The Electron Ion Collider

Abhay Deshpande

Lecture 1 of 2

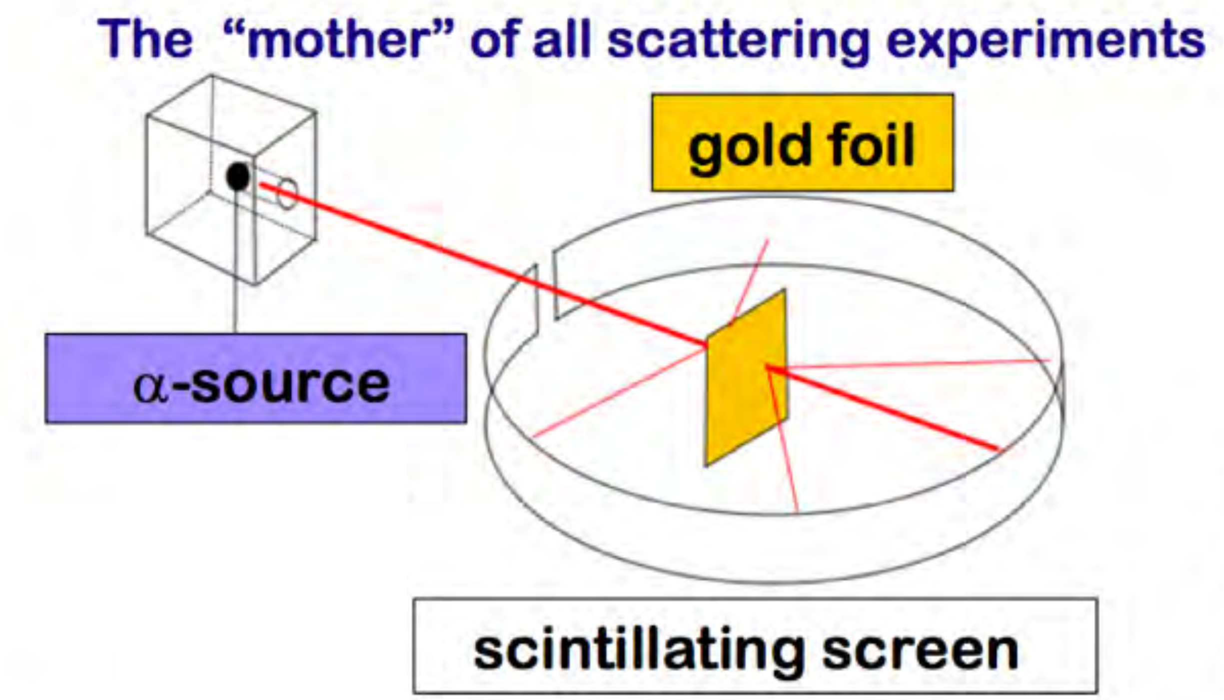
Overview of these lectures

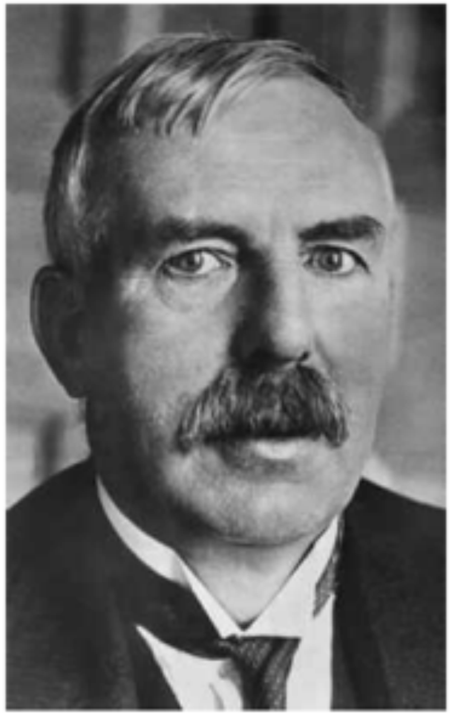
- *Extensive discussion of JLab6 and Jlab12 – Rolf Ent in the 1st week*

- **Lecture 1: Past and current studies in QCD**
  - Brief History: The Standard Model & experimental methods (mostly reminders)
  - Problems in QCD discovered, but not solved!
    - Spin: **EMC) spin crisis**: inclusive and semi-inclusive DIS and current status
    - Nuclei: Another **puzzle (EMC effect)** and its current status and experimental difficulties
    - ***Polarized*** Relativistic Heavy Ion Collier: Gluon Spin measurement
    - The transverse spin puzzle: *neglected clues* ***another lesson*** *to keep in mind*

- **Lecture 2: The US Electron Ion Collider: Frontiers in investigations of QCD**
  - Solving the spin puzzle: **3D imaging** of the nucleon
  - Partons in nuclei: how they **organize**, and **build** nuclei, do they **saturate**?
  - Designing an EIC detector and integration in to the Interaction Region (IR)
  - EIC: Status and prospects

Beginning of experimental particle/nuclear physics?





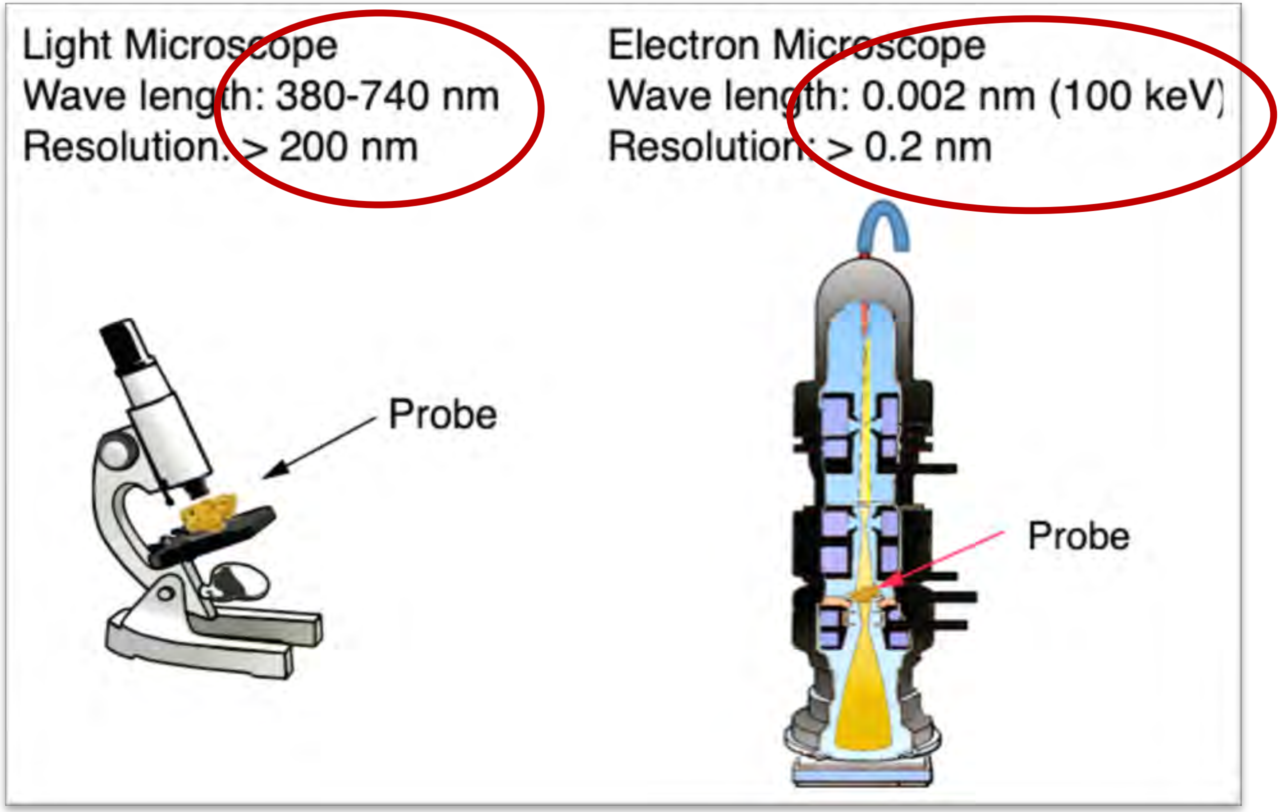
Rutherford

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

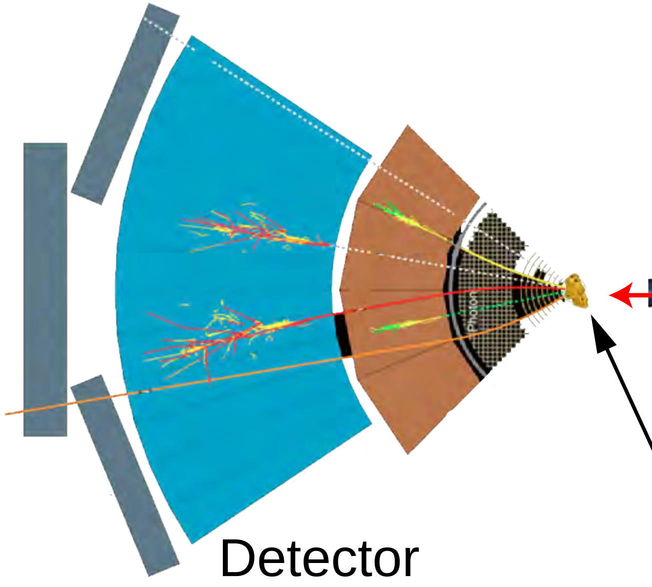
Resolution and momentum….

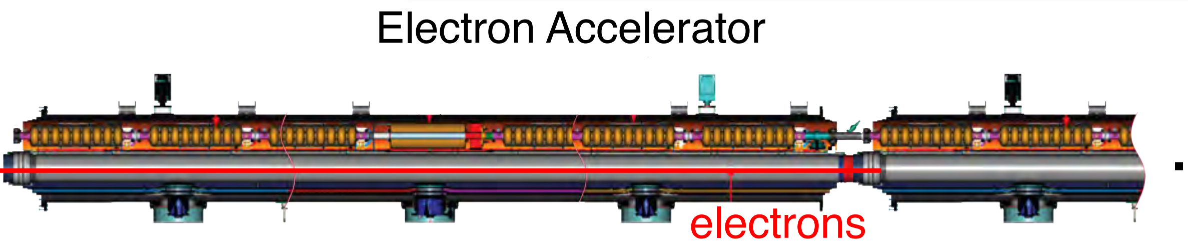
Studying smaller and smaller things…

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


Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm

Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

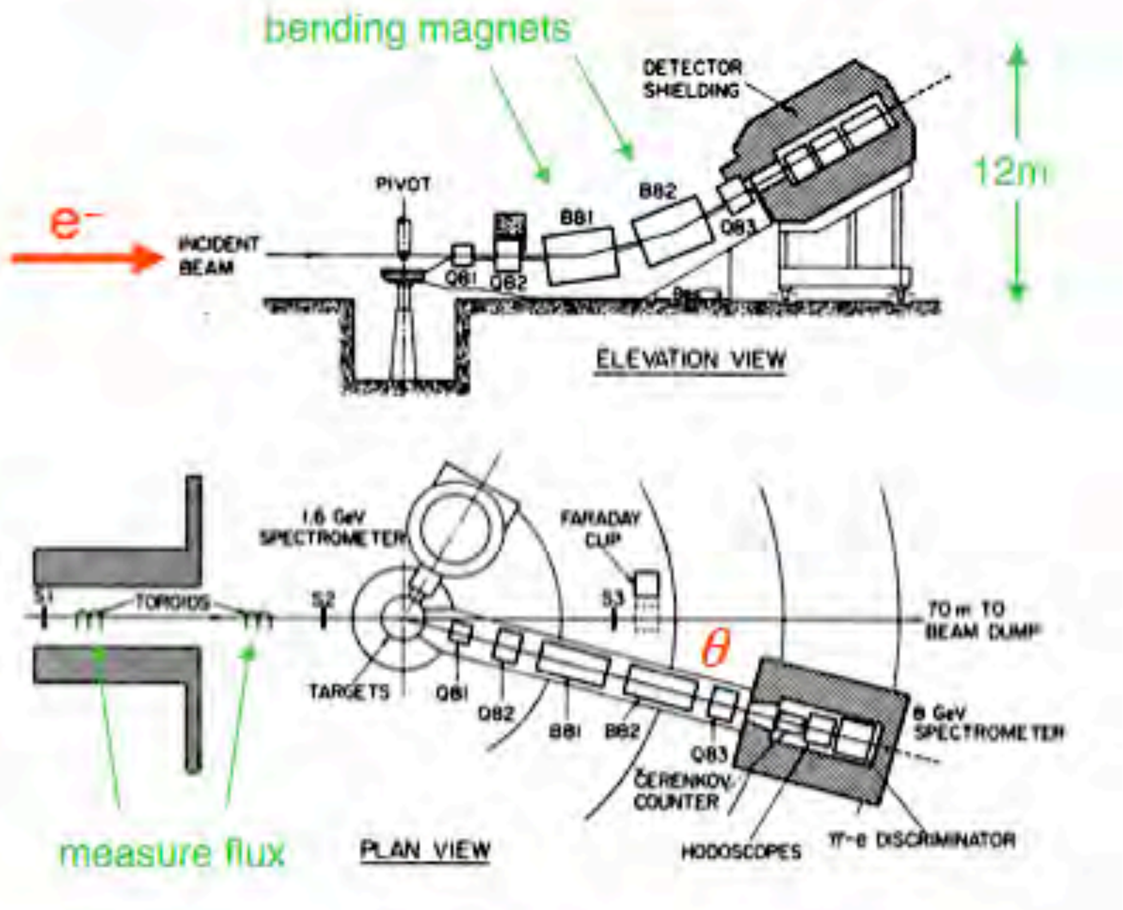




SLAC, EMC, NMC, E665, BCDMS,
HERMES, JLab, COMPASS, …

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”



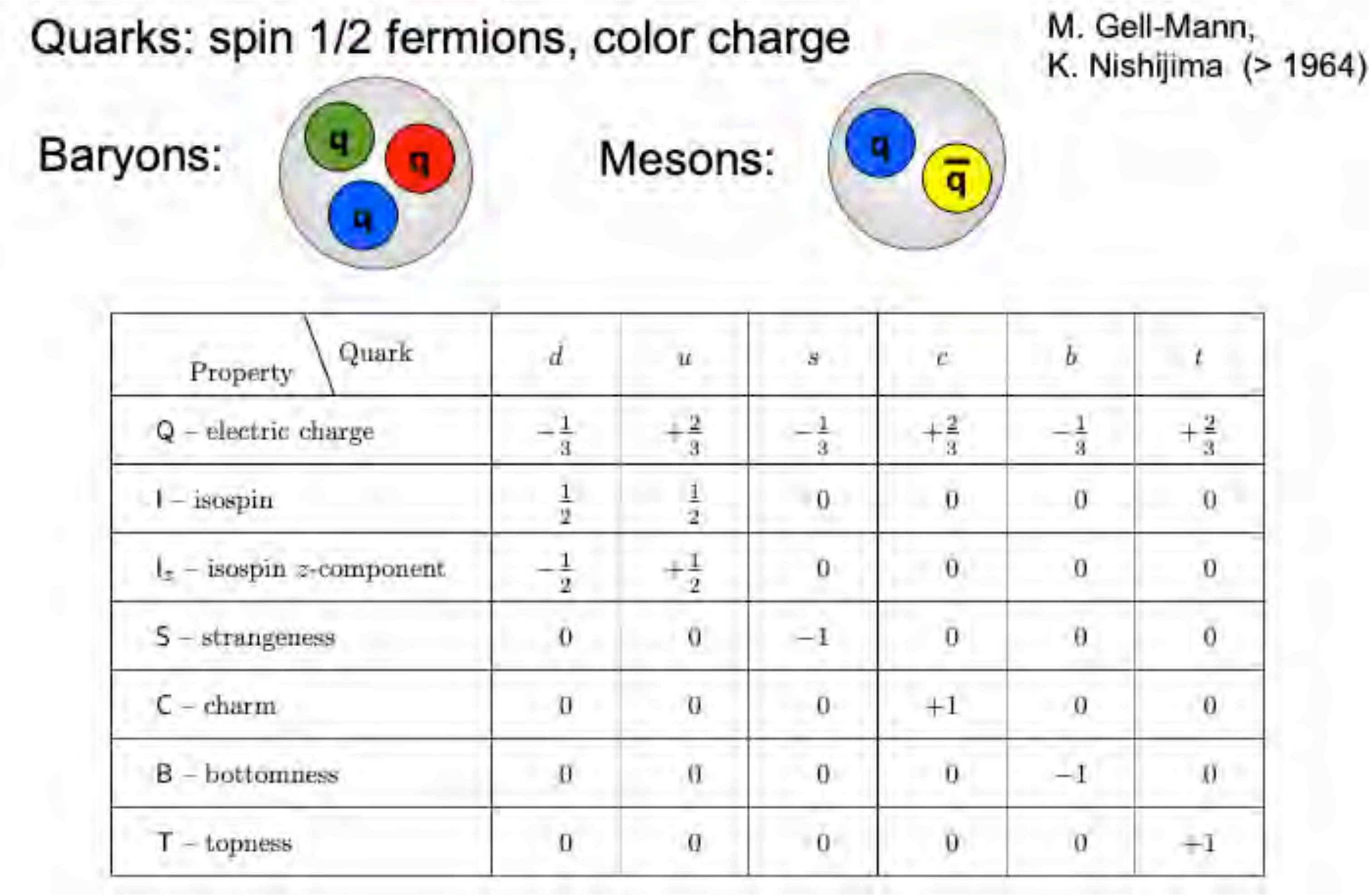
Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

determine *E’*

Spectrometer can rotate in the horizontal plane,

vary θ

The Static Quark Model



Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
K. Nishijima (> 1964)

Baryons:

Mesons:

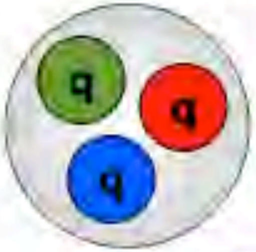
Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

The Static (Constituent) Quark Model

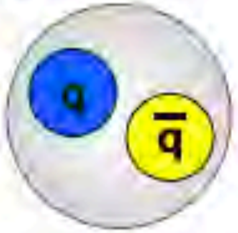
Quarks: spin 1/2 fermions, color charge

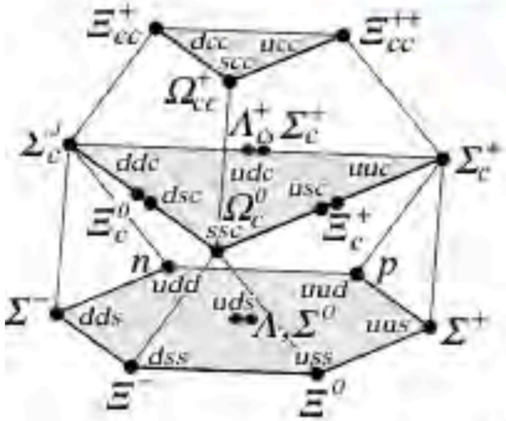
M. Gell-Mann,
K. Nishijima (> 1964)

Baryons:

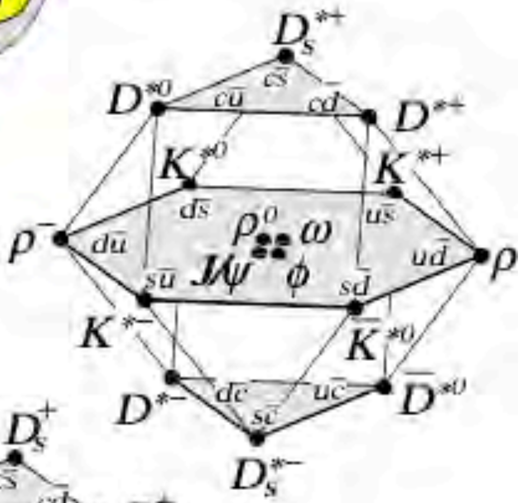


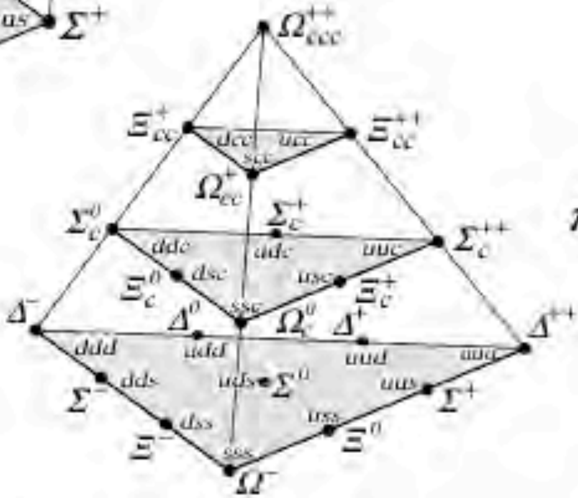
Mesons:

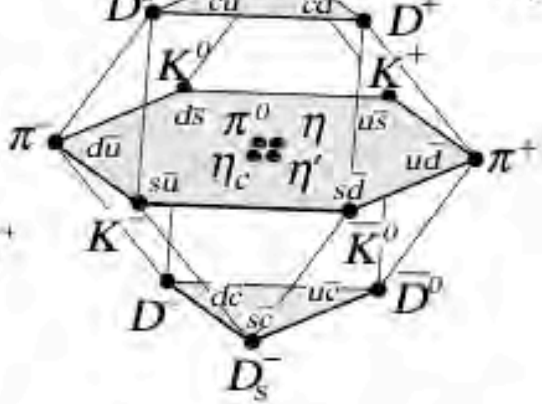




Eight-fold Way:
Account for every hadron we found so far







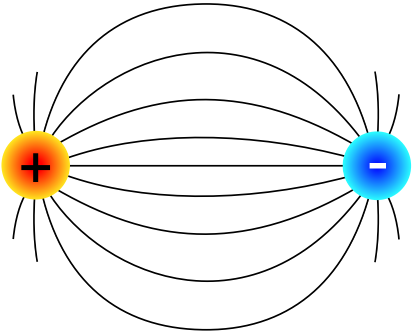
For detailed properties of the multiquark systems the model failed

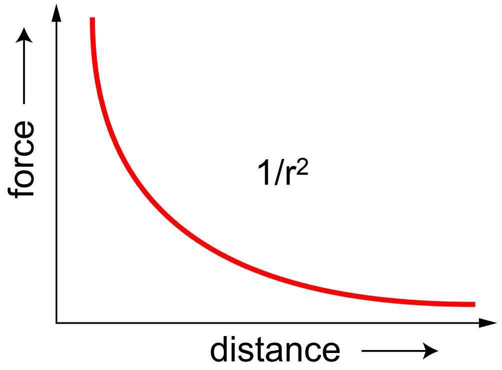
How come? What was missing?

Quantum Electrodynamics (QED)

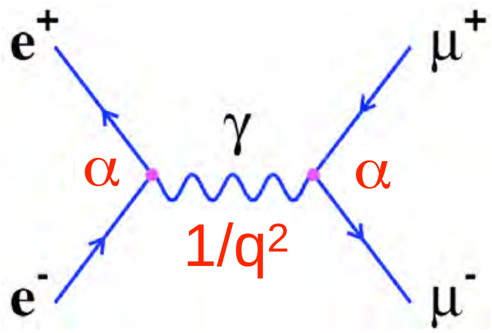
Theory of electromagnetic interactions

- 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

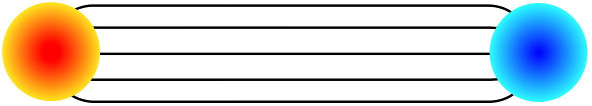
In QED: $\alpha_{em} = 1/137$

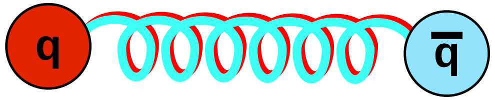
Quantum Chromodynamics (QCD)

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

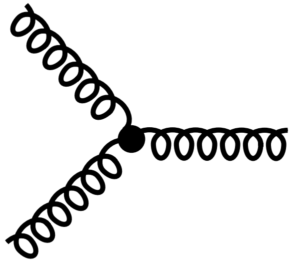
F. Wilczek, hep-ph/9907340

- 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

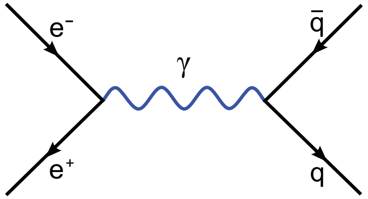
long range ~ r

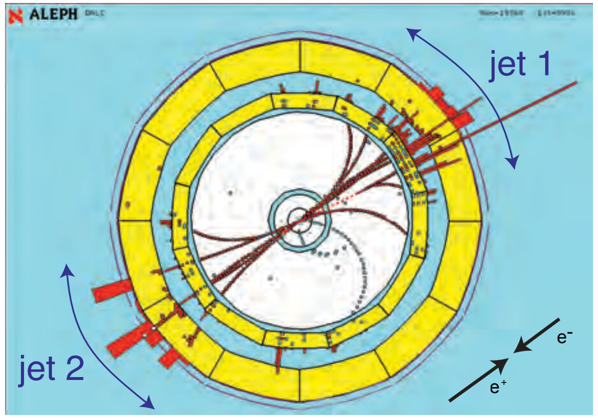
Long range aspect ⇒ quark confinement and existence of nucleons

Gluons!

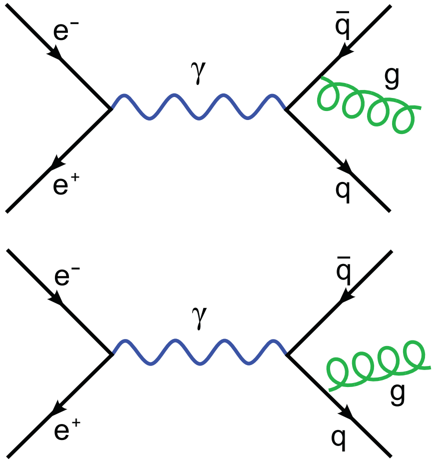
Discovery of gluons: Mark-J, Tasso, Pluto, Jade experiments at PETRA (e+e- collider) at DESY (CM energy 13-32 GeV)

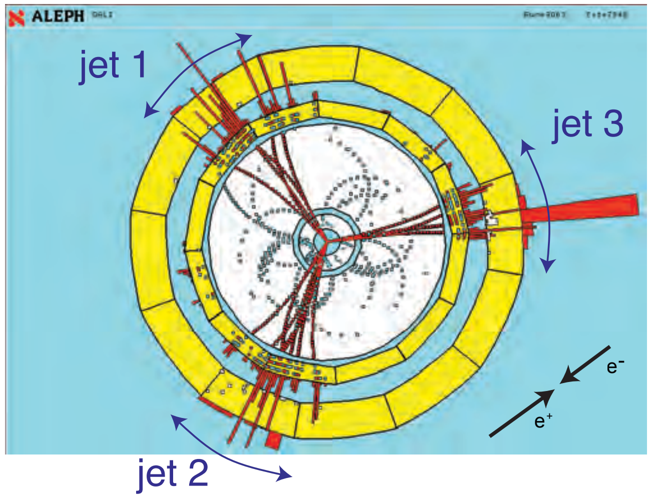
- $e^+ e^- \rightarrow q \bar{q} \rightarrow$ 2-jets





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





Standard Model (SM) of physics: Fundamental building blocks

+2/3	1968: SLAC *u* up quark	1974: Brookhaven & SLAC *c* charm quark	1995: Fermilab *t* top quark	1979: DESY *g* gluon
-1/3	1968: SLAC *d* down quark	1947: Manchester University *s* strange quark	1977: Fermilab *b* bottom quark	1923: Washington University* γ photon
0	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
-1	1897: Cavendish Laboratory *e* electron	1937 : Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN *Z* *Z* boson

18 Nobel
Prizes since
1950

2012: CERN

H

- H BOSON

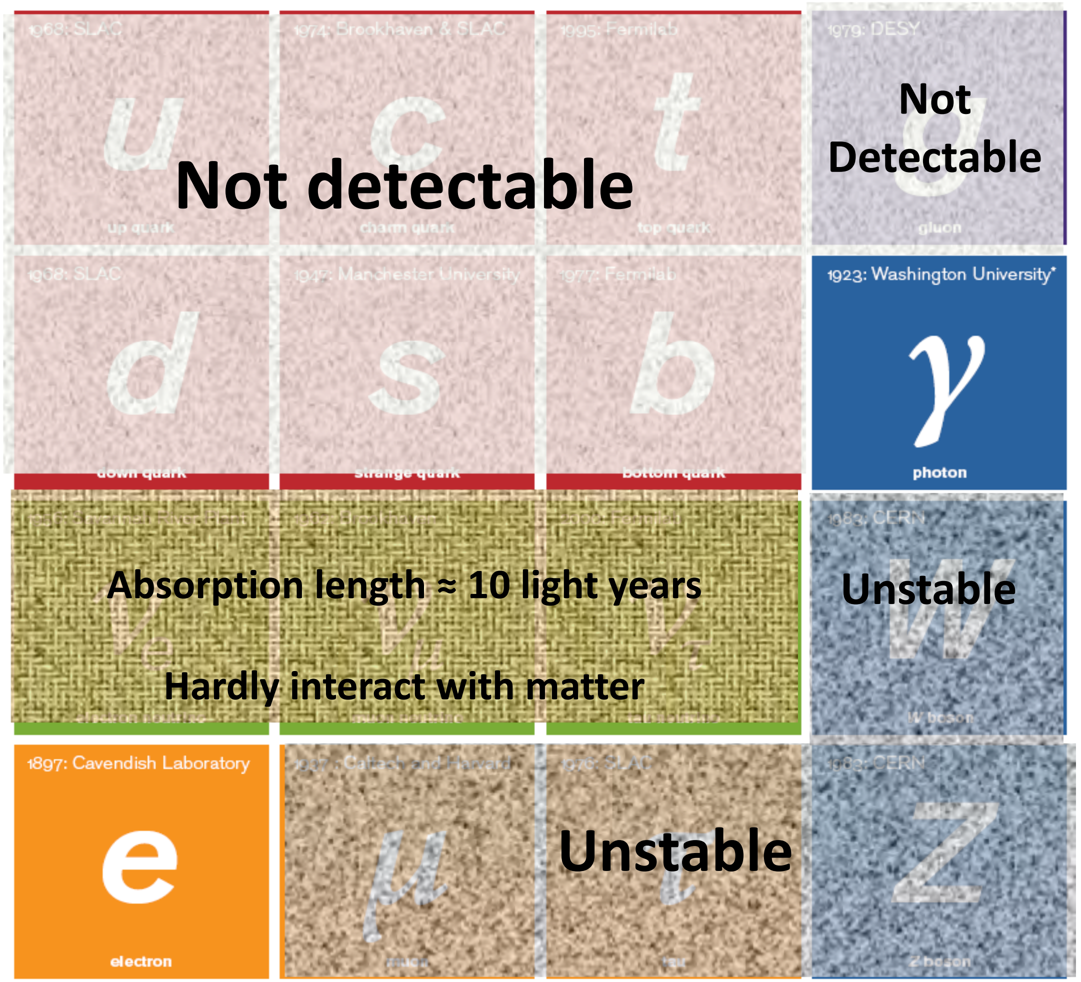
\+

2015 Gravitational waves

Einstein gravity

Difficulties in understanding our universe

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: 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



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:

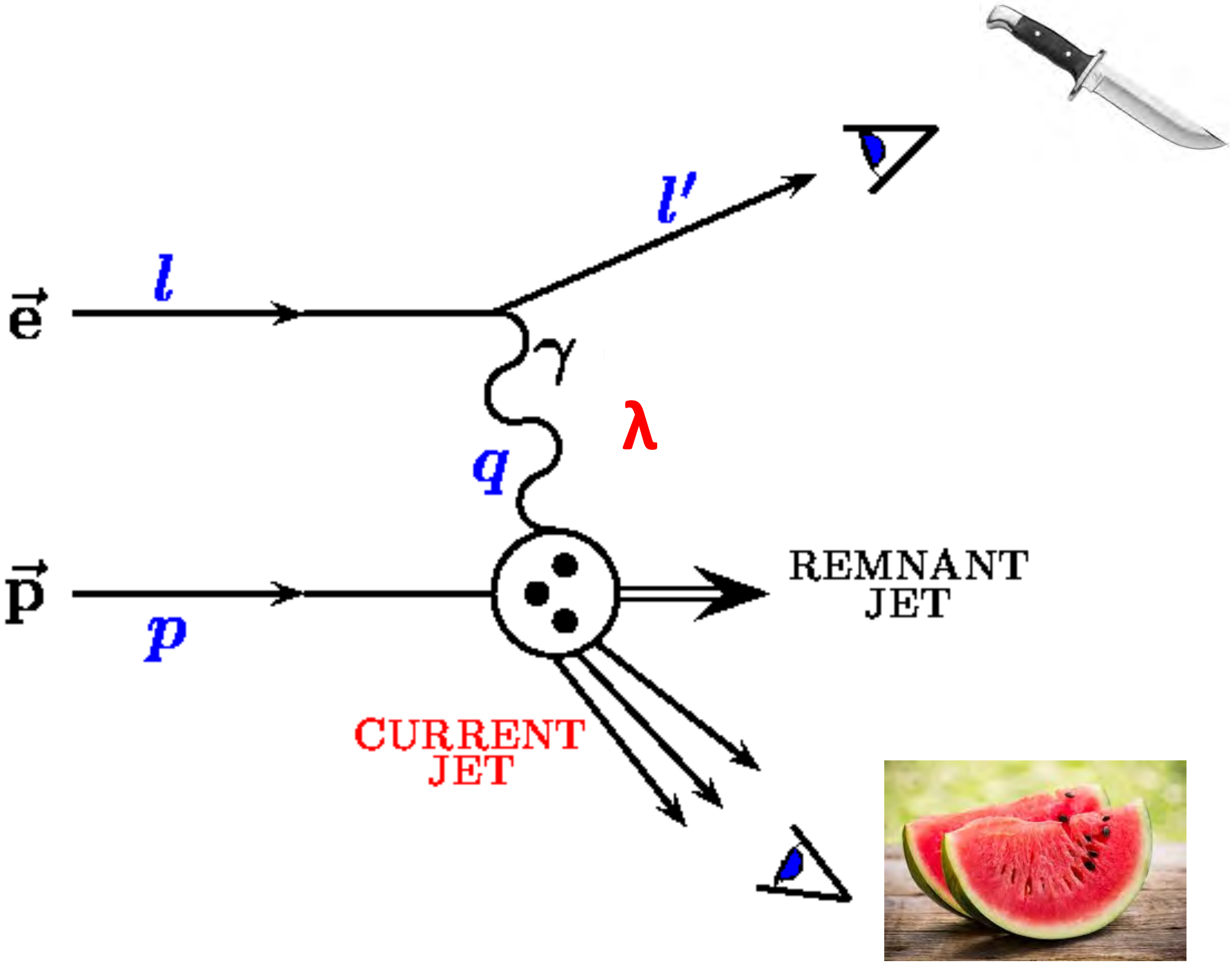
A-A (RHIC/LHC)

1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

Deep Inelastic Scattering



q = h/λ

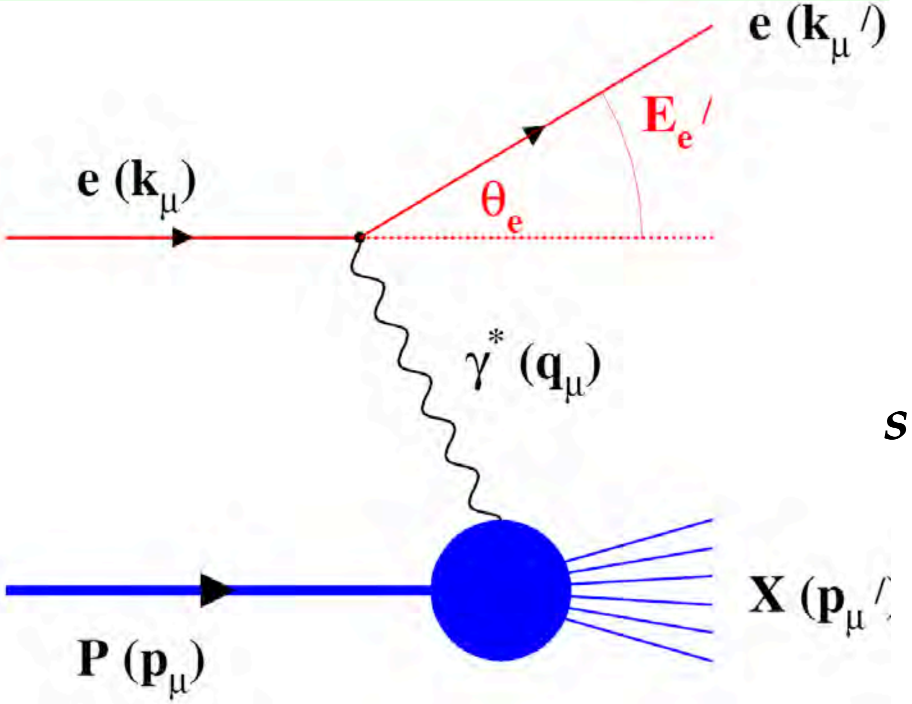
h = constant

λ = wavelength

q = momentum transferred

Deep Inelastic: (λ << Proton Size)

Deep Inelastic Scattering: Precision & Control



Kinematics:

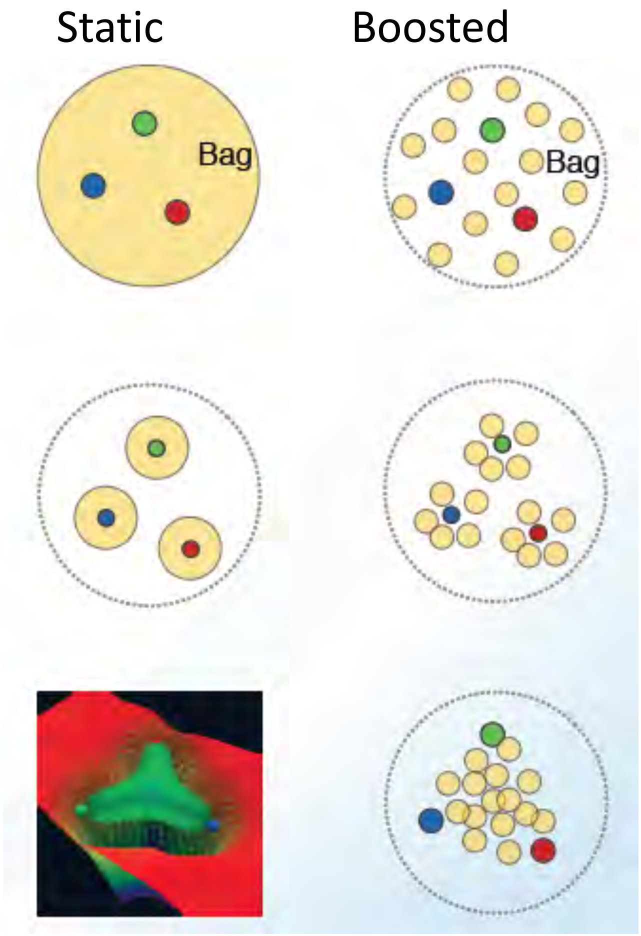
$$s = 4\,E_e\,E_p$$

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)

What does a proton look like in transverse dimension?



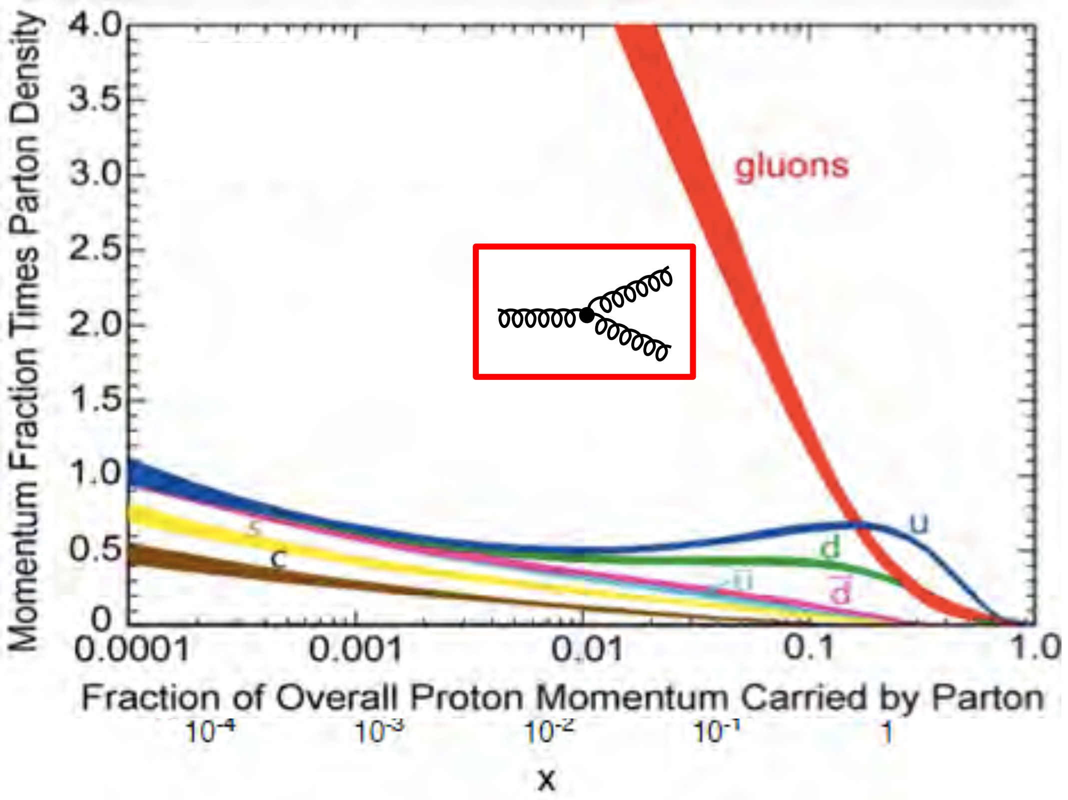
Bag Model: Gluon field distribution is wider than the fast moving quarks. Color (Gluon) radius > Charge (quark) Radius

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

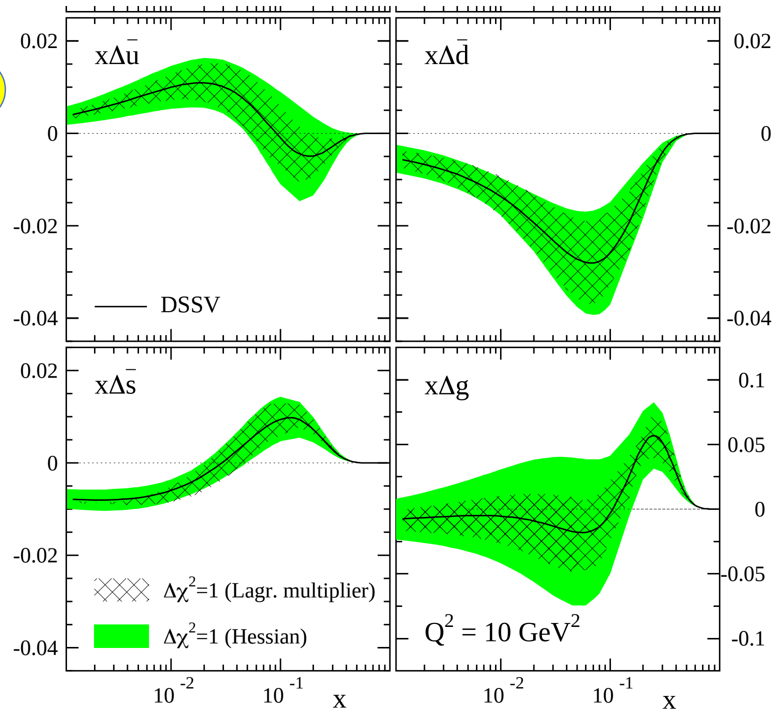
Need *transverse* images of the quarks *and gluons* in protons

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



QCD
Terra-incognita!

High Potential for Discovery



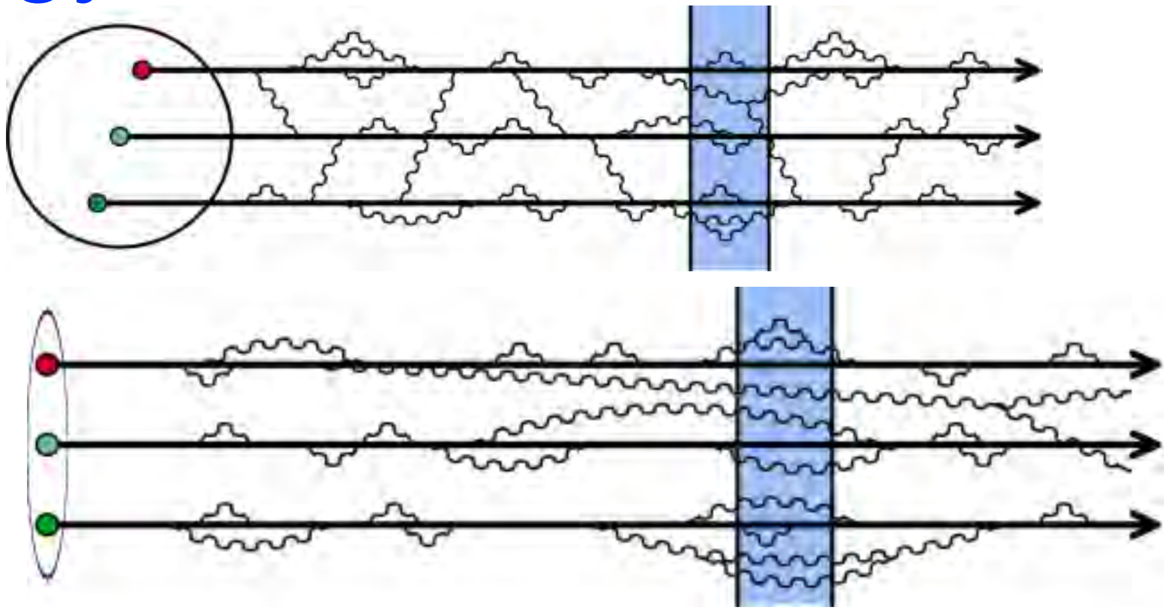
Need to go beyond 1-dimension!

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

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:

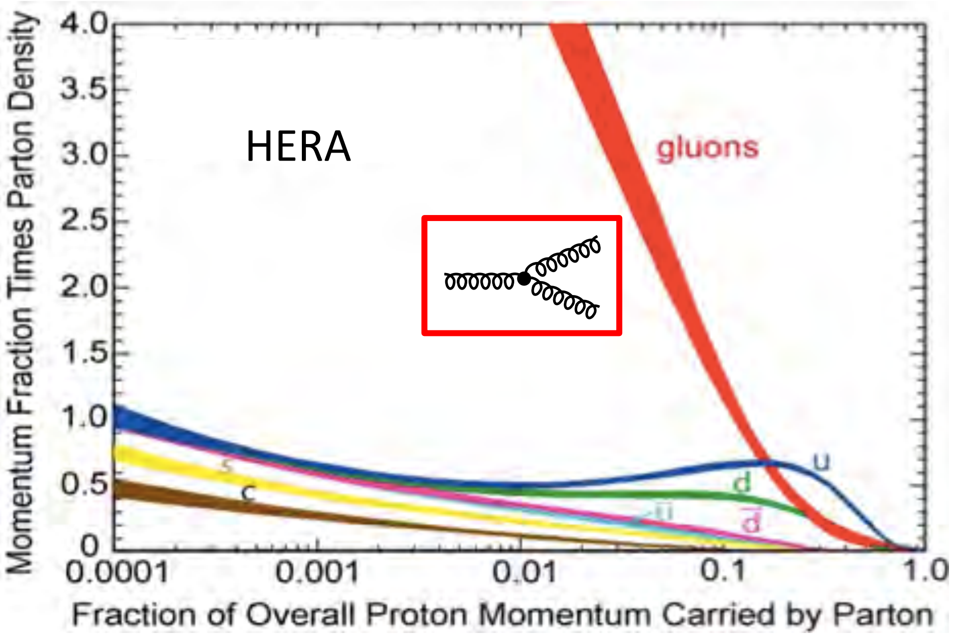
Gluons carry color charge ➔ Can interact with other gluons!

“…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:

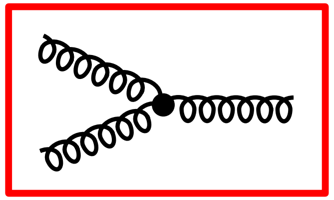
Gluons carry color charge ➔ Can interact with other gluons!



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!

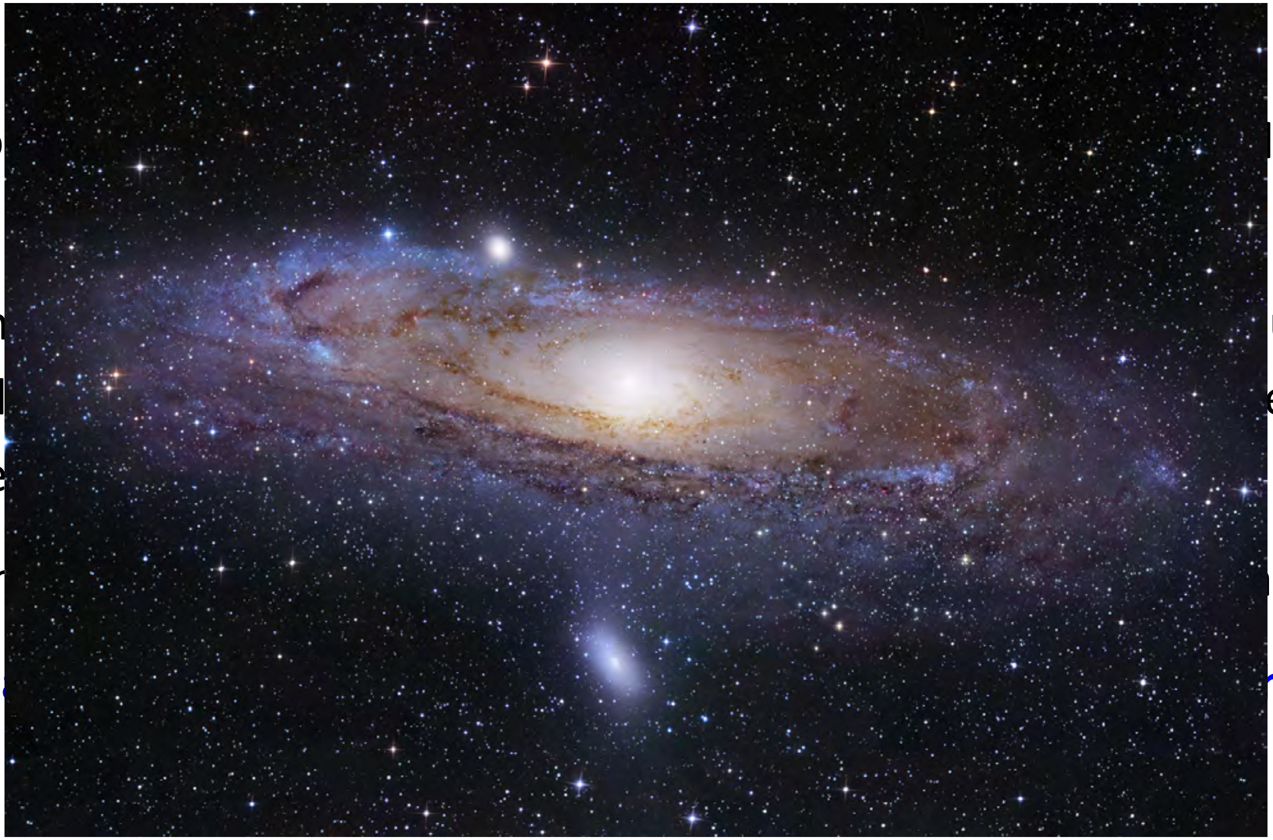
If true, effective theory of this →“Color Glass Condensate”

Emergent Dynamics in QCD

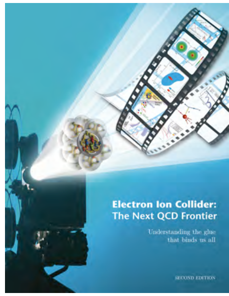
Without gluons,* there would be no nucleons, no atomic nuclei… *no visible world!

- 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-nucleor ppens remains a mystery

Experimental insight **adrons & nuclei emerge**



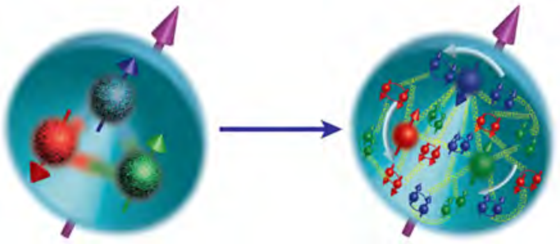
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

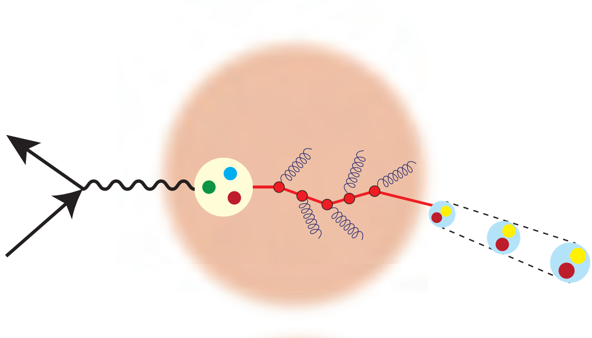


Electron Ion Collider: The Next QCD Frontier

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

How do the nucleon properties emerge from them and their interactions?





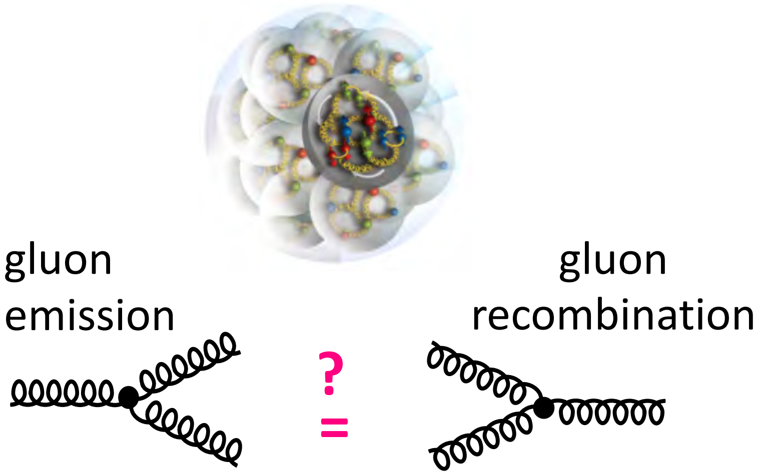
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

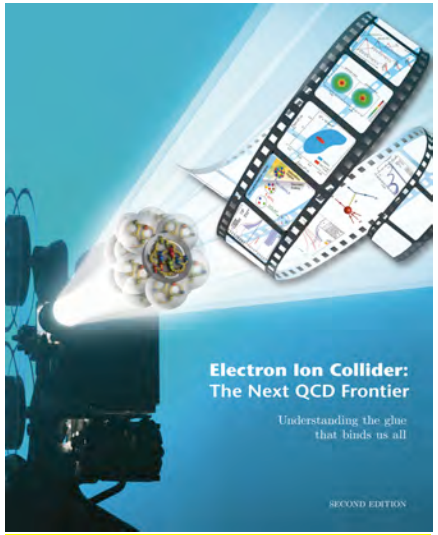
How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

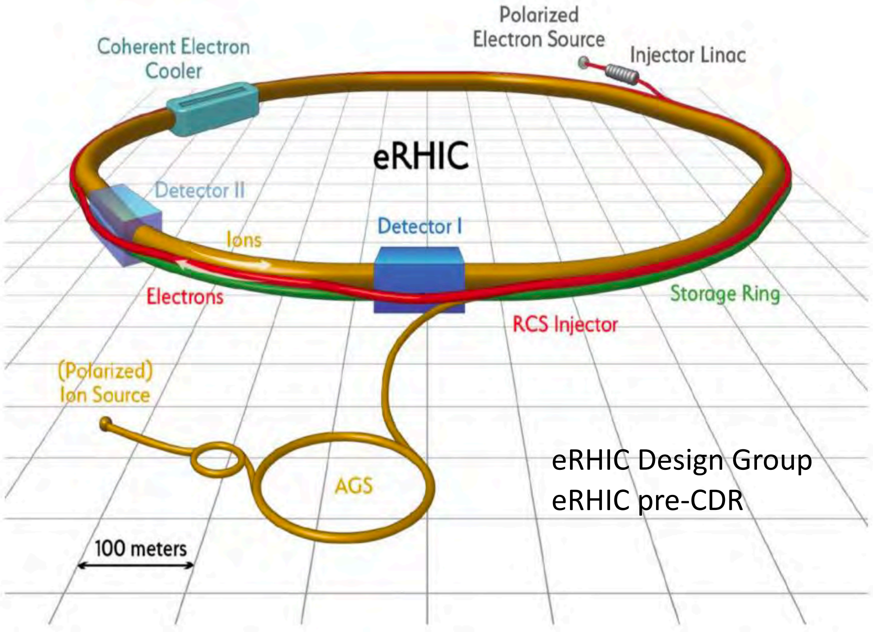
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
  - ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

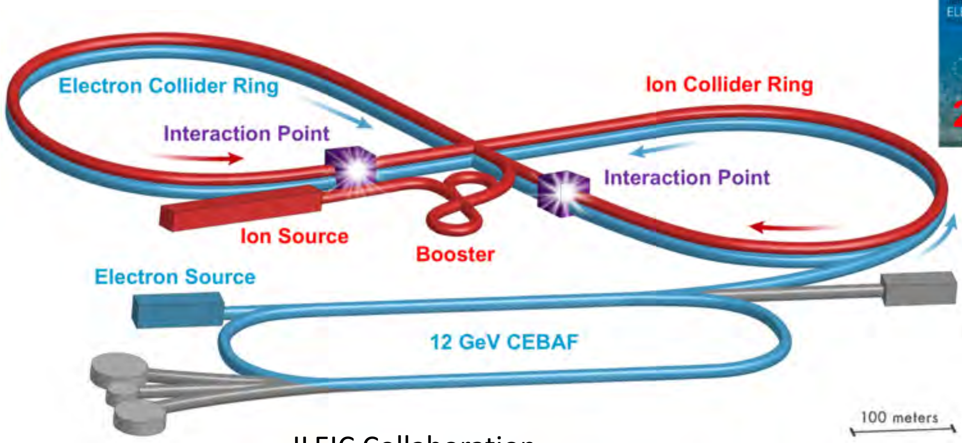
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



eRHIC Design Group
eRHIC pre-CDR

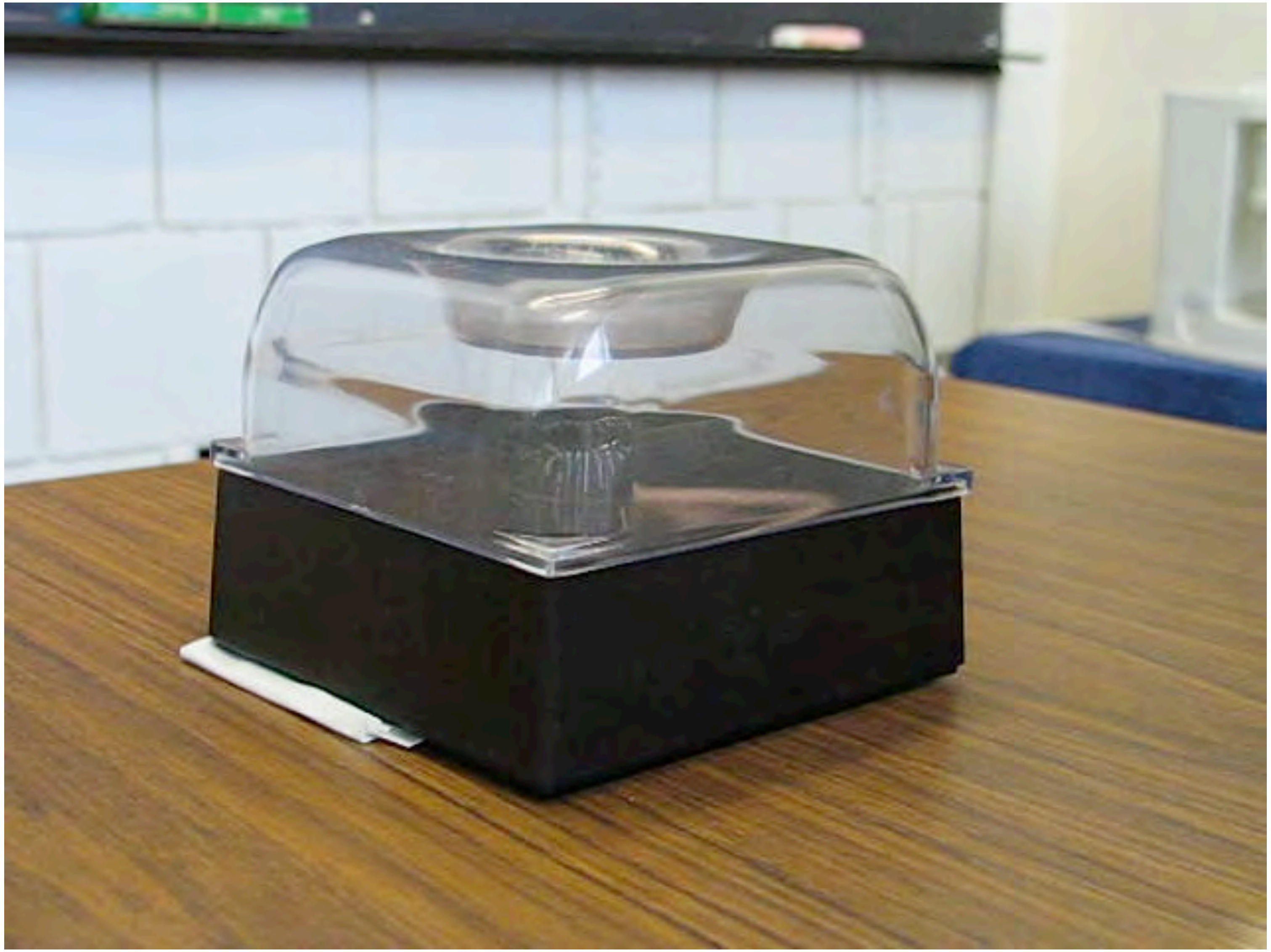
2018



JLEIC Collaboration
JLEIC Pre-CDR about to be finalized

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.

1955
Bohr & Pauli
Trying to understand
The tippy top toy

1900’s a Century of Spin Surprises!

Experiments that fundamentally changed the way we think about physics!

- Stern Gerlach Experiment (1921)
  - Space quantization associated with direction
- Goudsmit and Uhlenbeck (1926)
  - Atomic fine structure and electron spin
- Stern (1933)
  - Proton’s anomalous magnetic moment : 2.79 (proton not a point particle)
- Kusch (1947)
  - Electron’s anomalous magnetic moment: 1.00119 (electron a point particle)
- Yale-SLAC Experiment (Prescott et a.)
  - Electroweak interference in polarizded e-D scattering
- European Muon Collaboration (EMC) (1988)
  - The Nucleon Spin Crisis (now – a puzzle)

20th Century could be called a "*Century of Spin Surprises!*"

In fact, it has noted by :

Prof. Elliot Leader (University College London) that

"Experiments with spin have killed more theories in physics, than any other single physical variable"

Prof. James D. Bjorken (SLAC), jokingly, that

"If theorists had their way, they would ban all experiments involving spin"

Lets get in to details of e-p scattering: what do we learn?

Lepton Nucleon Cross Section:

Assume only γ^* exchange

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k, q, s,)W^{\mu\nu}(P, q, S)$$

Nucleon spin

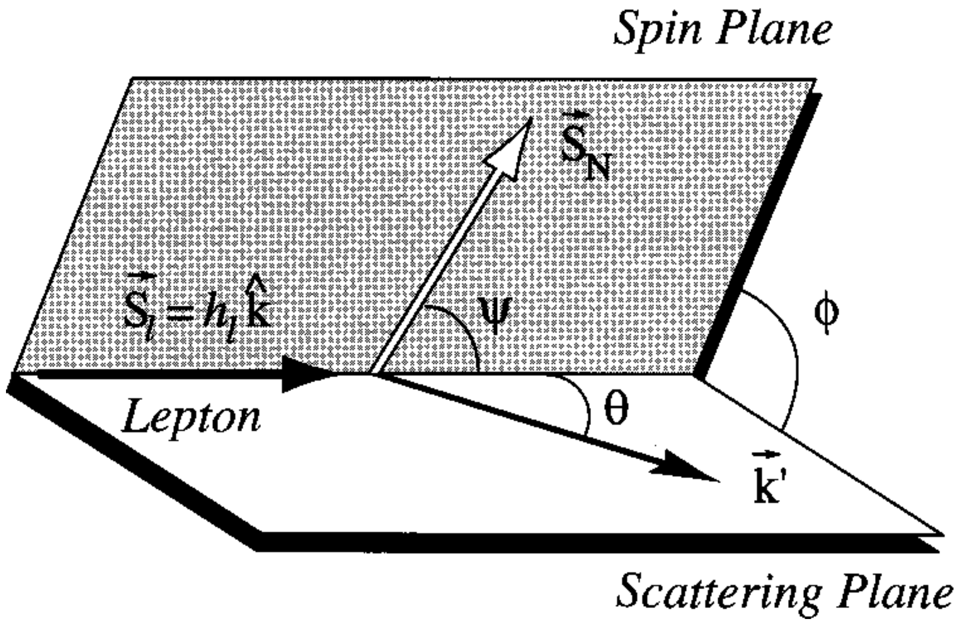
Lepton spin

- Lepton tensor $L_{\mu\nu}$ affects the kinematics (QED)
- Hadronic tensor $W^{\mu\nu}$ has information about the hadron structure

$$W^{\mu\nu}(P, q, S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2})\underline{F_1(x, Q^2)} + (p^\mu - \frac{P \cdot q}{q^2} q^\mu)(p^\nu - \frac{P \cdot q}{q^2} q^\nu)\frac{1}{P \cdot q}\underline{F_2(x, Q^2)}$$

$$-i\epsilon^{\mu\nu\lambda\sigma} q_\lambda \left[\frac{MS_\sigma}{P \cdot q}(\boxed{g_1(x, Q^2)} + \boxed{g_2(x, Q^2)}) - \frac{M(S \cdot q)P_\sigma}{P \cdot q} \boxed{g_2(x, Q^2)} \right]$$

Lepton-nucleon cross section…*with spin*



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

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

For high energy scattering γ is small

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

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

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:

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

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

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

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

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

- $A_{||}$ could be written down in terms of spin structure function g_1, and A_2 along with kinematic factors:

$$\frac{A_{\parallel}}{D} = (1+\gamma^2)\ \frac{g_1}{F_1} + (\eta - \gamma) A_2$$

Where A_1 is bounded by 1, and A_2 by sqrt($R=\sigma_T/\sigma_L$), when terms related A_2 can be neglected, and γ is small,

$$A_1 \simeq \frac{A_{\parallel}}{D}, \quad \frac{g_1}{F_1} \simeq \frac{1}{1+\gamma^2}\ \frac{A_{\parallel}}{D}$$

$$F_1 = \frac{1+\gamma^2}{2x(1+R)}\ F_2 \qquad\qquad A_2 = \frac{1}{1+\eta\xi}\left(\frac{A_{\perp}}{d} + \xi\ \frac{A_{\parallel}}{D}\right)$$

Relation to spin structure function g_1

$$g_1(x) = \frac{1}{2}\sum_{i=1}^{n_f} e_i^2 \Delta q_i(x)$$

$$\Delta q_i(x) = q_i^+(x) - q_i^-(x) + \overline{q}_i^+(x) - \overline{q}_i^-(x)$$

$q_i^+ \ (\overline{q}_i^+)$ and $q_i^- (\overline{q}_i^-)$

Quark and anti-quark with spin orientation along and against the proton spin.

- In QCD quarks interact with each other through gluons, which gives rise to a Q^2 dependence of structure functions

- At any given Q^2 the spin structure function is related to polarized quark & gluon distributions by coefficients C_q and C_g

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

$\Delta\Sigma$

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

First moment of $g_1^p(x)$: Ellis-Jaffe SR

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

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025 \qquad a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

Assuming $SU(3)_f$ & $\Delta s = 0$, Ellis & Jaffe: $\boxed{\Gamma_1^p = 0.170 \pm 0.004}$

Measurements were done at SLAC (E80, E130) Experiments:

- Low 8-20 GeV electron beam on fixed target
- Did not reach low enough x → $x_{min} \sim 10^{-2}$
- Found consistency of data and E-J sum rule above

Spin Crisis

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

Experimental Needs in DIS

Polarized target, polarized beam

- Polarized targets: hydrogen (p), deuteron (pn), helium (^{3}He: 2p+n)
- Polarized beams: electron,muon used in DIS experiments

Determine the kinematics: measure with high accuracy:

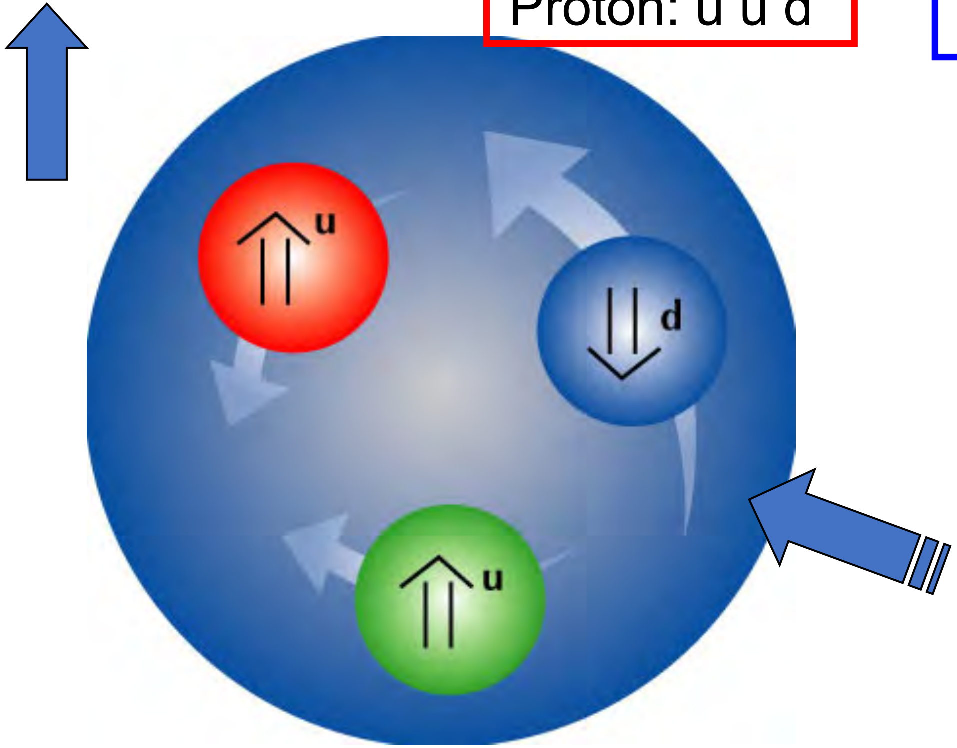
- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**

Control of false asymmetries:

- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

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

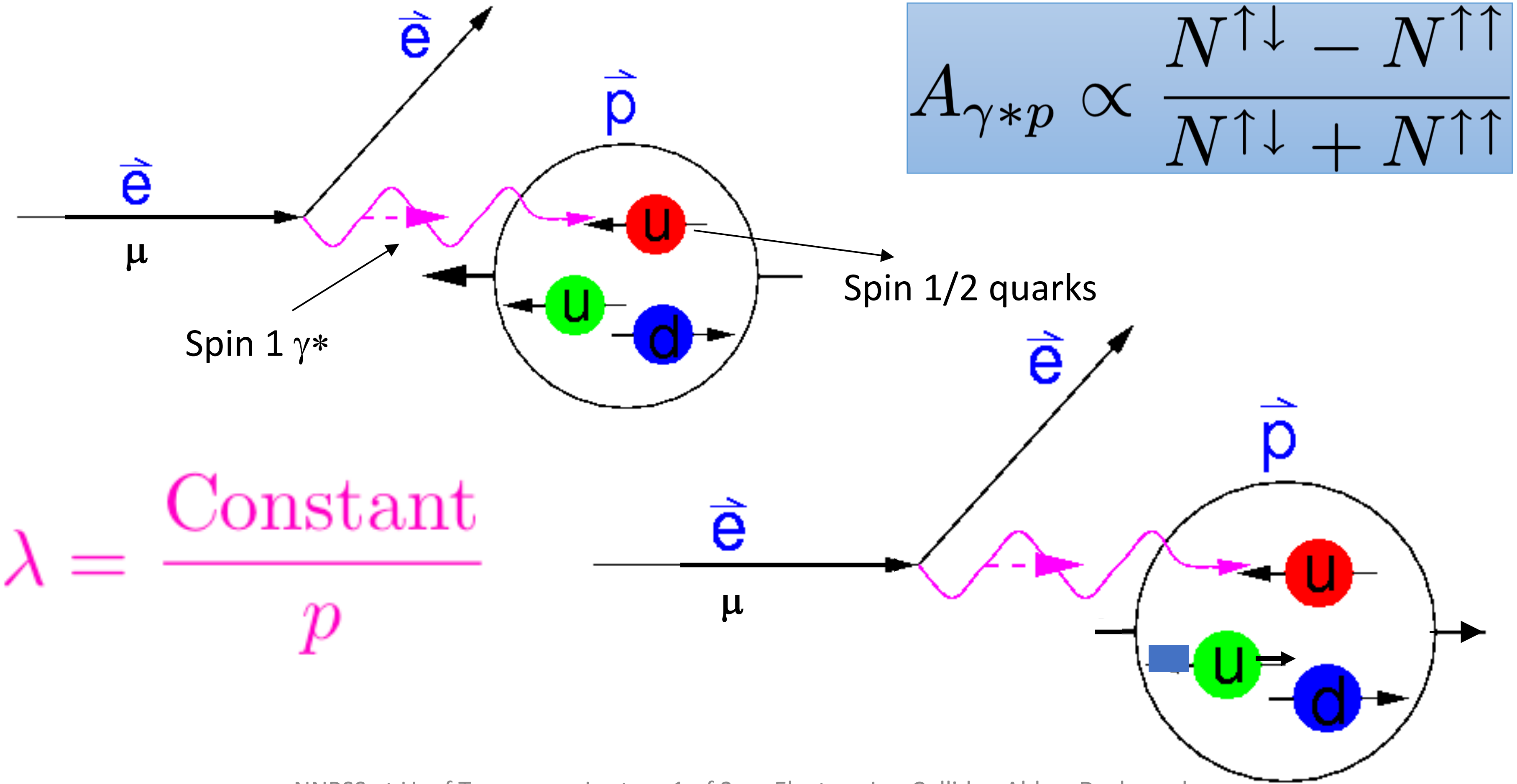
S_{proton} = Sum of all quark spins!

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

$$\boxed{1/2 = 1/2 - 1/2 + 1/2}$$

How was the Quark Spin measured?

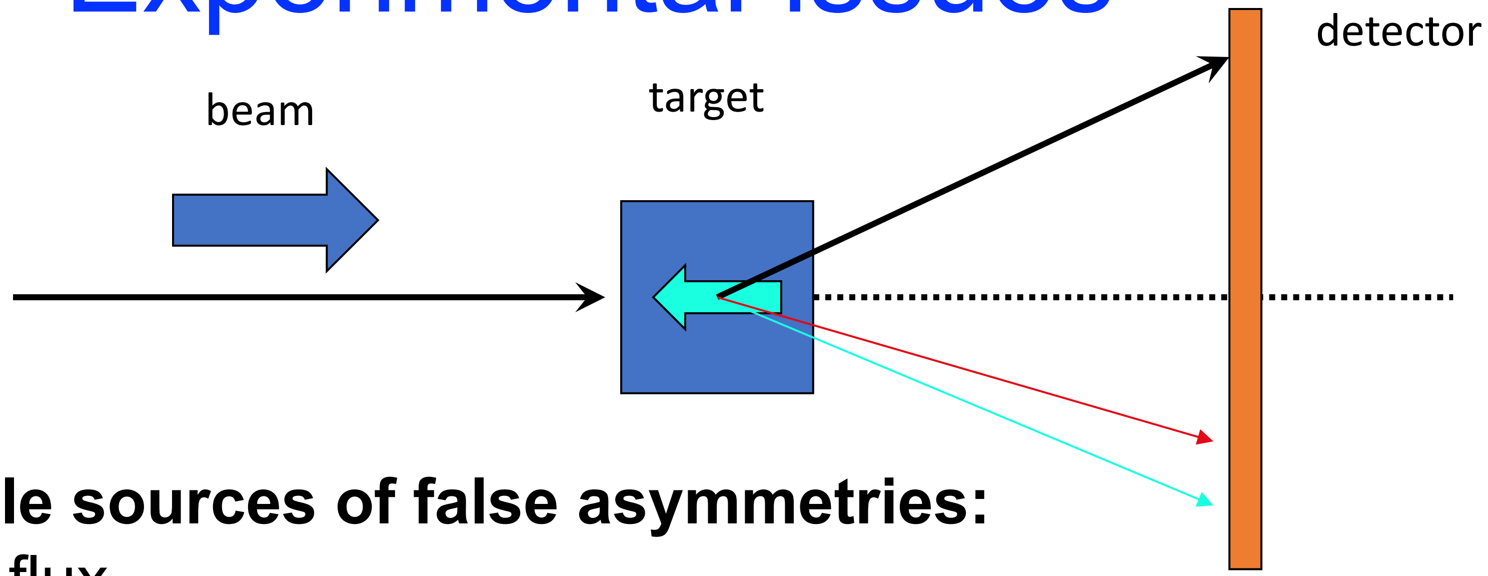
- Deep Inelastic polarized electron or muon scattering



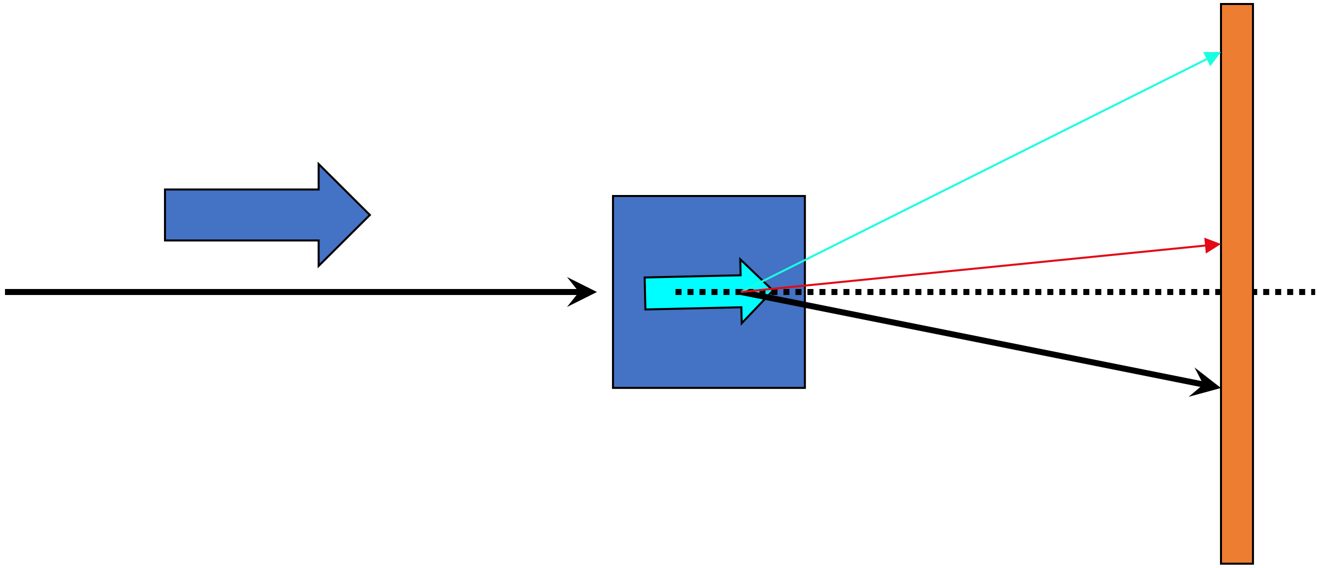
$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

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

Experimental issues



Possible sources of false asymmetries:
- beam flux
- target size
- detector size
- detector efficiency



An Ideal Situation

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

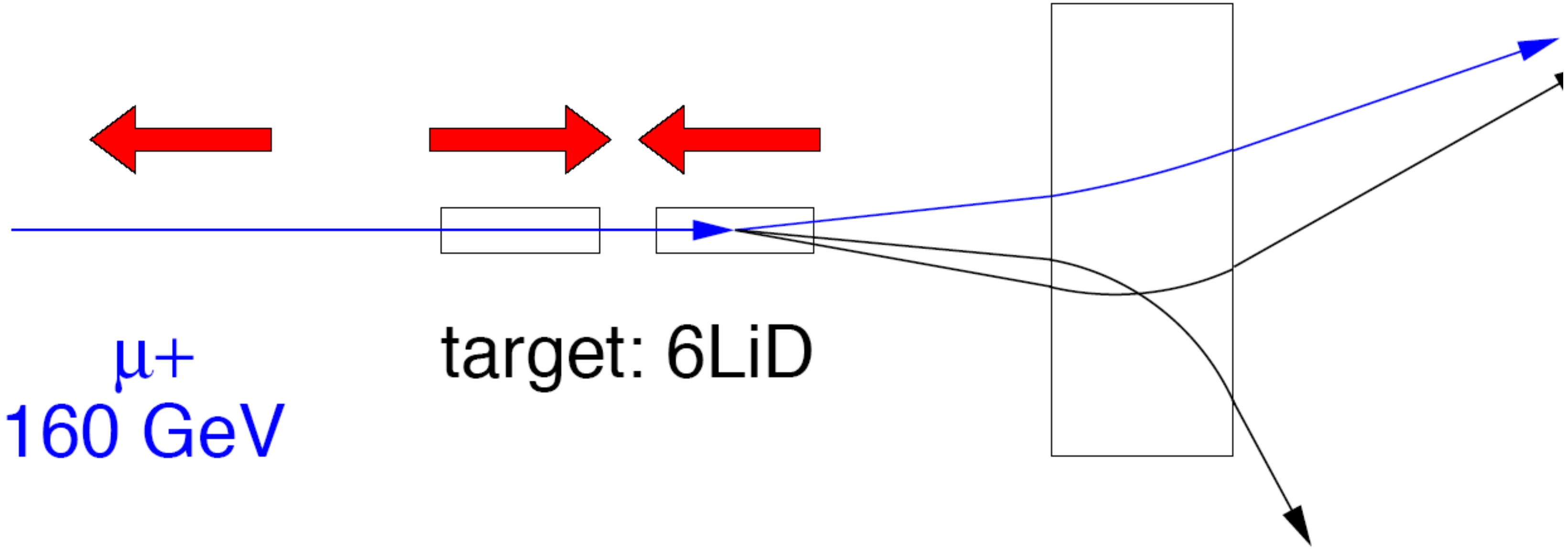
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

If all other things are equal, they cancel in the ratio and….

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

A Typical Setup

- Experiment setup (EMC, SMC, COMPASS@CERN)



- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Asymmetry Measurement

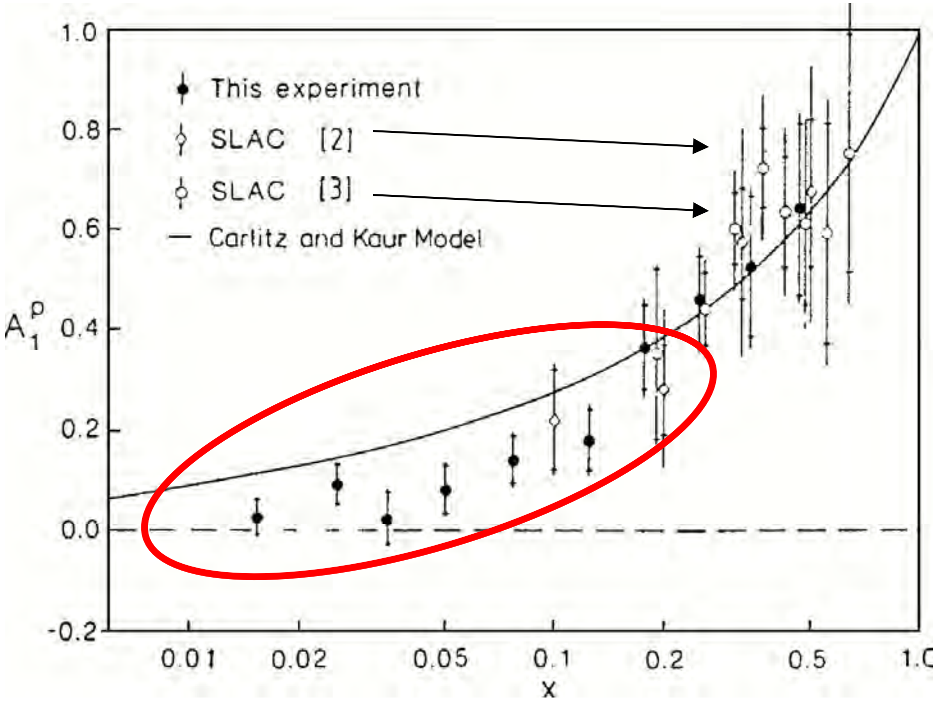
$$\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{measured} = P_{beam} \cdot P_{target} \cdot f \cdot A_{||}$$

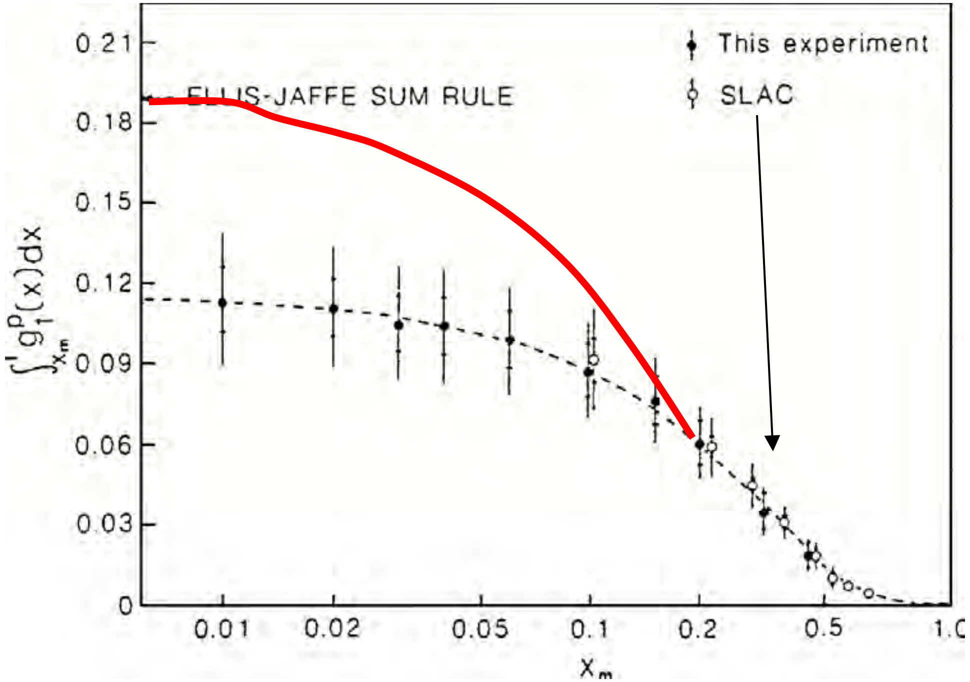
- f = dilution factor proportional to the polarizable nucleons of interest in the target "material" used, for example for $NH_{3,}$ f=3/17

$$g_1 \approx \frac{A_{||}}{D} \cdot F_1 \approx \frac{A_{||}}{D} \frac{F_2}{2 \cdot x} \qquad \int_0^1 g_1^p(x, Q_0^2)dx = \Gamma_1^p(Q_0^2)$$

- D is the depolarization factor, kinematics, polarization transfer from polarized lepton to photon, D ~ y^2

Proton Spin Crisis (1989)!



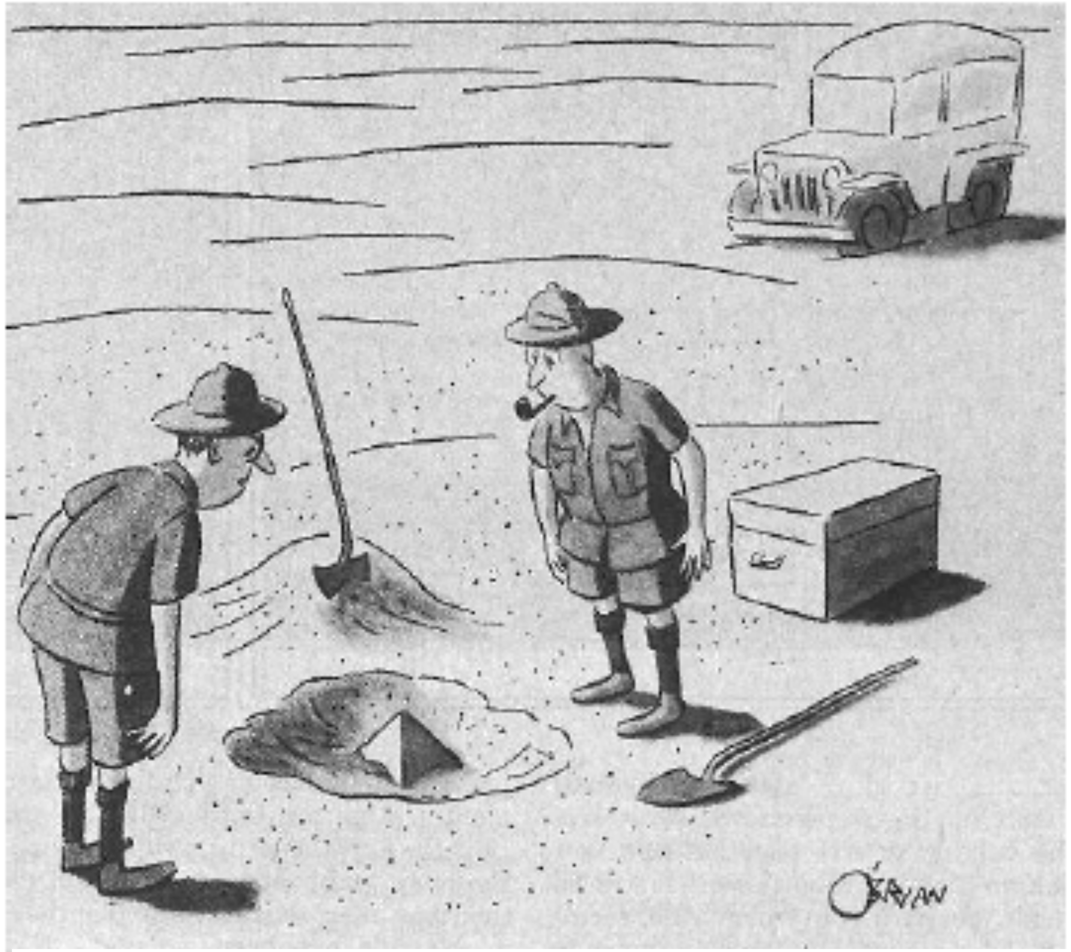


$\Delta\Sigma = (0.12)$ +/- (0.17) (EMC, 1989)

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

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

How significant is this?



of course, on how far down it goes.

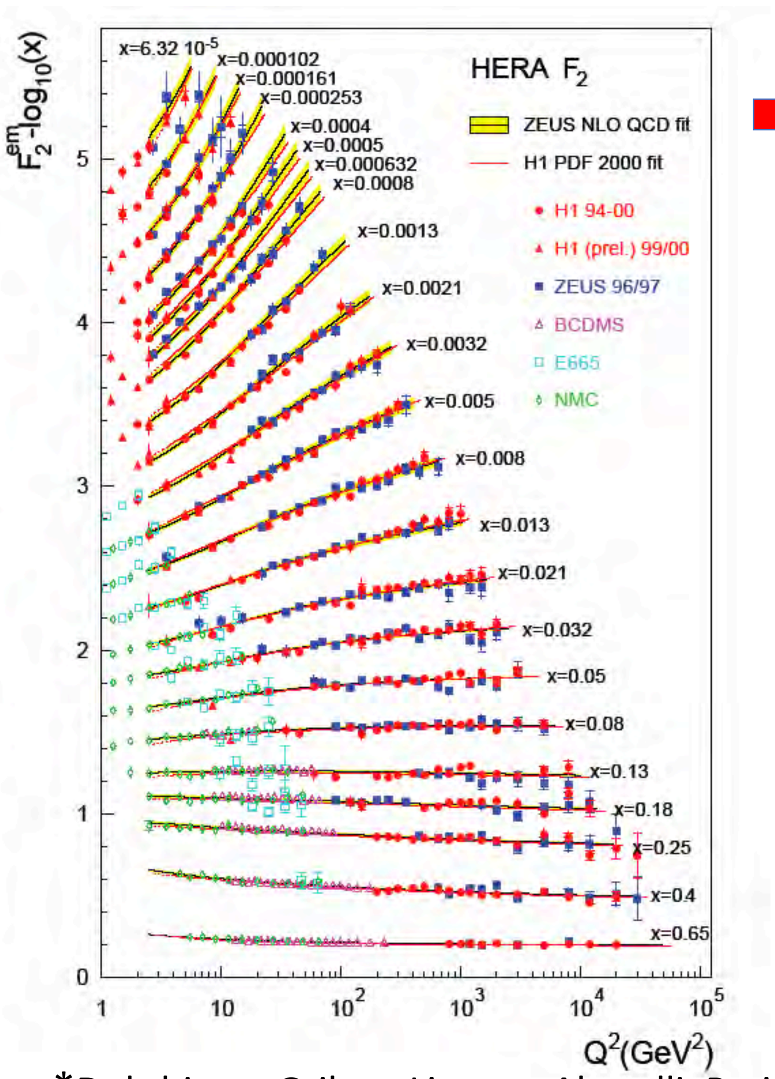
"It could the discovery of the century. Depending, of course on how far below it goes…"

Measurement of unpolarized glue at HERA

F_2 Structure Function

Vs.

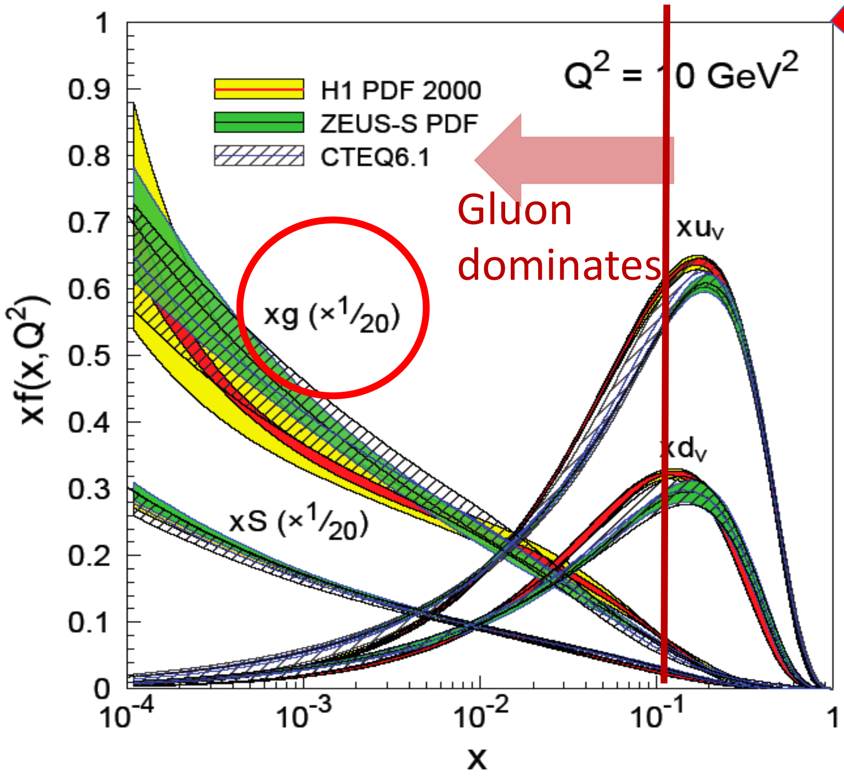
Q^2 mom. exchanged



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

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

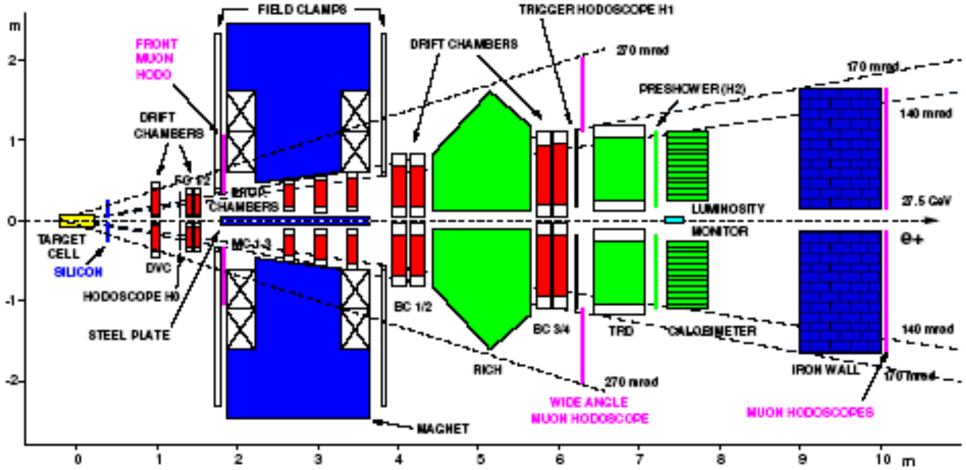
- NLO pQCD analyses: fits with **linear** DGLAP* equations



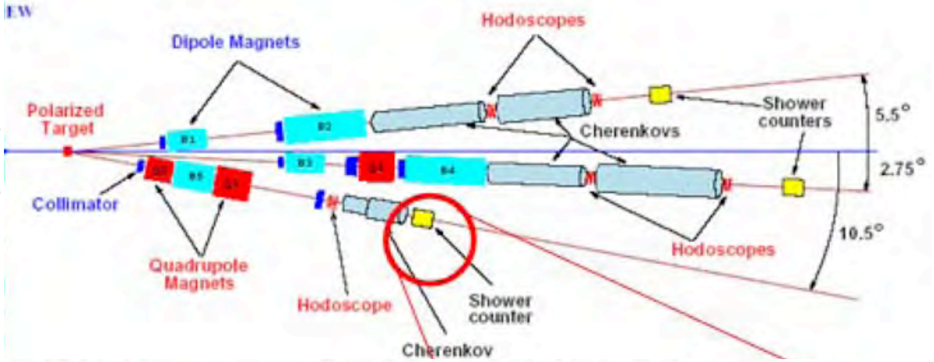
Gluon dominates

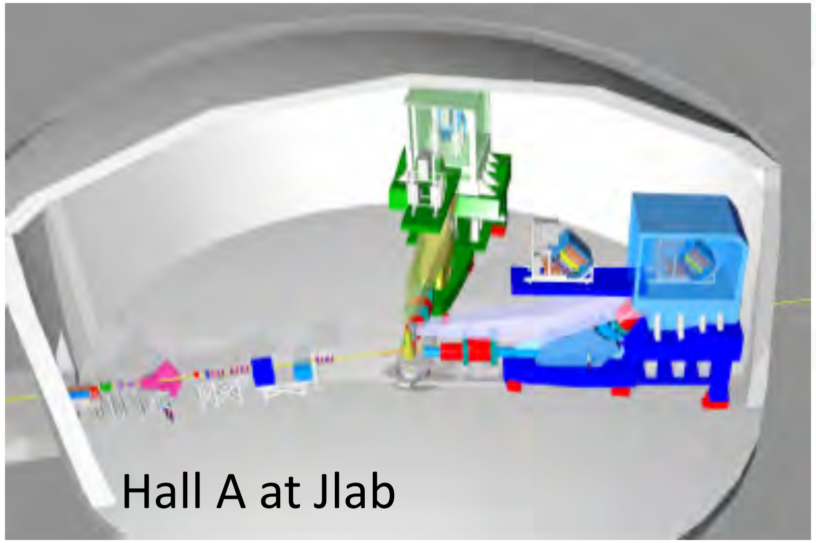
*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Experiments

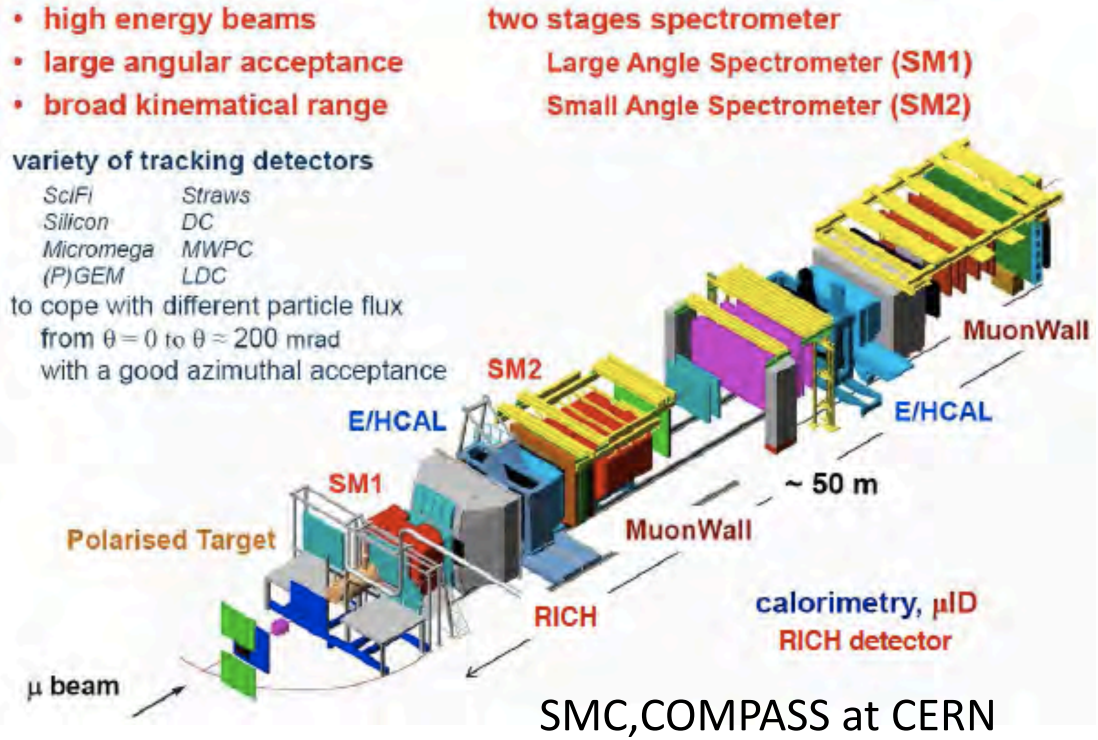


HERMES at DESY





Hall A at Jlab



- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

SciFi	Straws
Silicon	DC
Micromega	MWPC
(P)GEM	LDC

to cope with different particle flux from θ = 0 to θ ≈ 200 mrad with a good azimuthal acceptance

calorimetry, μID

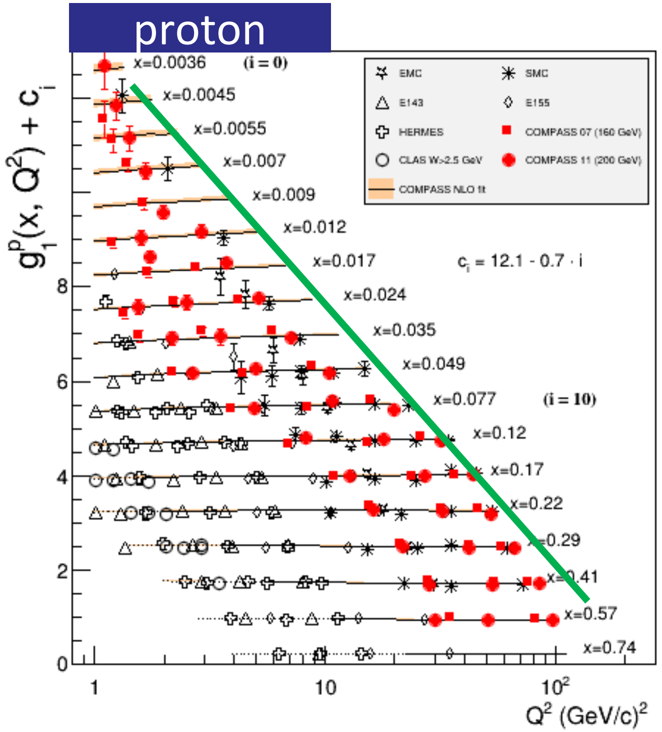
RICH detector

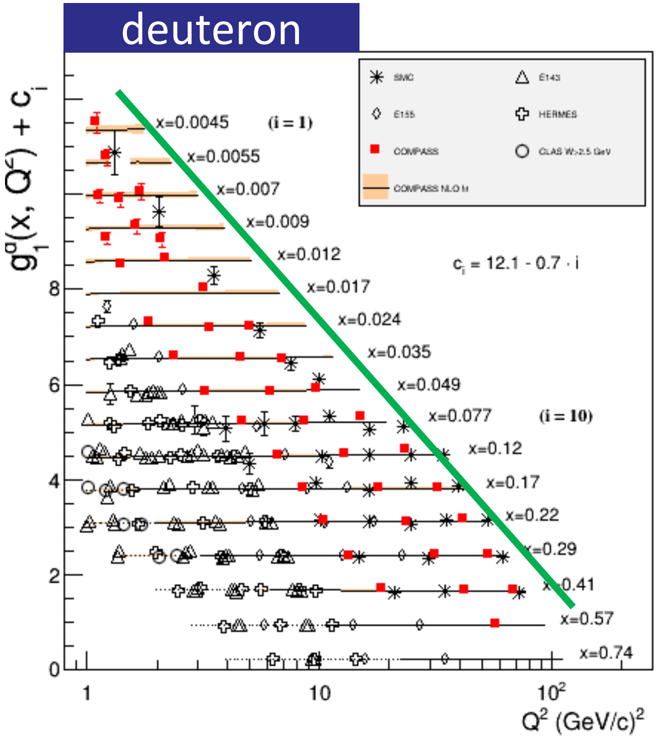
SMC,COMPASS at CERN

QCD fits- World data on g_1^p and g_1^d

→ $g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$$\frac{dg_1}{d\ln Q^2} \propto -\Delta g(x, Q^2)$$





x and Q^2 coverage not yet sufficient for precise Δg

Can be improved by constraining from pp data (as DSSV, NNPDF…)

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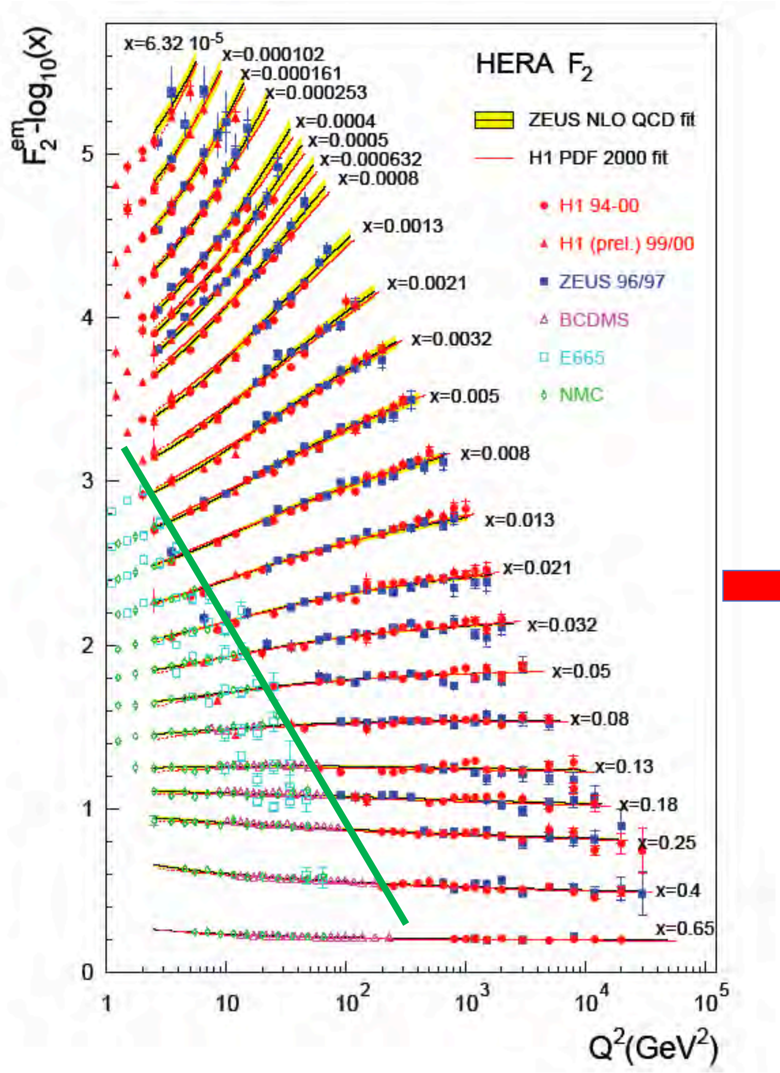
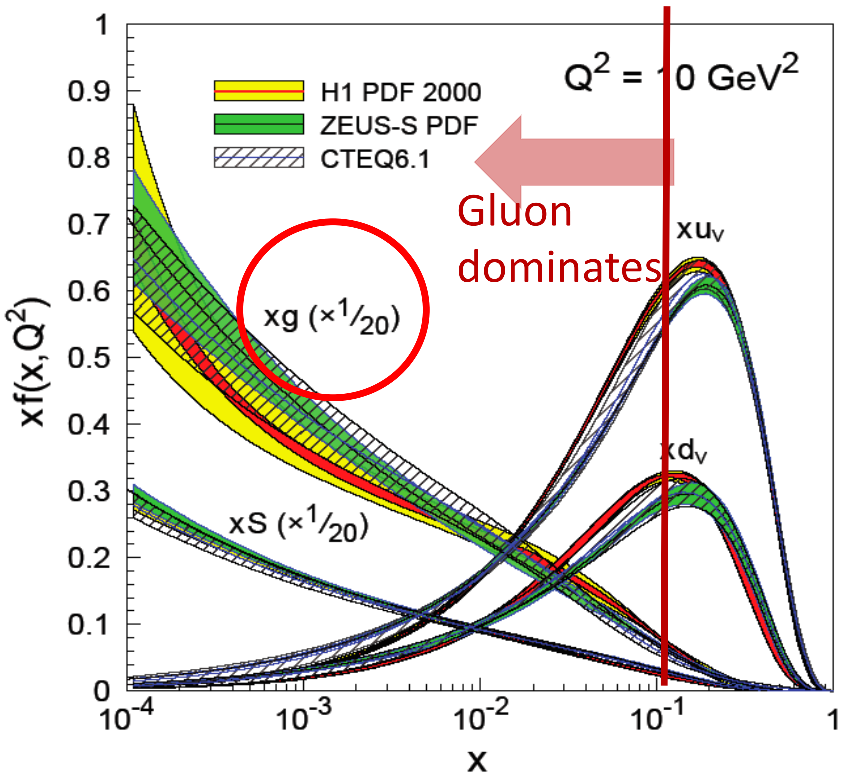
Similar to extraction of PDFs at HERA

(RECALL)



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

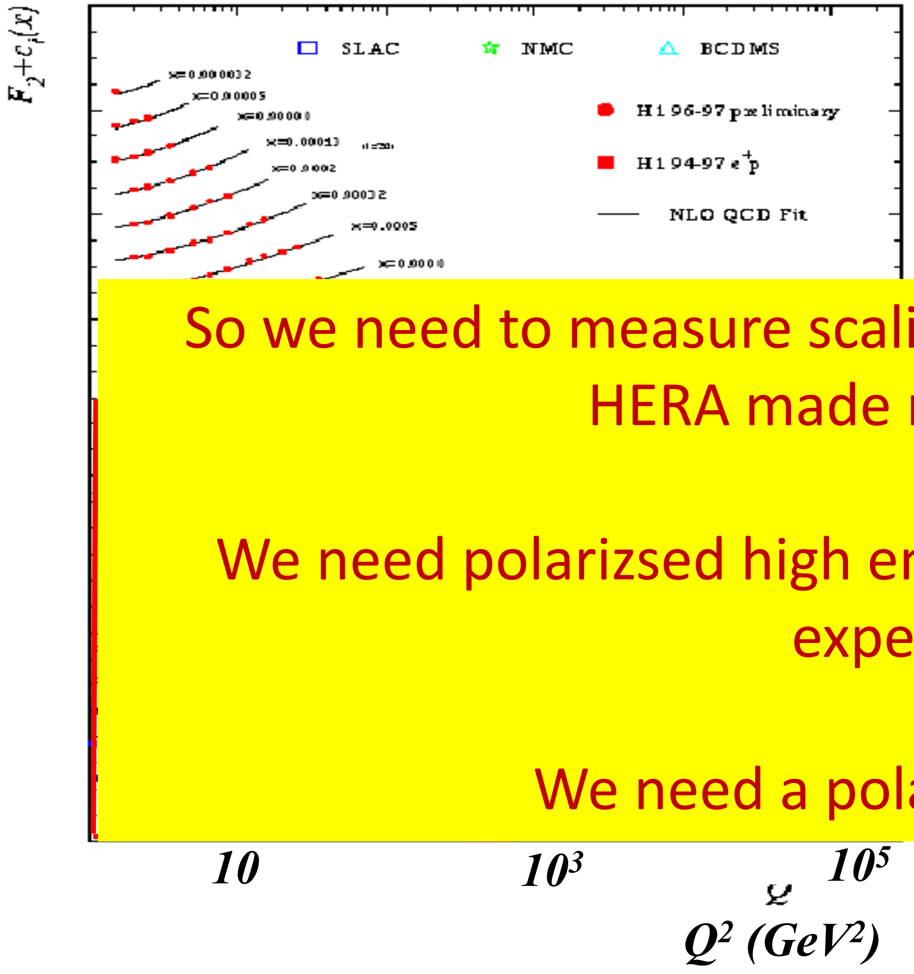


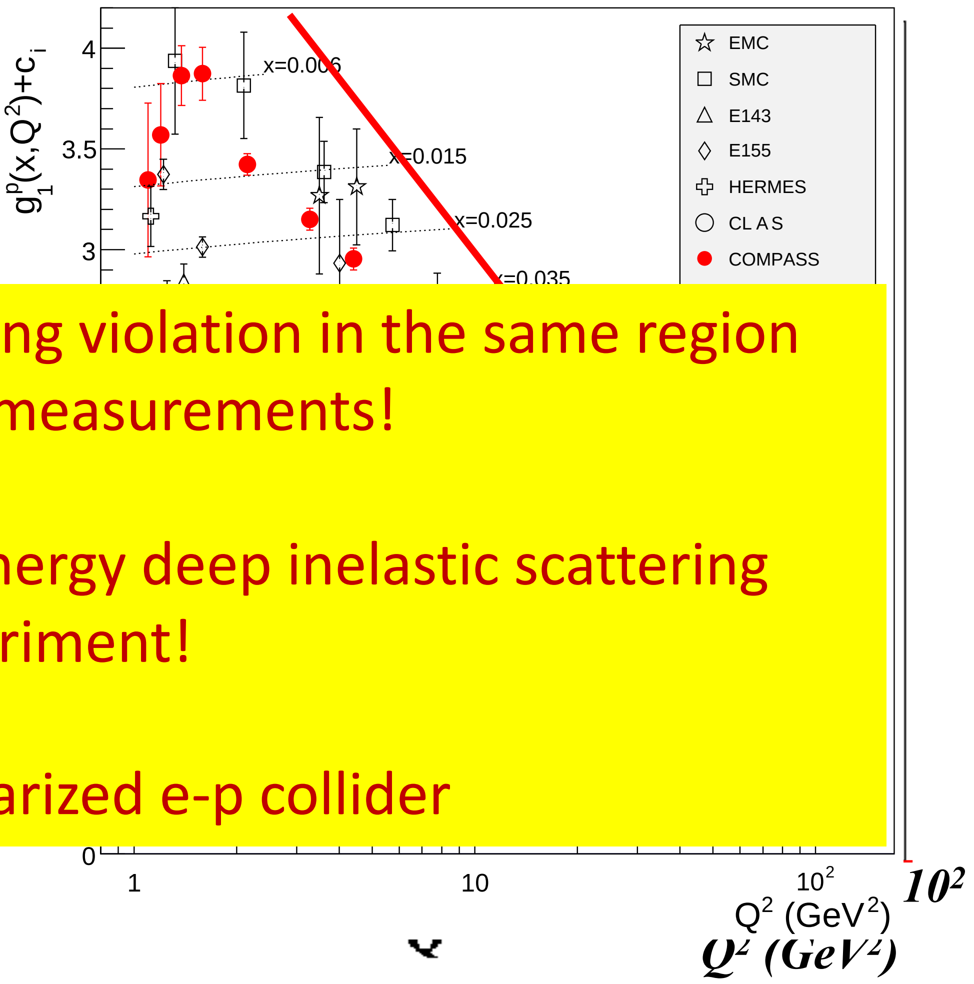
Gluon dominates

*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

F_2 vs. g_1 structure function measurements

Aidala et al.1209.2803v2





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

We need polarizsed high energy deep inelastic scattering experiment!

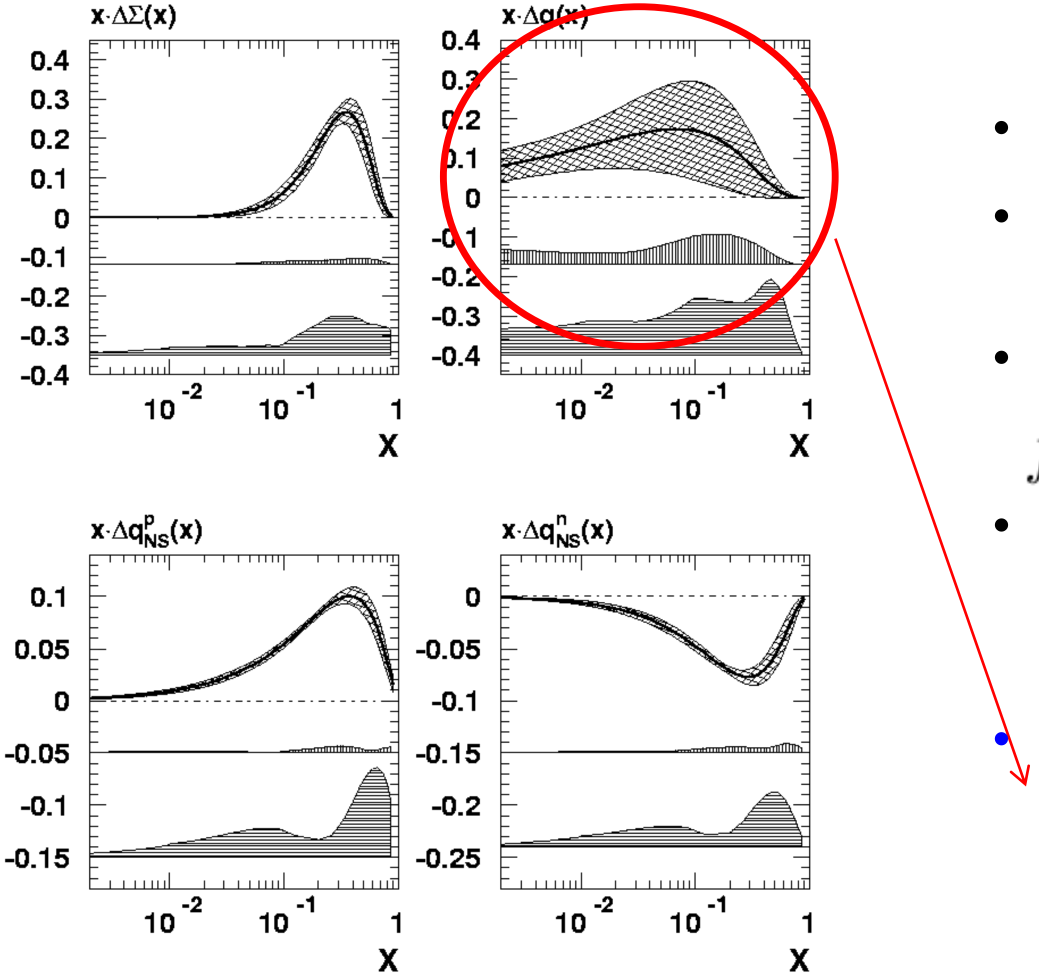
We need a polarized e-p collider

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

Global analysis of Spin SF

ABFR analysis method by
SMC PRD 58 112002 (1998)



- World's all available g_1 data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP

$$f(x) = x^{\alpha}(1-x)^{\beta}(1+ax+bx^2)$$

- Quark distributions fairly well determined, with small uncertainty
  - $\Delta\Sigma$ = 0.23 +/- 0.04
- Polarized Gluon distribution has largest uncertainties
  - ΔG = 1 +/- 1.5

Consequence:

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

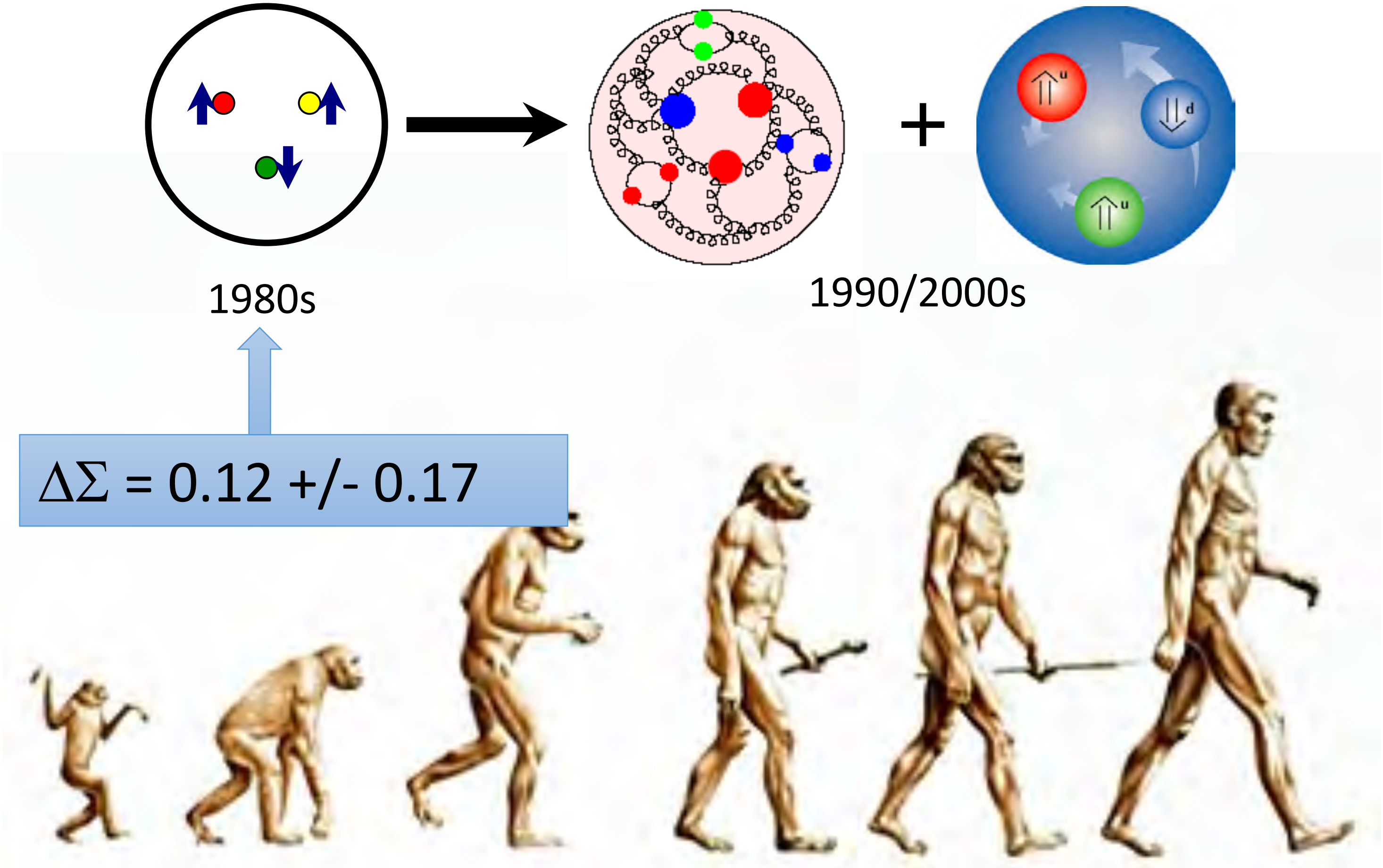
$$\Delta\Sigma = 0.30 \pm 0.05$$

- 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

Evolution: Our Understanding of Nucleon Spin



1980s

1990/2000s

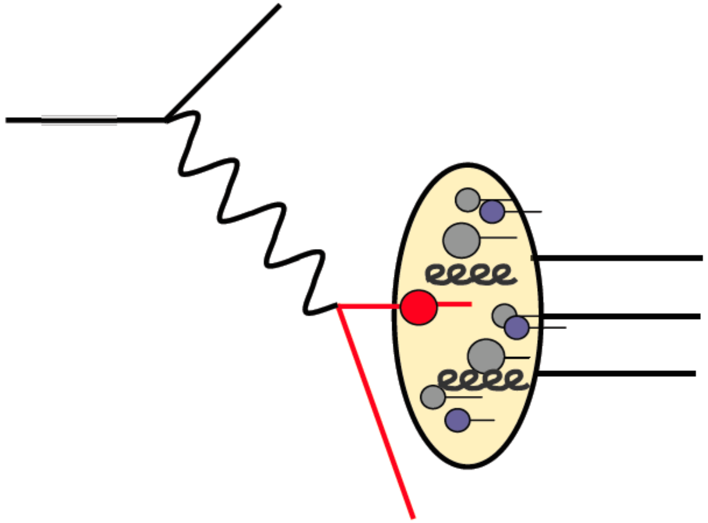
$\Delta\Sigma$ = 0.12 +/- 0.17

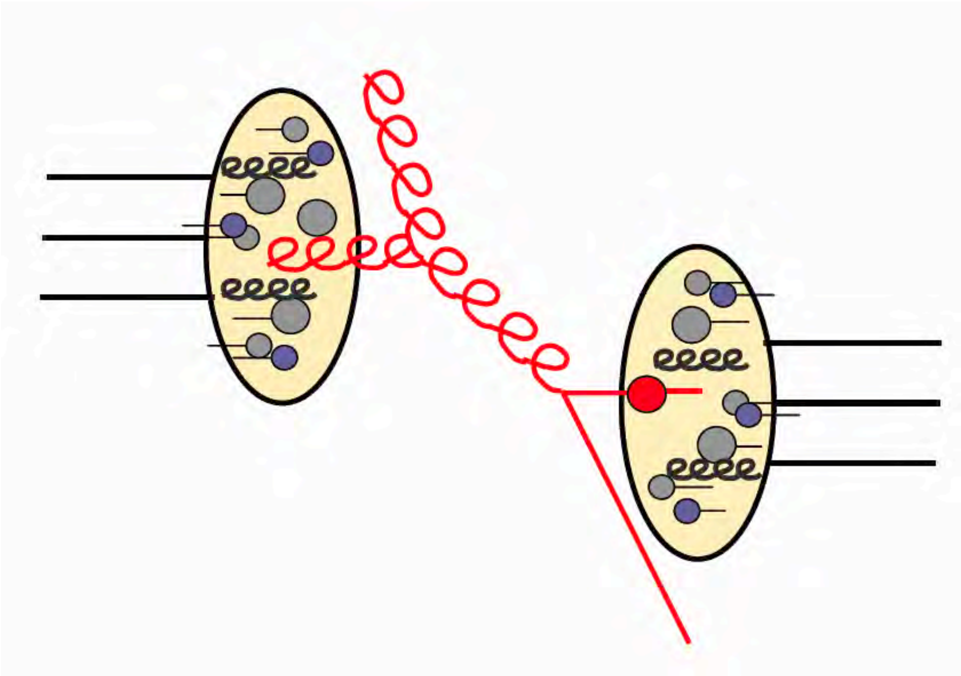
We have come a long way, but do we understand nucleon spin?

RHIC Spin program and the Transverse Spin puzzle

Evidence for transverse spin had been observed but ***ignored*** for almost 3 decades…

Complementary techniques



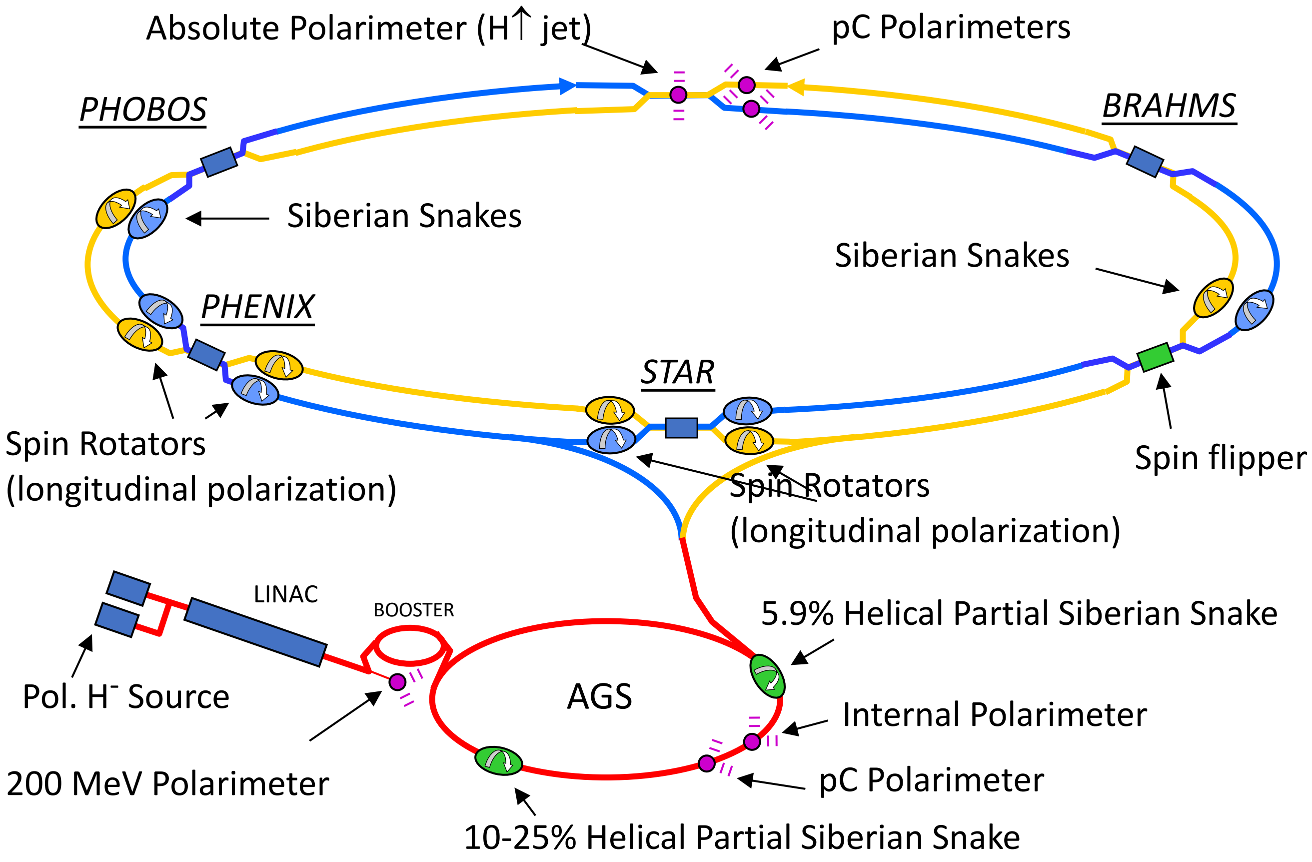


Photons colorless: forced to interact at NLO with gluons

Can’t distinguish between quarks and anti-quarks either

Why not use polarized quarks and gluons abundantly available in protons as probes ?

RHIC as a Polarized Proton Collider

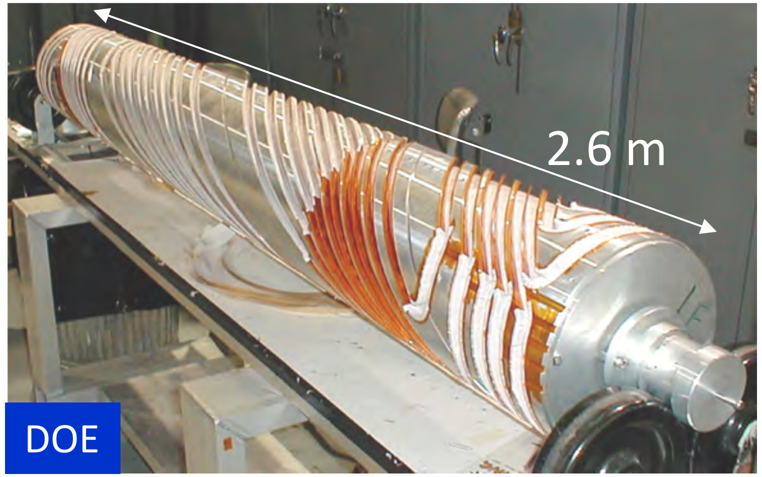


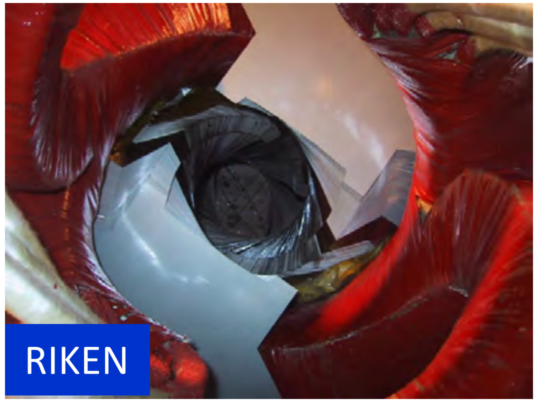
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances

With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances

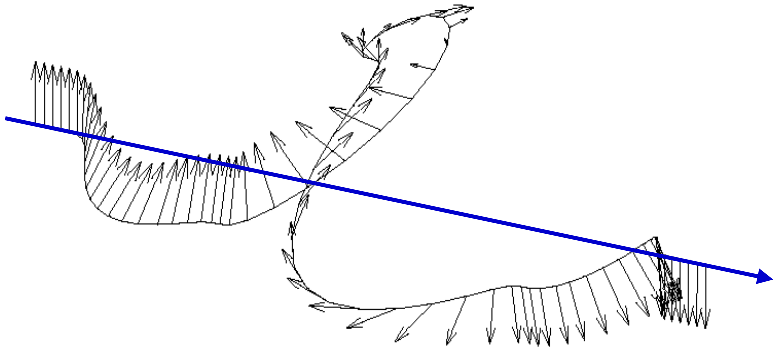
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

Siberian Snakes

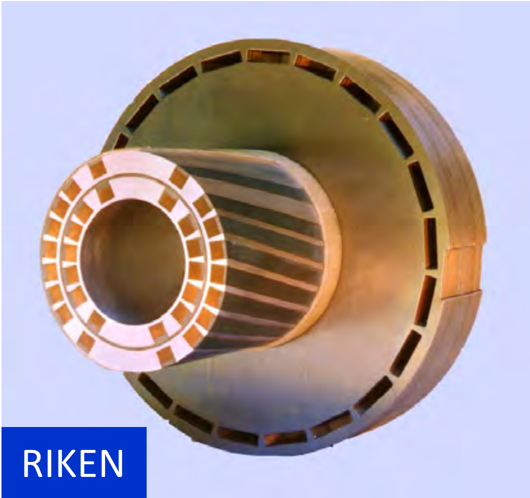




- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist

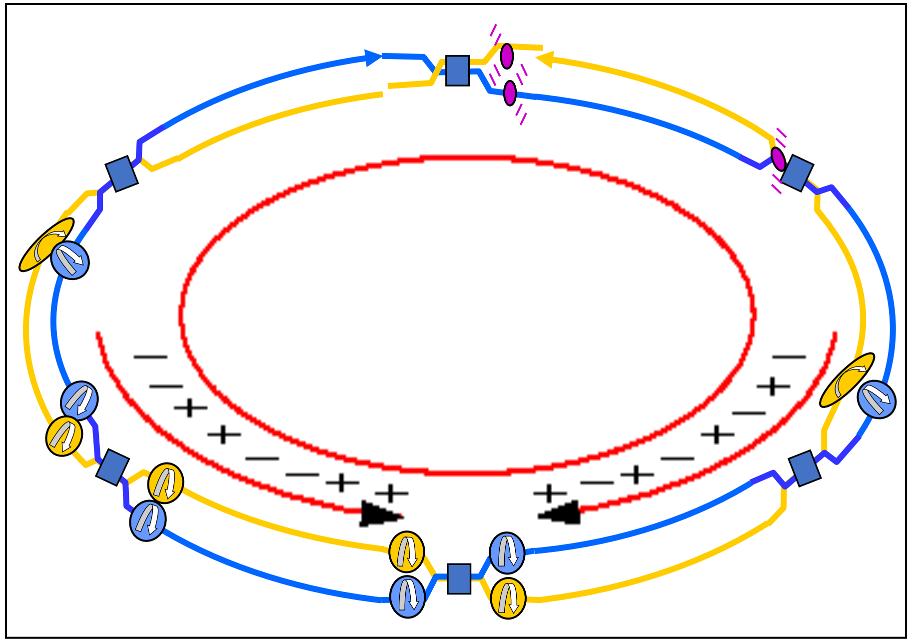


Courtesy of A. Luccio



Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



(N) Yield
(R) Relative Luminosity
(P) Polarization

Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

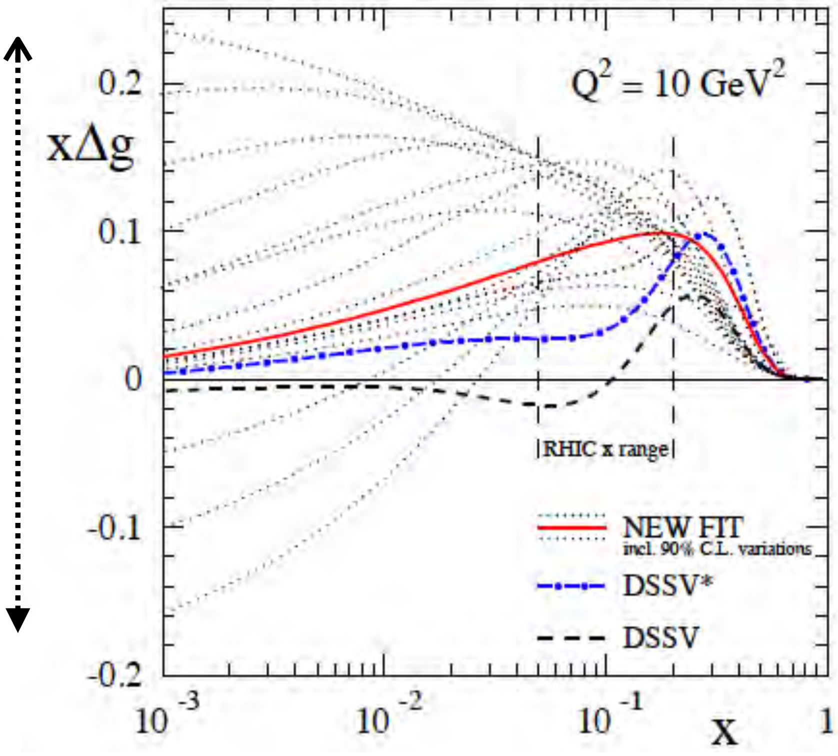
✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time
⇒ Possibility for false asymmetries are greatly reduced

Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

$\Delta G = 0.2$ +/- 0.02 +/- 0.5

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.



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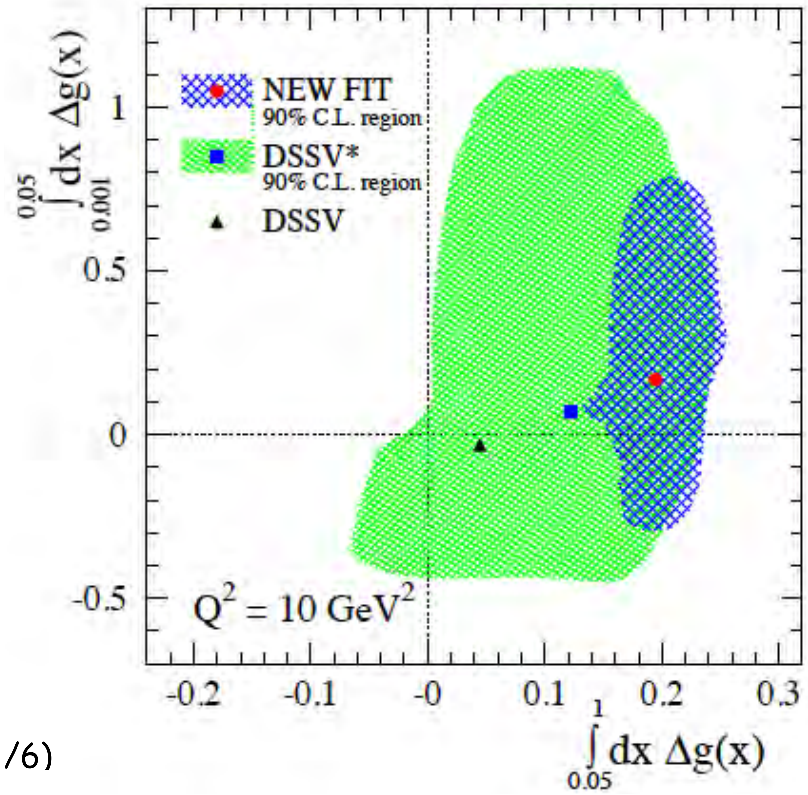
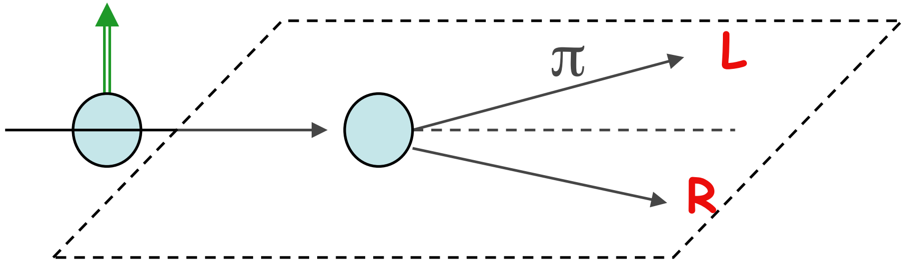


While RHIC made a huge impact on ΔG

large uncertainties to remain in the low-x unmeasured region!

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

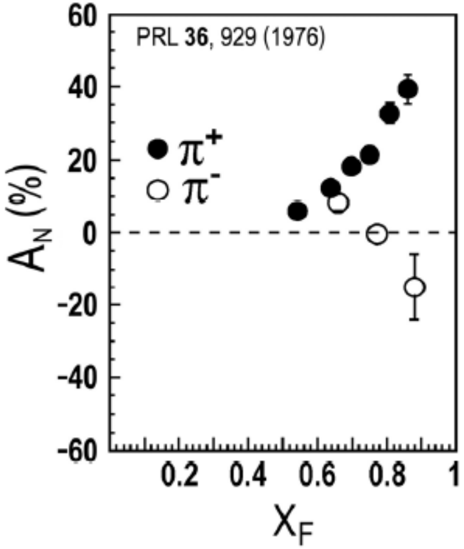
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

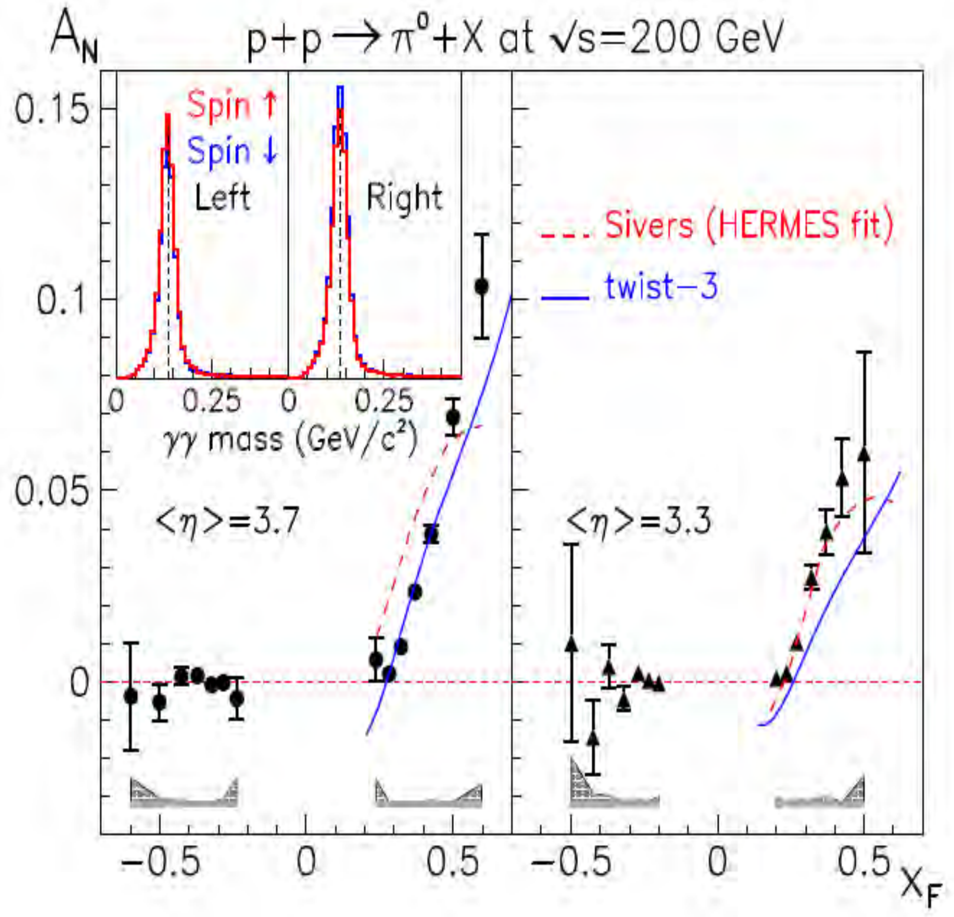
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was “neglected” as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

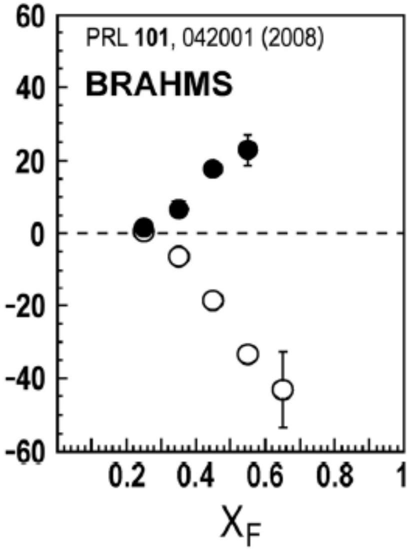
Pion asymmetries: at most CM energies!

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

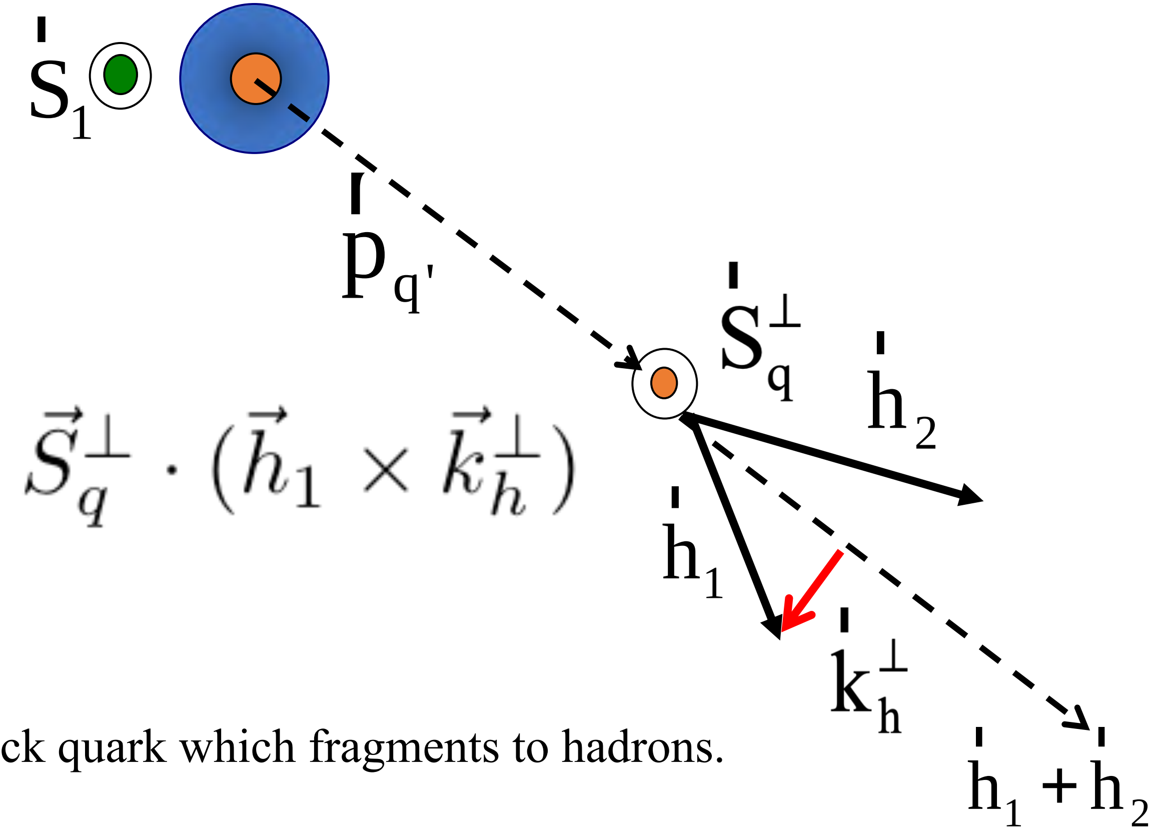


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Example: $\boxed{p^{\uparrow} + p \rightarrow h_1 + h_2 + X}$

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

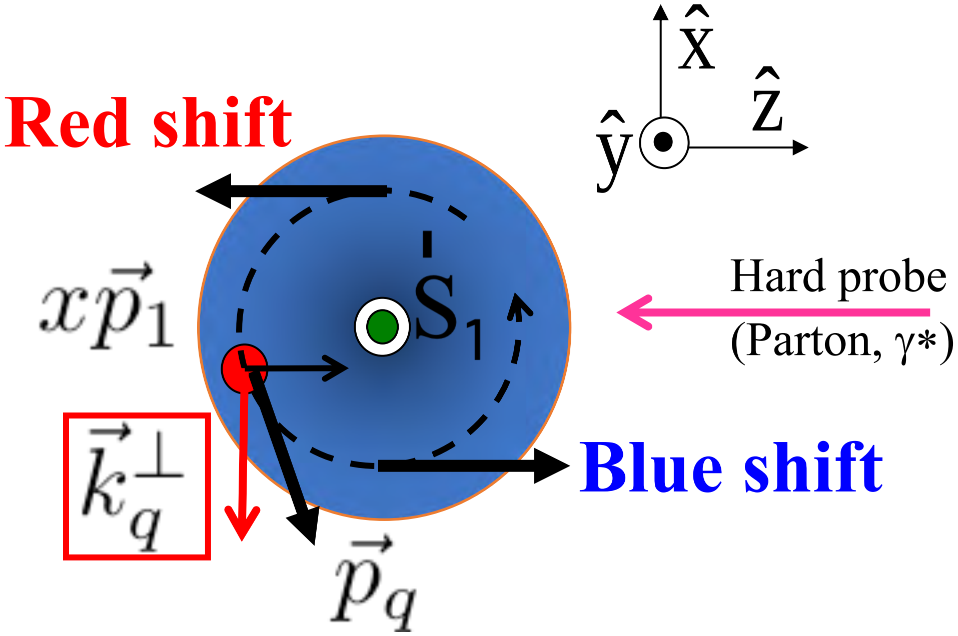


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

What does "Sivers effect" probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005

Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$f_{1T}^{\perp}(x, \vec{k}_q^{\perp})$

hep-ph/ 0703176

Quark Orbital angular momentum

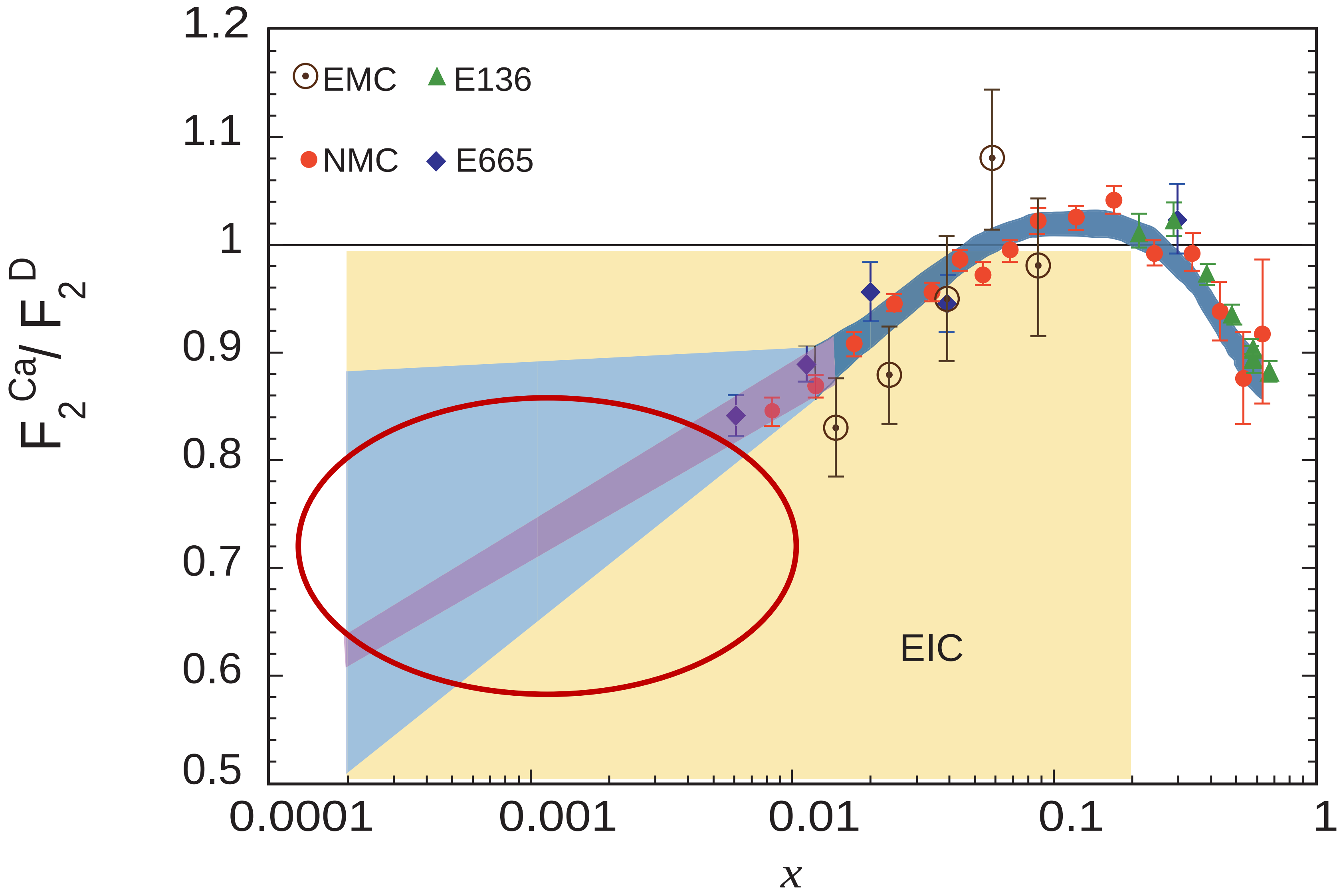
Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

Lepton nucleus scattering for understanding the nuclear structure and dynamics:

Nuclear structure a known unknown….

PDFs in nuclei are different than in protons!



Since 1980's we know the ratio of F_2's of nuclei to that of Deuteron (or proton) are different.

Nuclear medium modifies the PDF's.

Fair understanding of what goes on, in the x > 0.01.

However, what happens at low x?

Does this ratio saturate? Or keep on going? – Physics would be very different depending on what is observed.

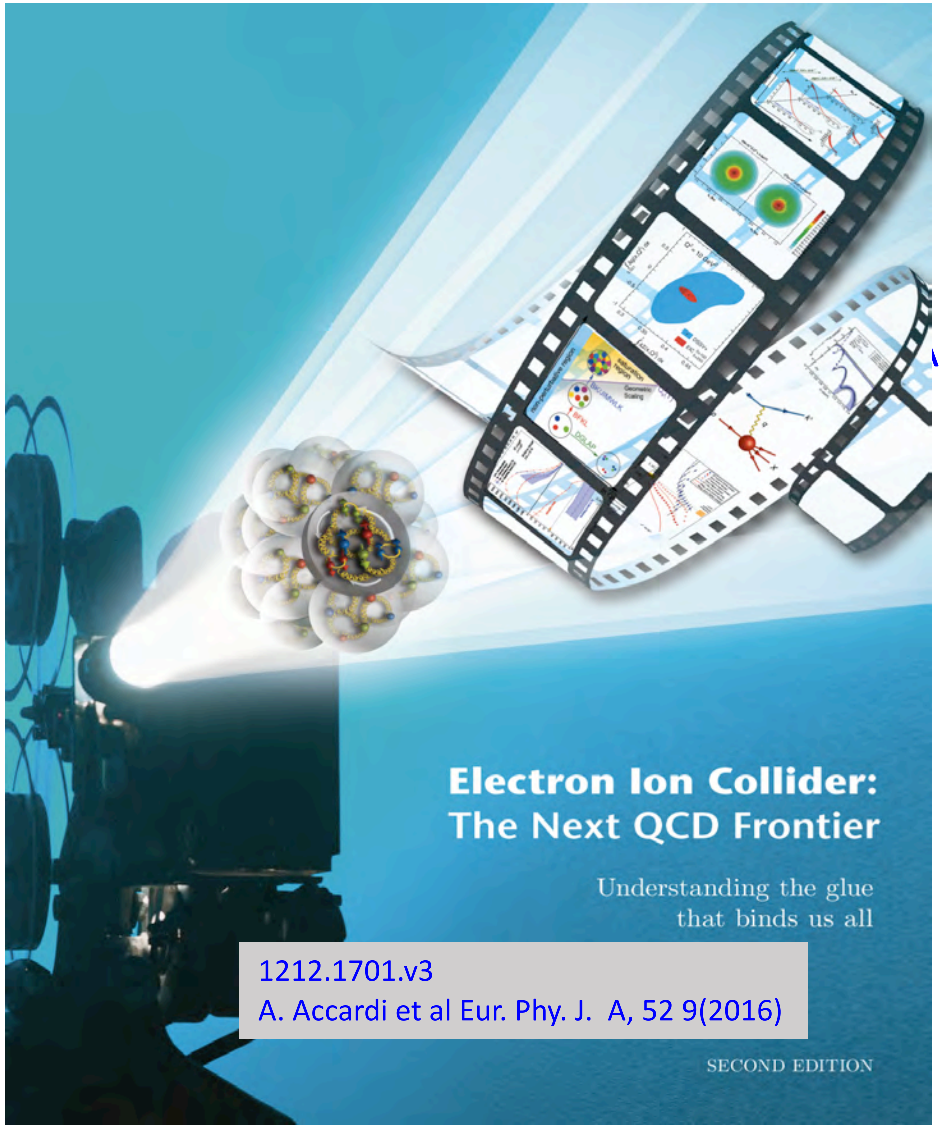
Data needed at low-x

Lessons learned:

- Proton and neutrons are not as easy to understand in terms of quarks, and gluons, as earlier anticipated:
  - Proton's spin is complex: alignment of quarks, gluons and possibly orbital motion
  - Proton mass: interactions amongst quarks and gluons, not discussed too much
- To fully understand proton structure (including the partonic dynamics) one needs to explore over a much broader x-Q2 range (not in fixed target but in collider experiment)
- e-p more precise than p-p as it probes with more experimental control and precision
- Low-x behavior of gluons in proton intriguing; Precise measurements of gluons critical.

We need a new polarized collider….

The Electron Ion Collider



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)