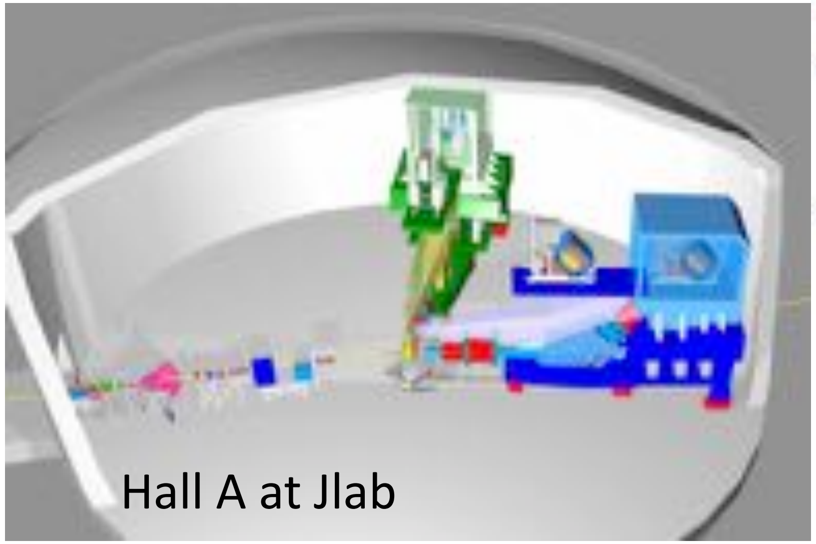


Experiments



HERMES at DESY



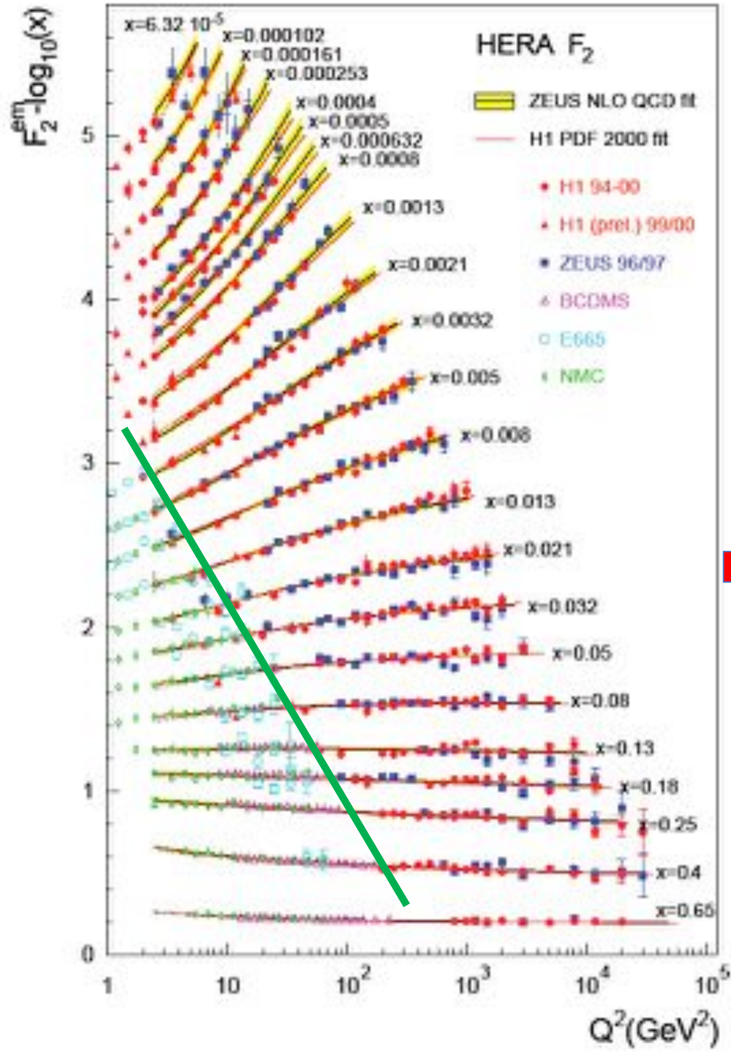


Hall A at Jlab

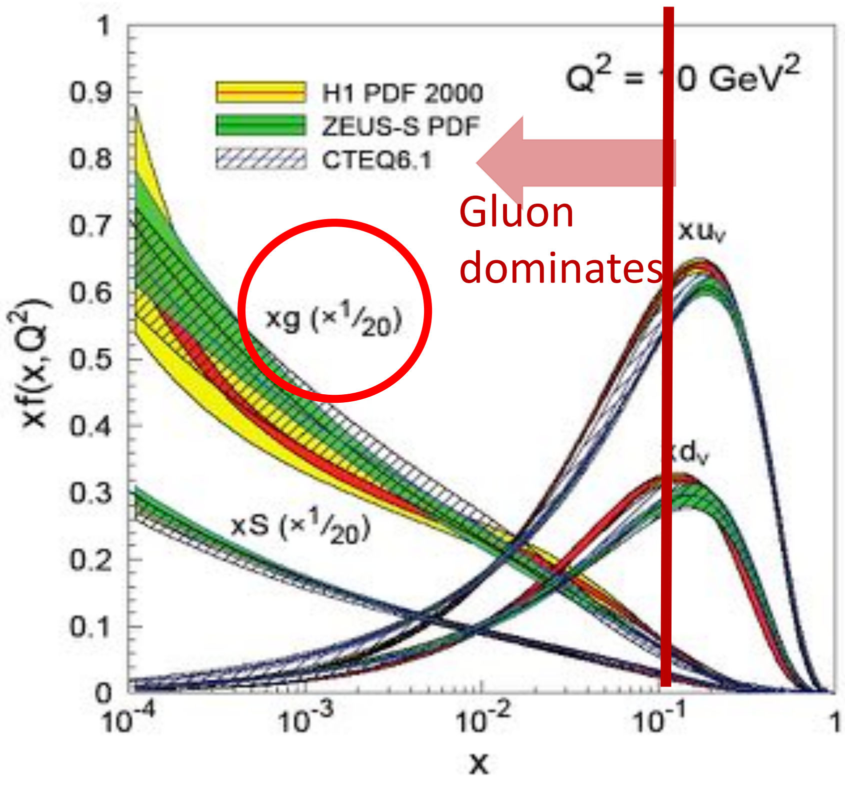
SMC,COMPASS at CERN

Similar to extraction of PDFs at HERA

(RECALL)

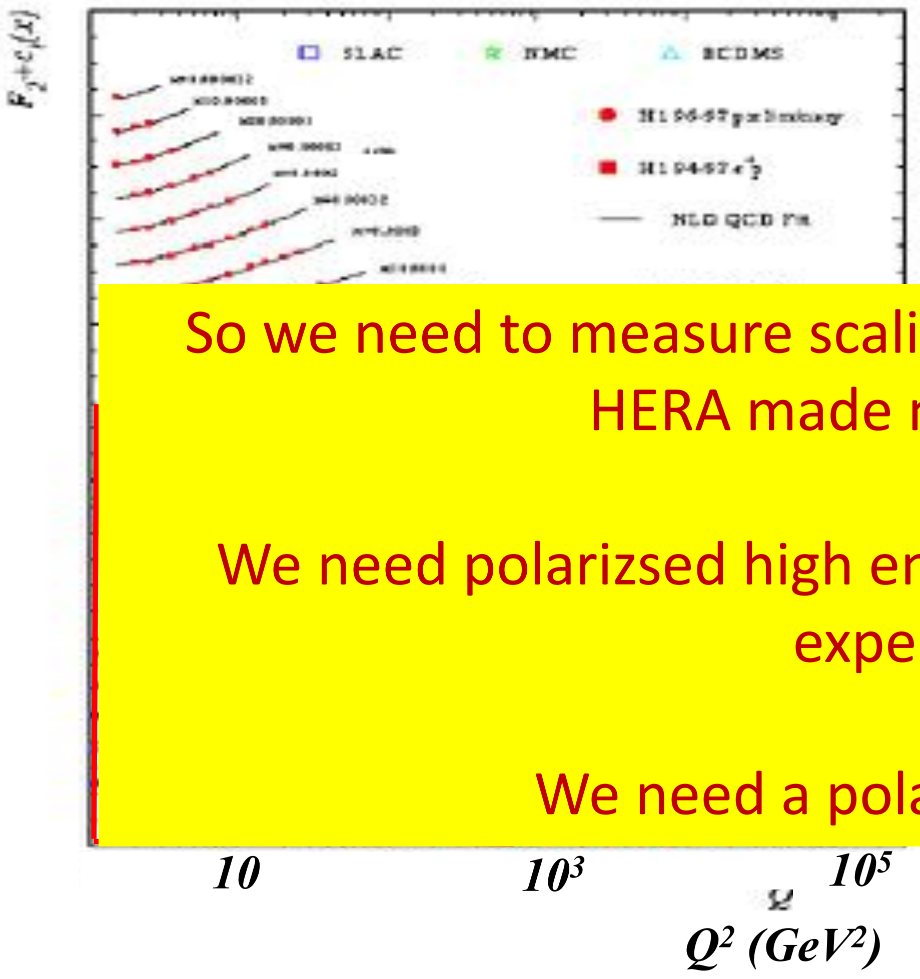


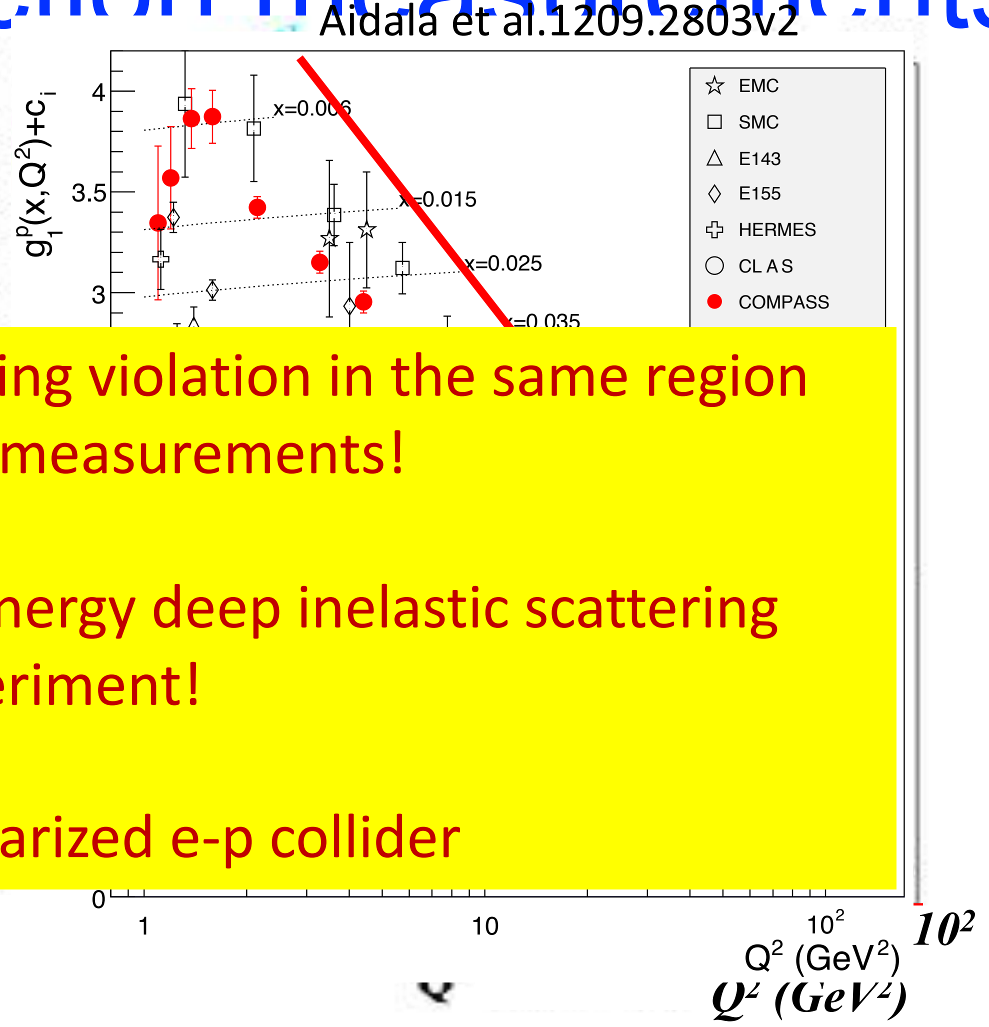
NLO pQCD analyses: fits with **linear** DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

F_2 vs. g_1 structure function measurements





So we need to measure scaling violation in the same region HERA made measurements!

We need polarizsed high energy deep inelastic scattering experiment!

We need a polarized e-p collider

Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

Consequence:

- Quark + Anti-Quark contribution to nucleon spin is definitely small: Ellis-Jaffe sum violation confirmed

$$\Delta\Sigma = 0.30 \pm 0.05$$

- Is this smallness due to some cancellation between quark+anti-quark polarization
- The gluon's contribution seemed to be large!

$$\Delta G = 1 \pm 1.5$$

- Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
    - Direct measurement of gluon spin with other probes warranted.
    - Seeded the RHIC Spin program ➔ Lecture 2