Center for Frontiers in Nuclear Science

Introduction to EIC (1)

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Lecture 1 of 2

CFNS Summer School 2022

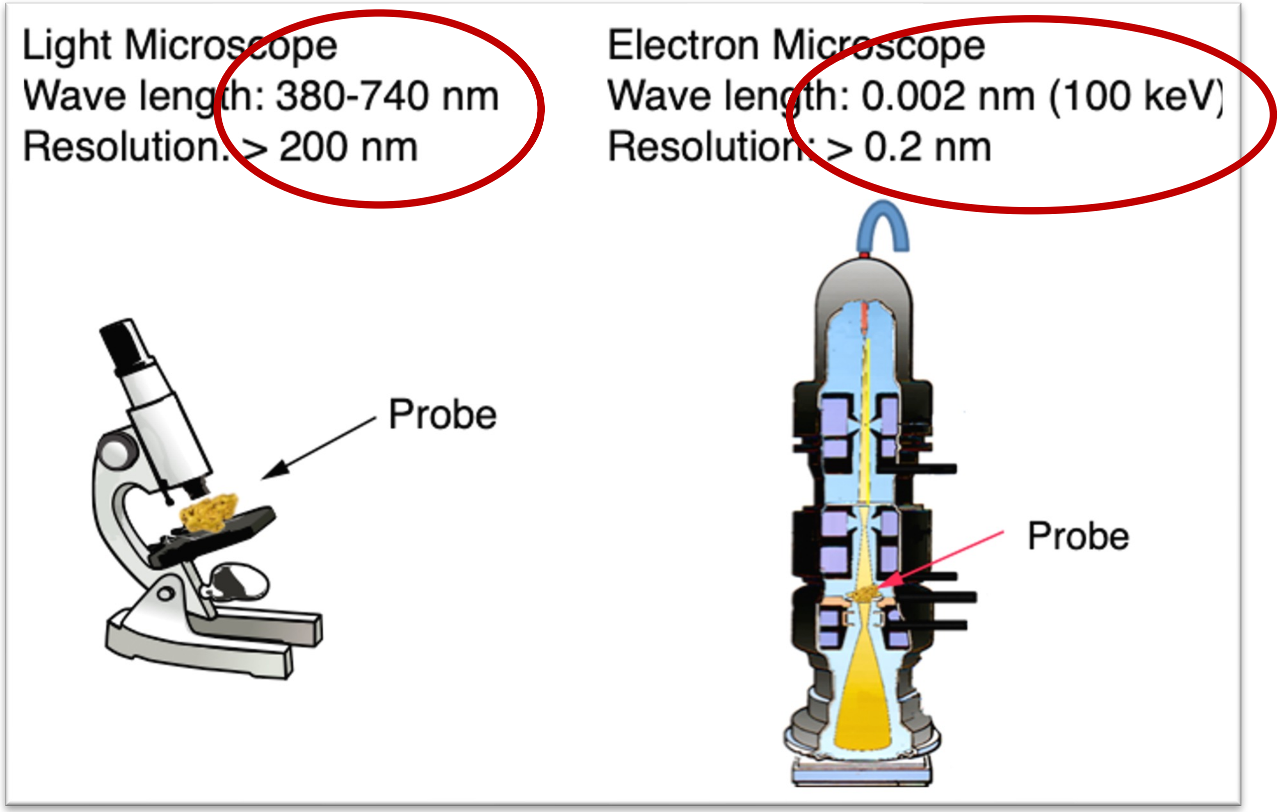
Stony Brook University

Brookhaven National Laboratory

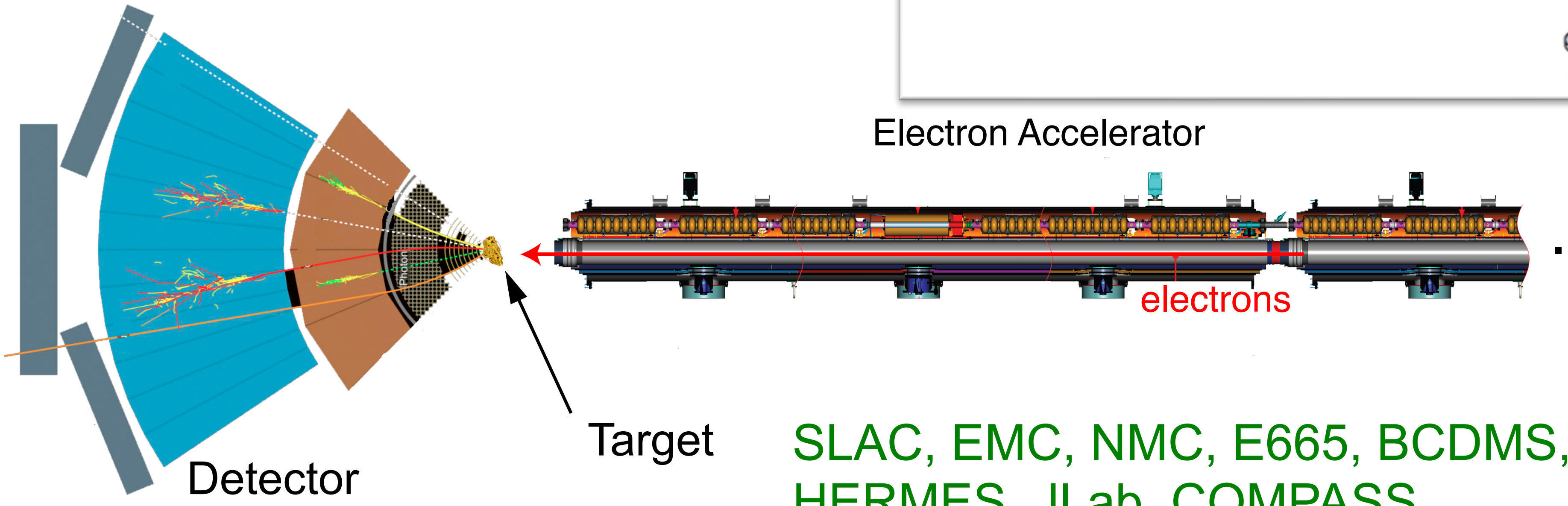
Introduction to EIC – two lectures

- Why EIC? (Lecture 1)
- What (is the) EIC? (Lecture 2)

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, …

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”

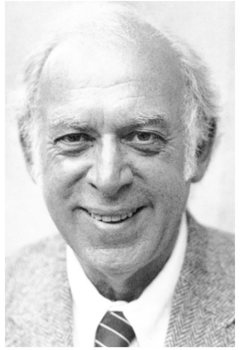


Photo from the Nobel Foundation archive.
Jerome I. Friedman
Prize share: 1/3

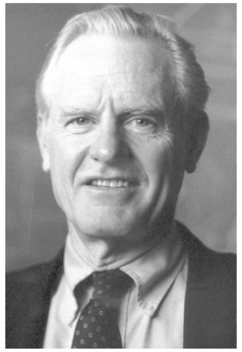
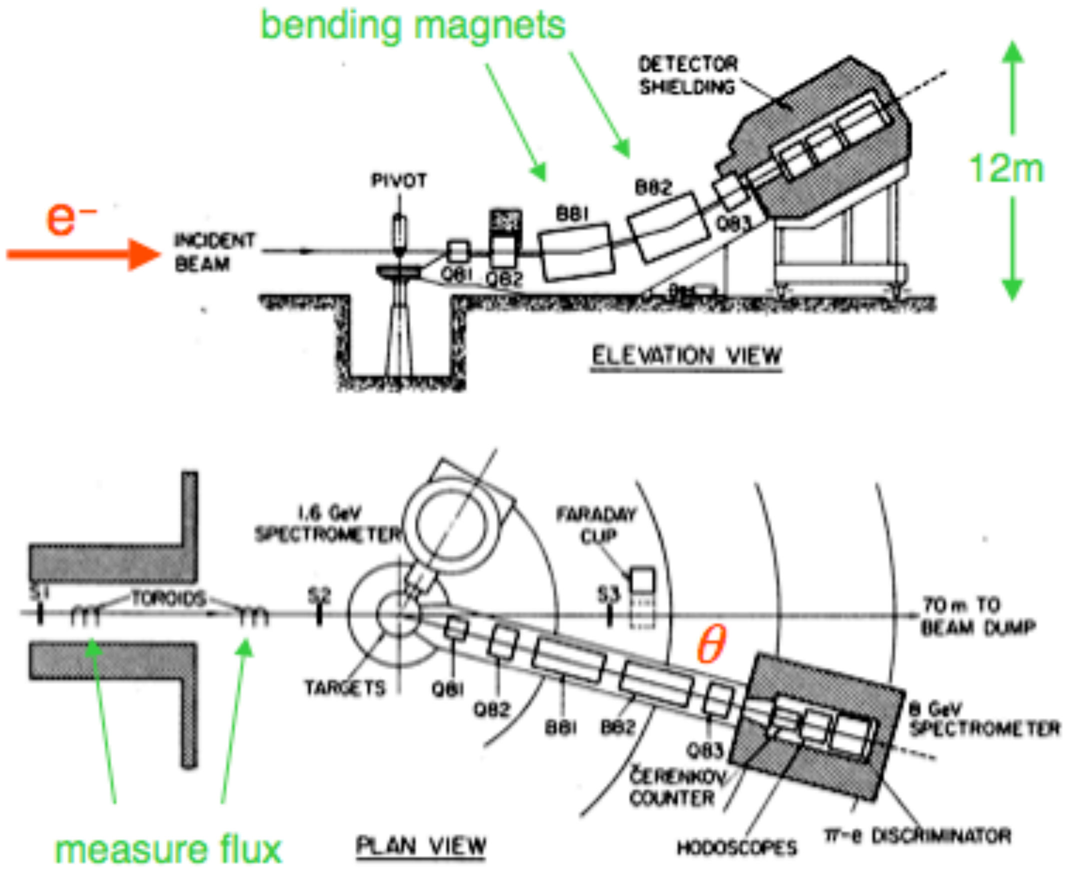


Photo from the Nobel Foundation archive.
Henry W. Kendall
Prize share: 1/3

Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

[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,

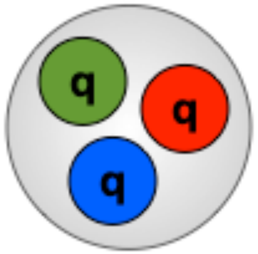
vary θ

The Static (Constituent) Quark Model

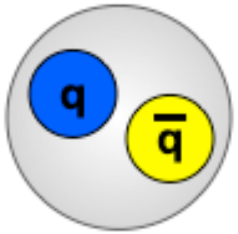
Quarks: spin 1/2 fermions, color charge

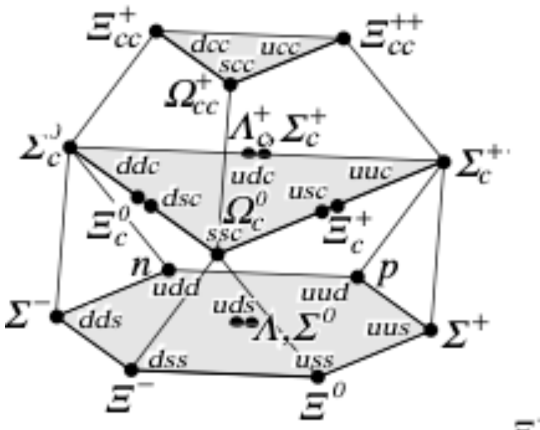
M. Gell-Mann,
K. Nishijima (> 1964)

Baryons:

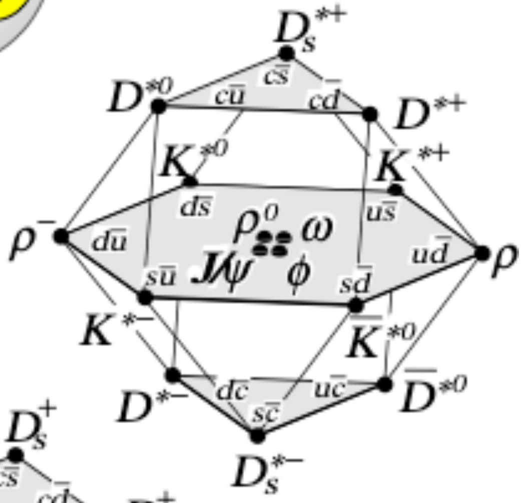


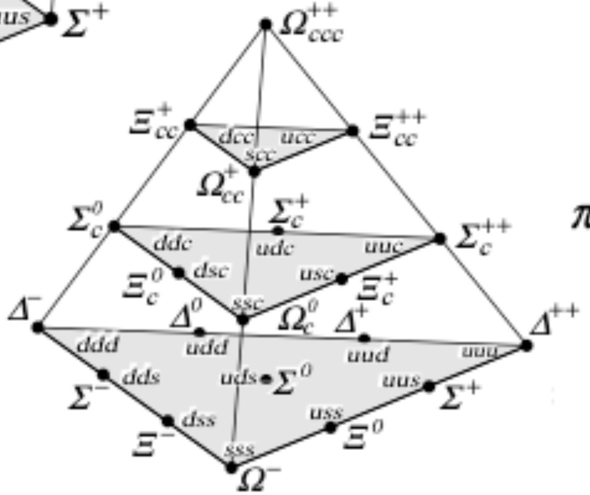
Mesons:

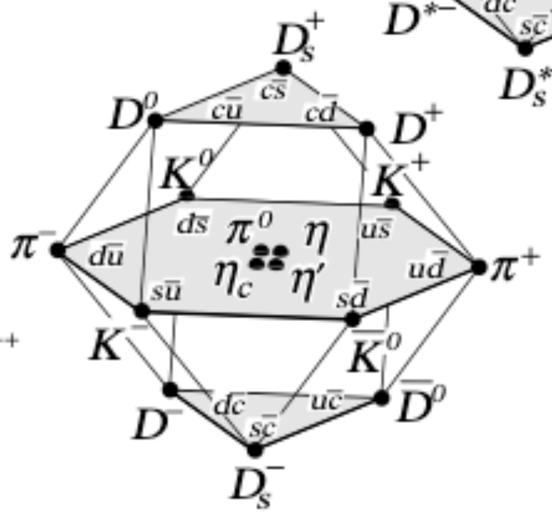




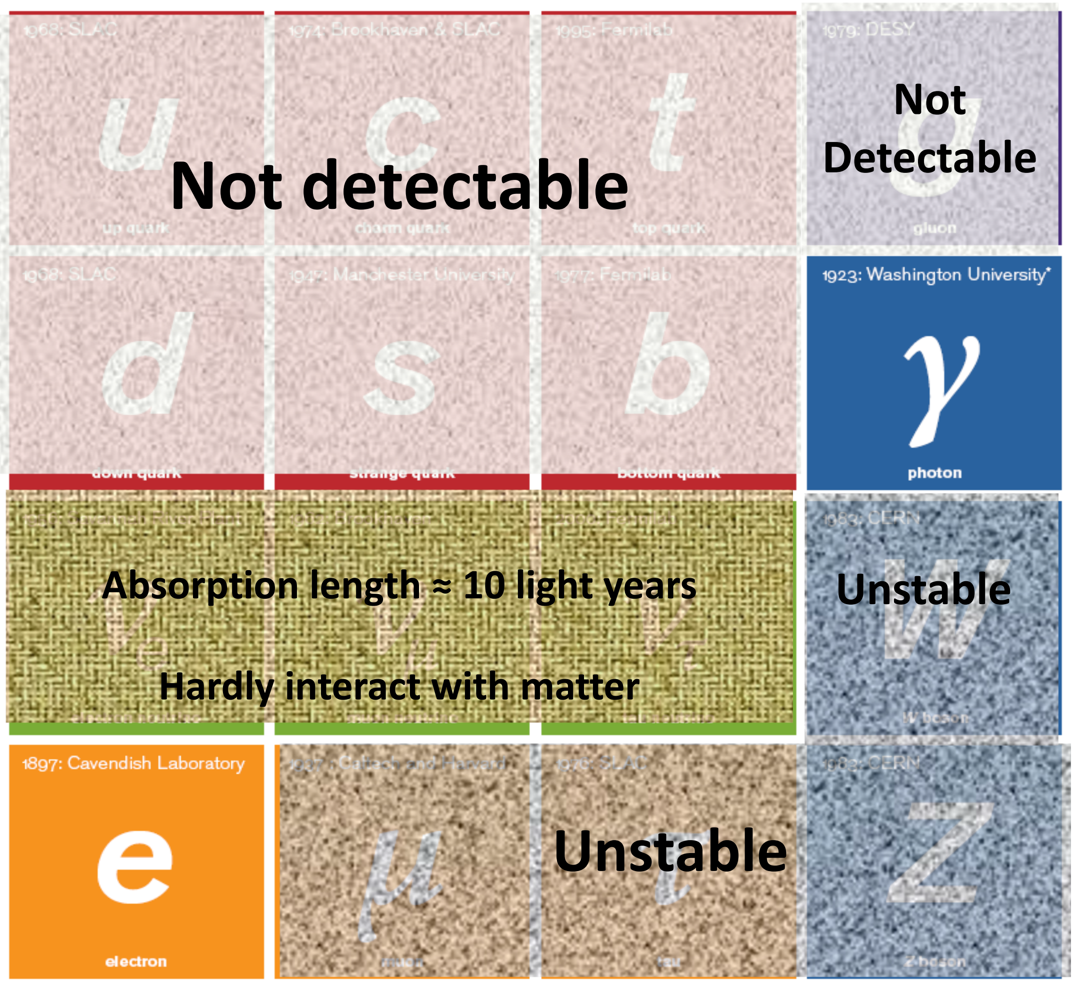
Eight-fold Way:
Account for every hadron we found so far







Difficulties in understanding our universe



Deep Inelastic Scattering (DIS)

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

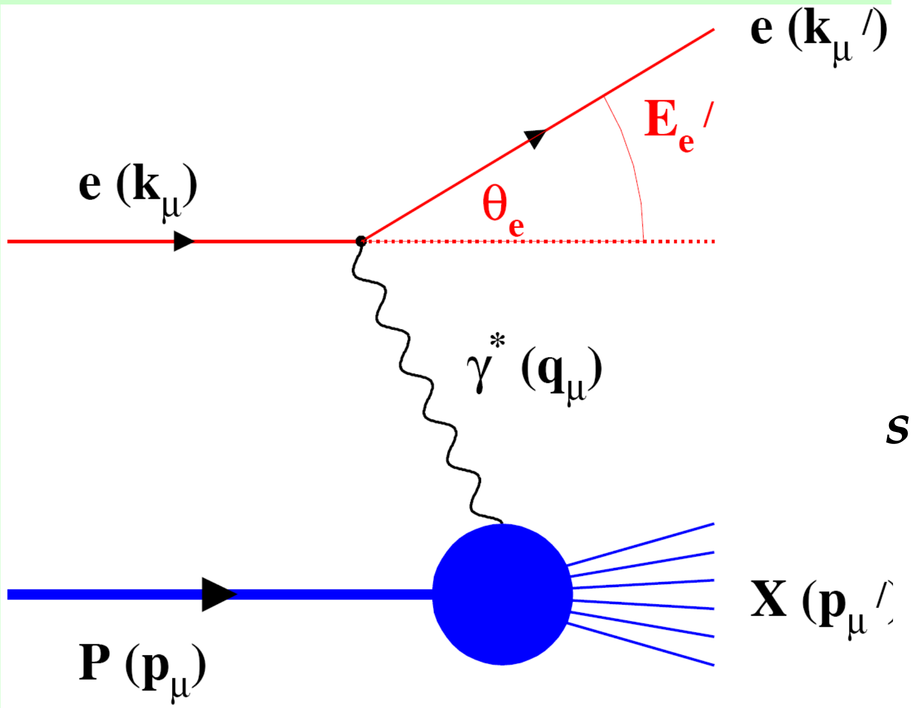
1) Violent collision of melons

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…

Unpolarized e-p/A DIS

DIS without Spin:

Inclusive Cross-Section:

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

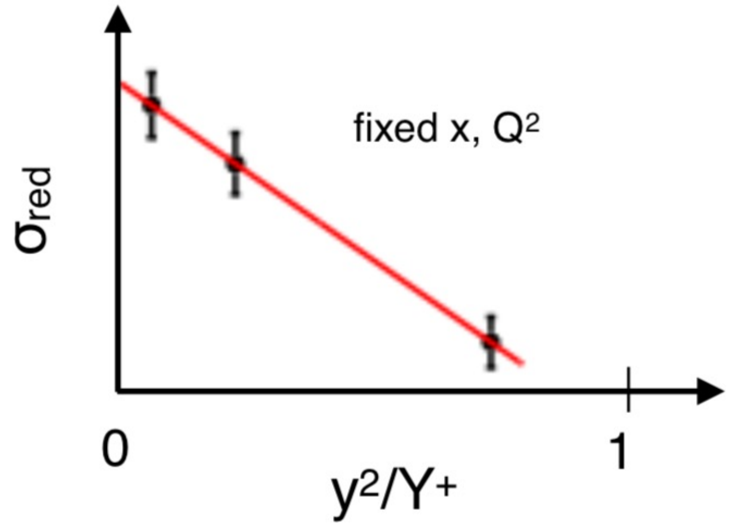
Reduced Cross-Section:

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

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

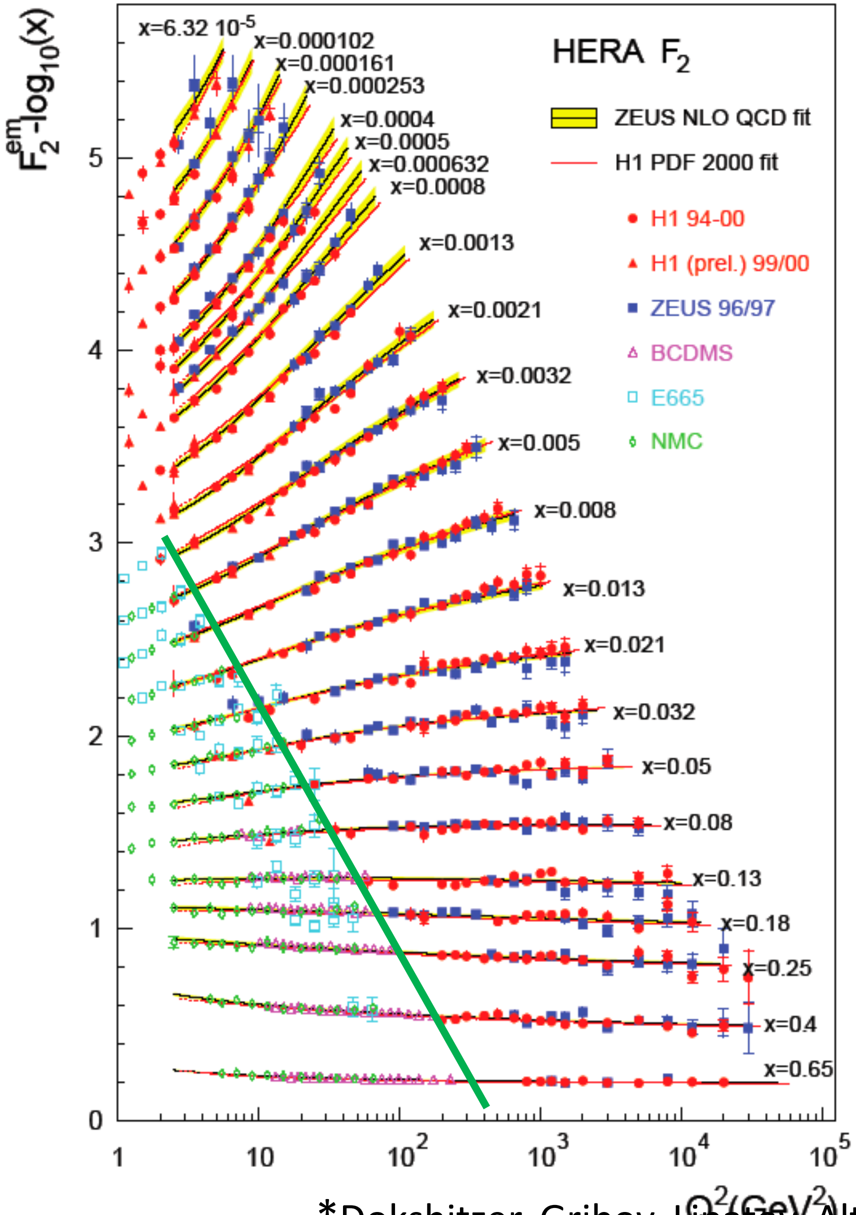
Rosenbluth Separation:

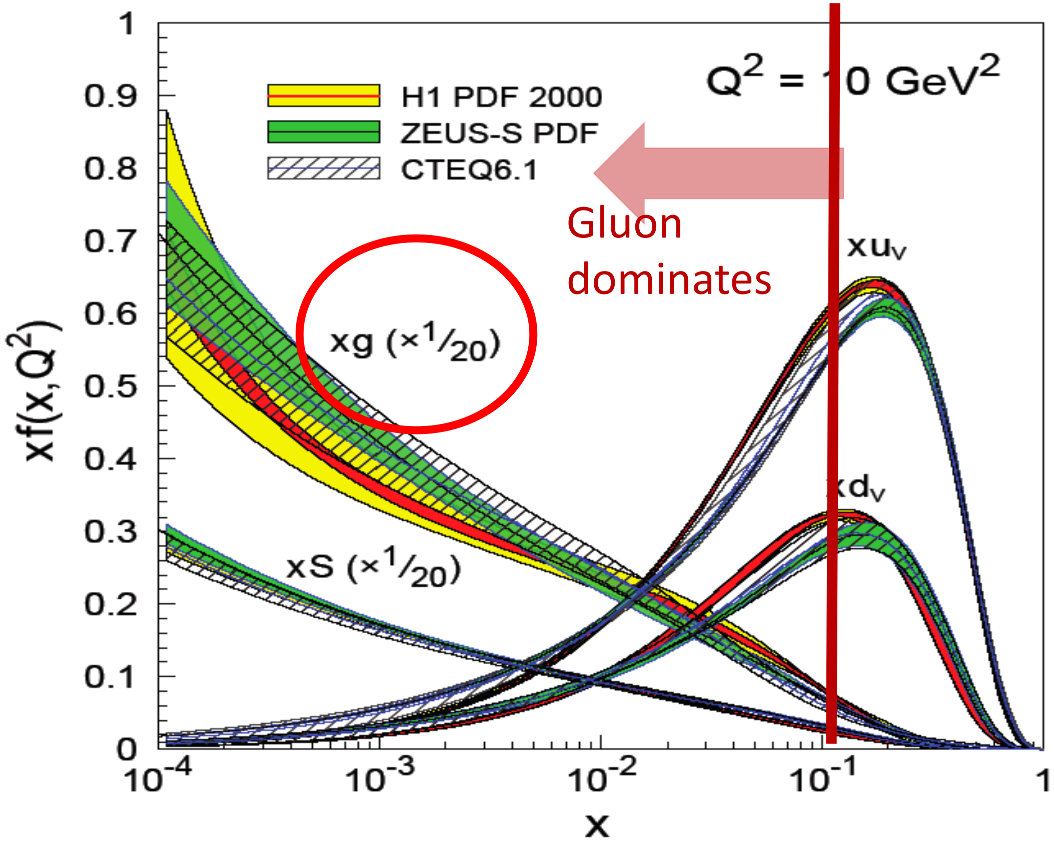
- Recall $Q^2 = x\, y\, s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$



Extraction of PDFs at HERA

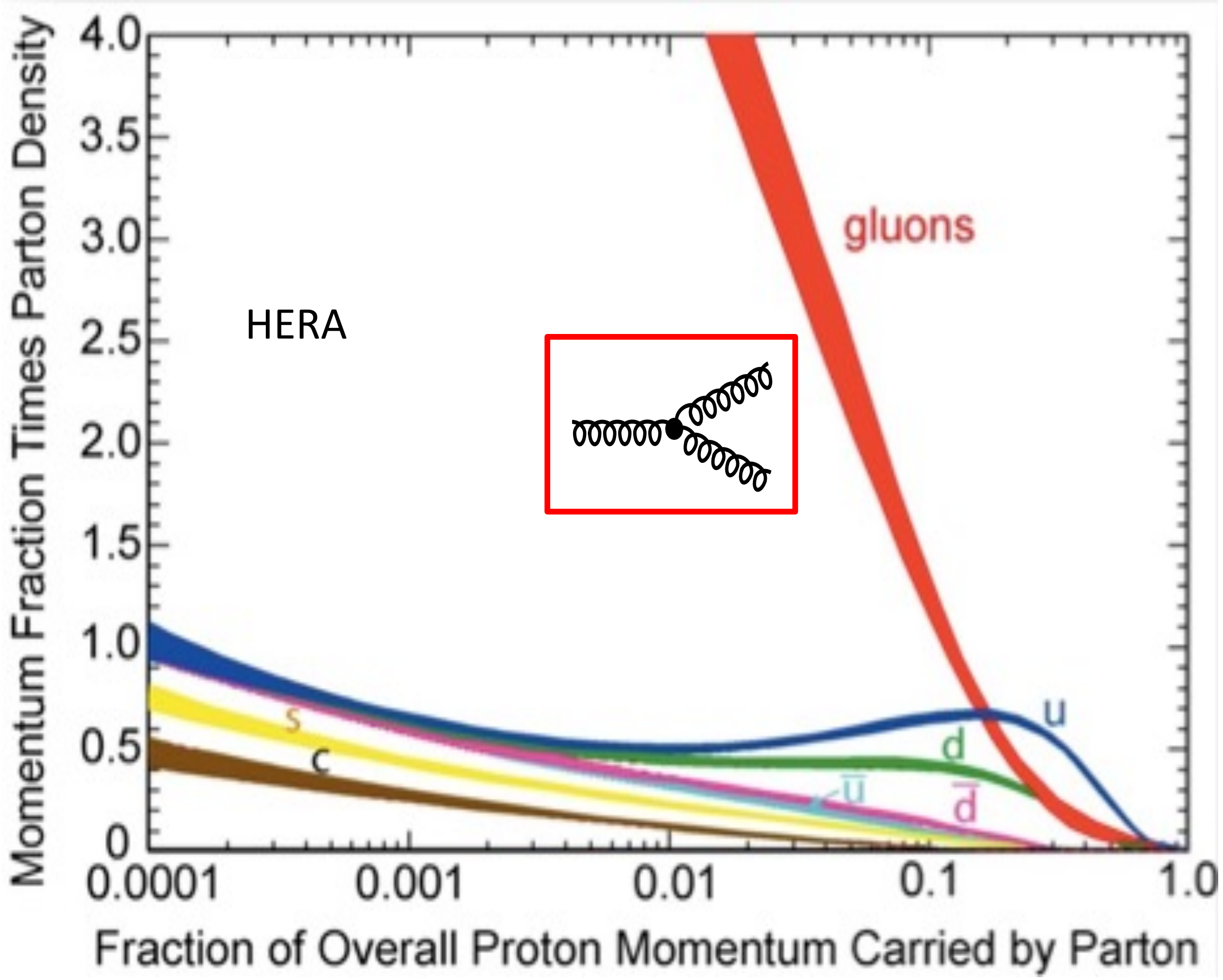
NLO pQCD analyses: fits with **linear** DGLAP* equations

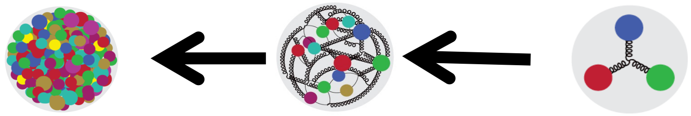




*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

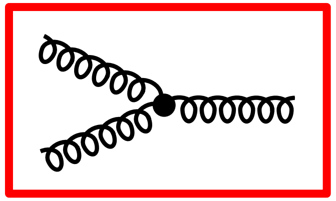
Gluons carry color – interact with each other



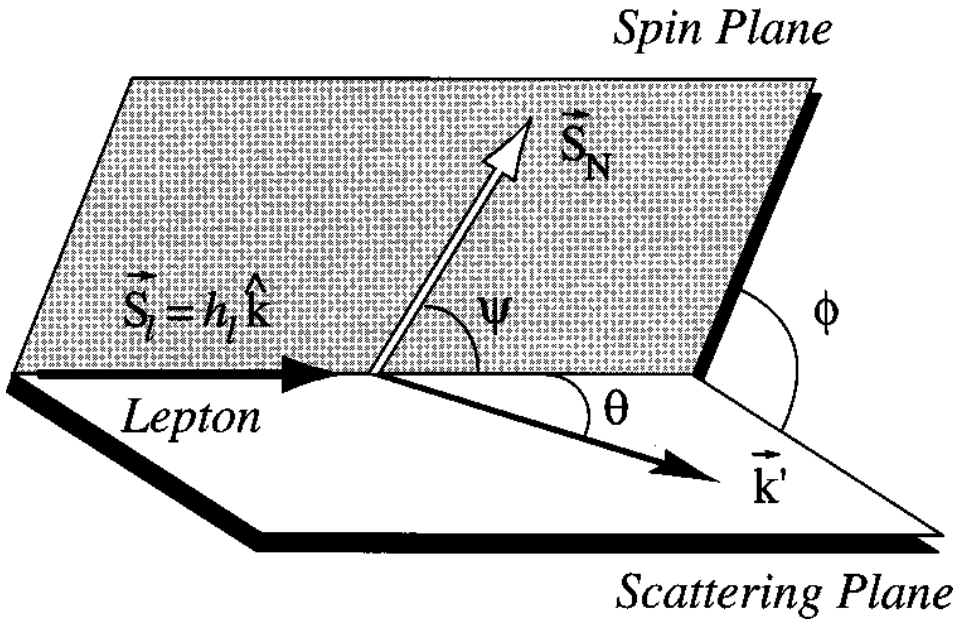


Apparent “indefinite rise” in gluon distribution in proton!

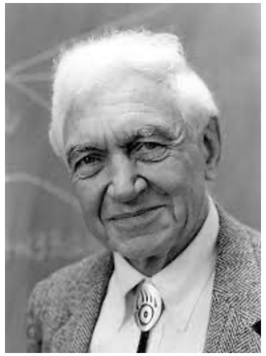
recombination



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

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

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

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:

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

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

$$\Delta q = \int_0^1 \Delta q(x)dx$$

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

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

Neutron decay

(3F-D)/3
Hyperon Decay

$\Delta\Sigma$

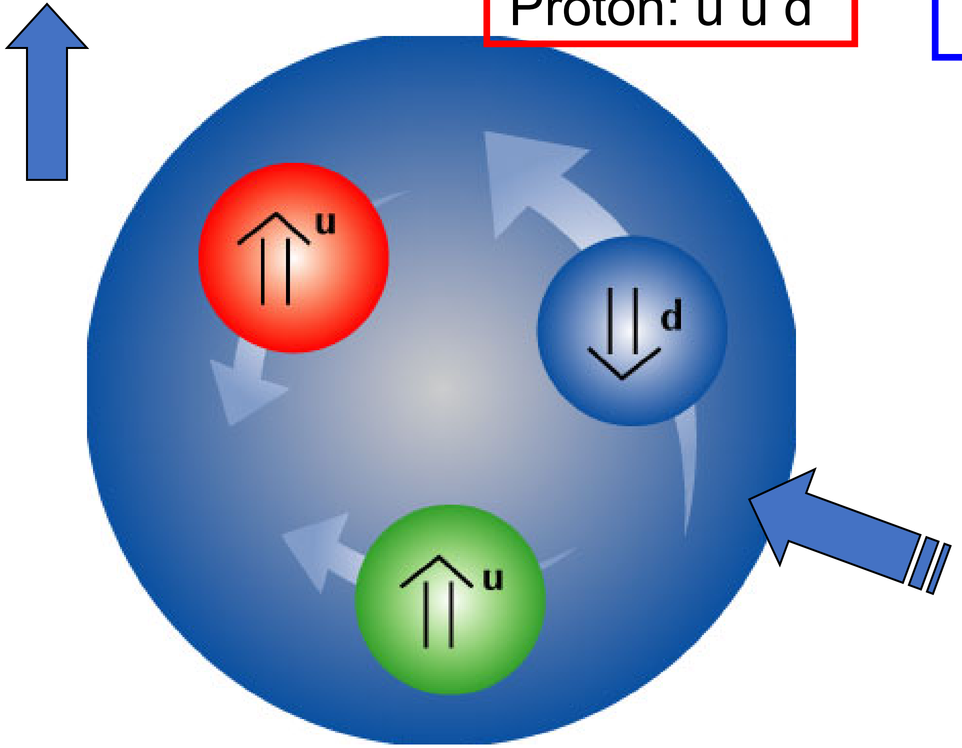
$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

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



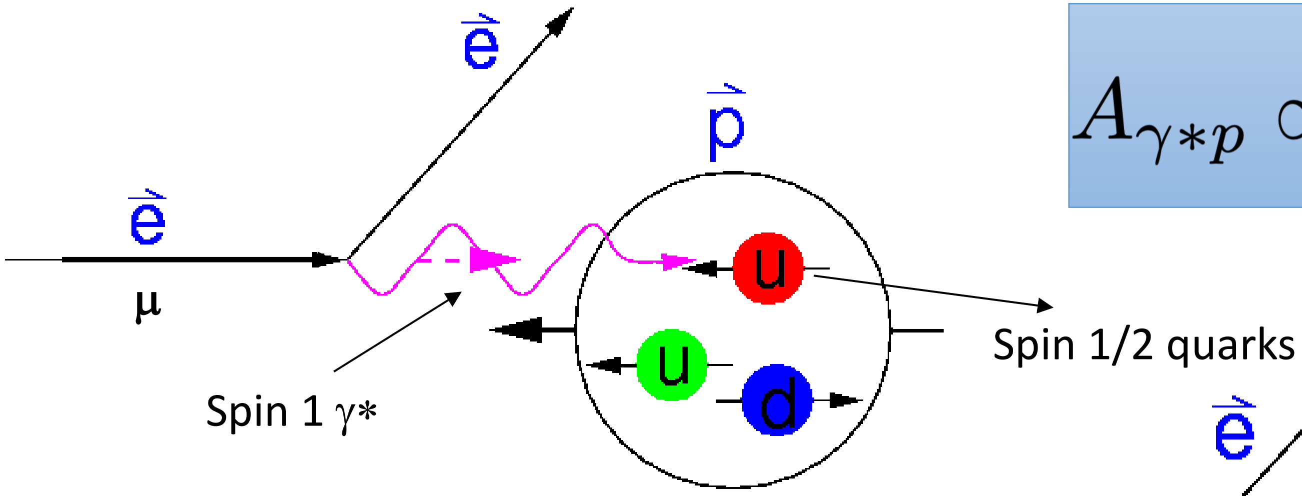
S_{proton} = Sum of all quark spins!

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

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

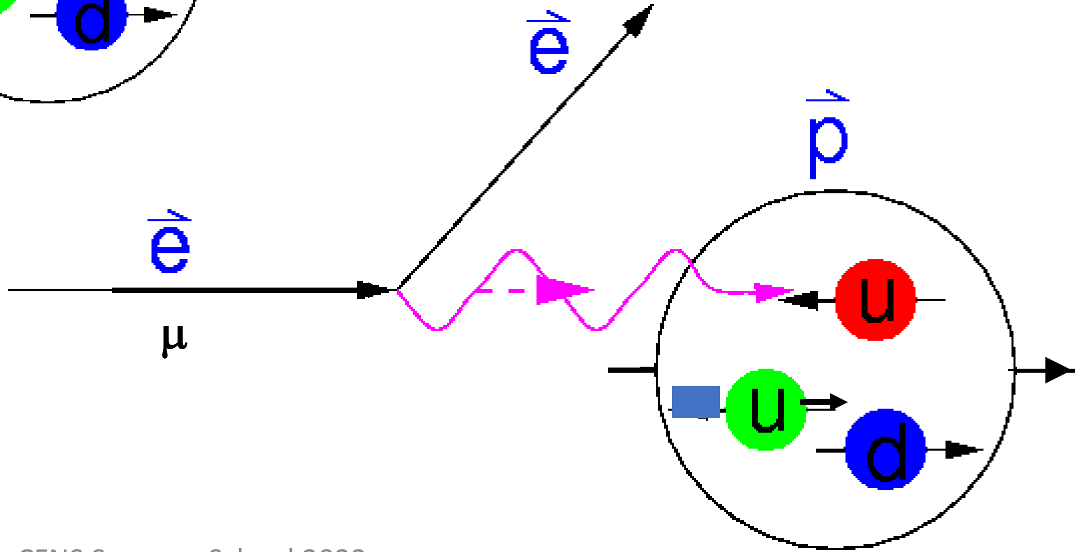
How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

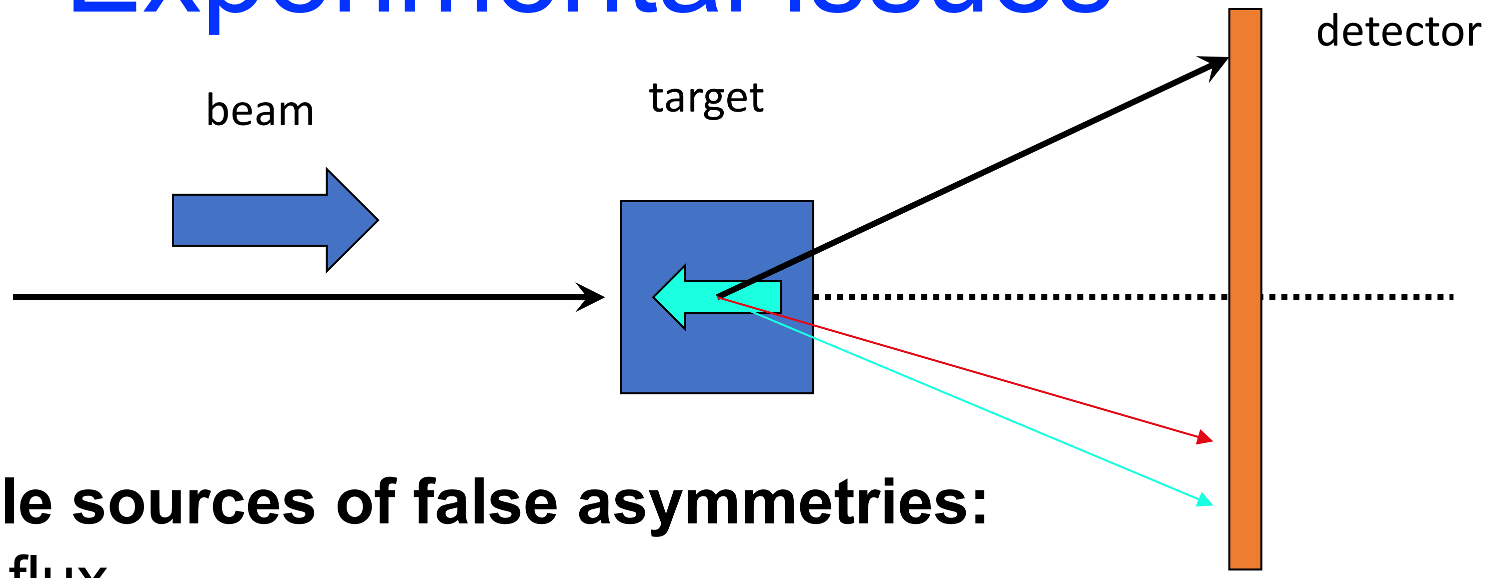


$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

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

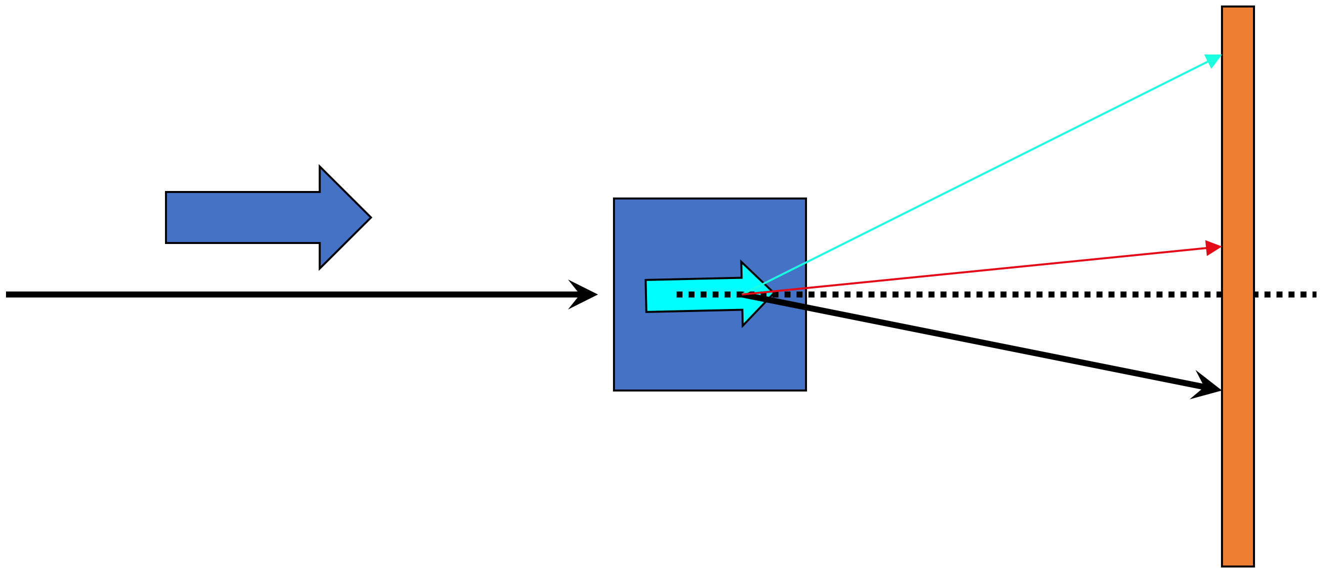


Experimental issues



Possible sources of false asymmetries:

- beam flux
- target size
- detector size
- detector efficiency



$A_{measured} = A_{LL}$
Double Longitudinal Spin asymmetry

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

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

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

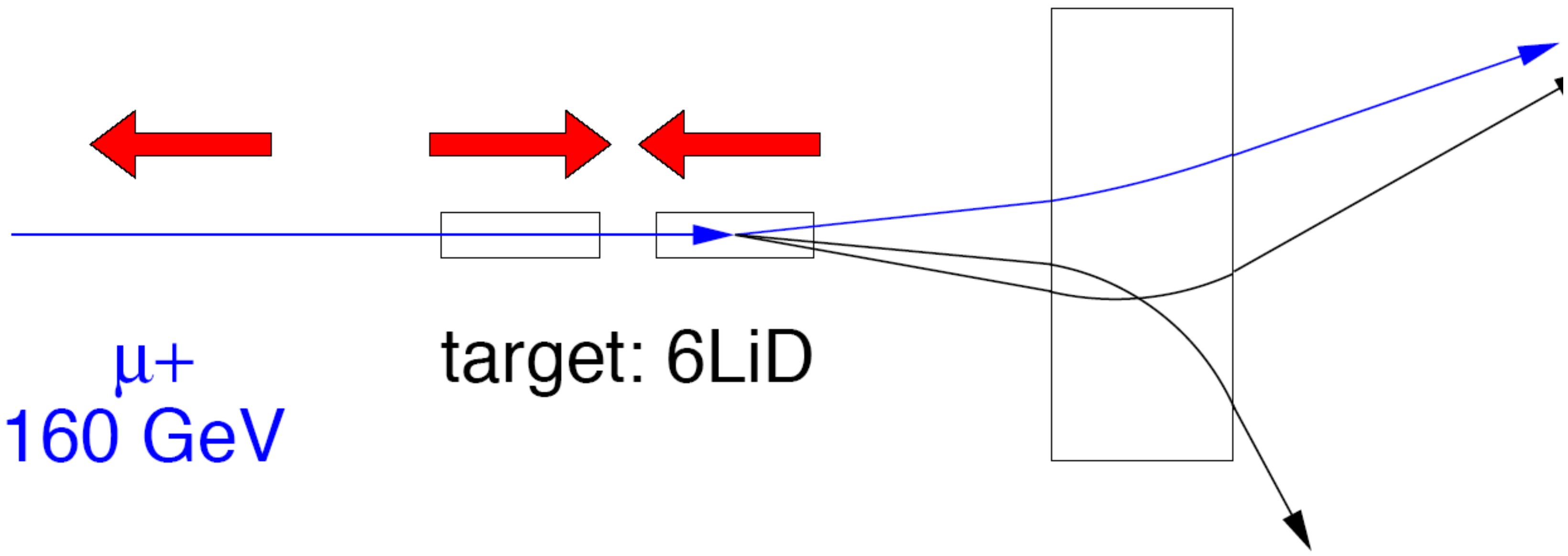
If all other things are equal,

they cancel in the ratio

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

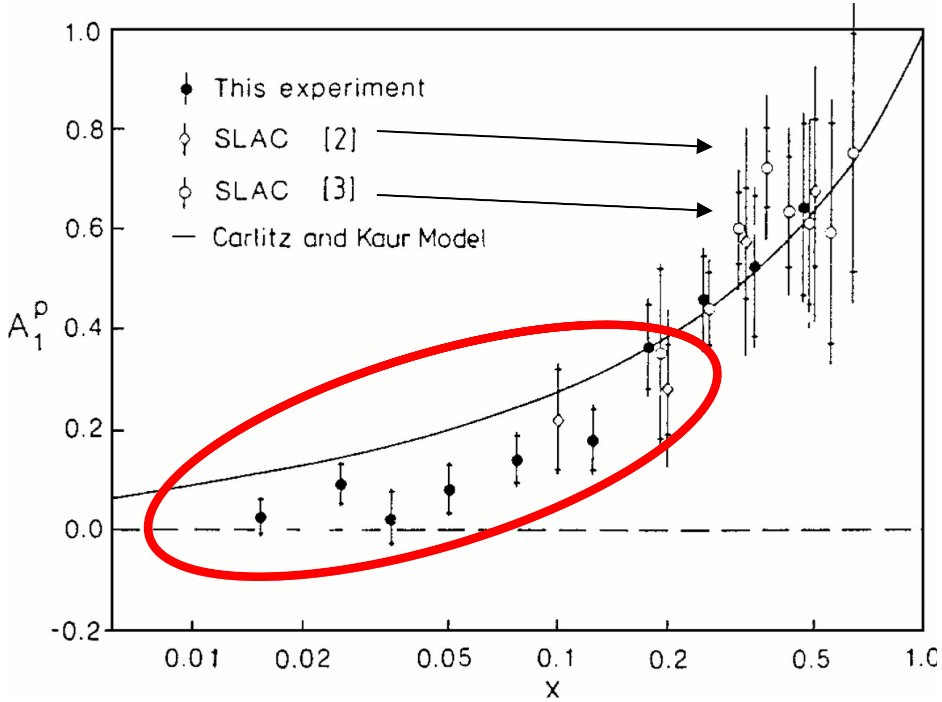
A Typical Setup

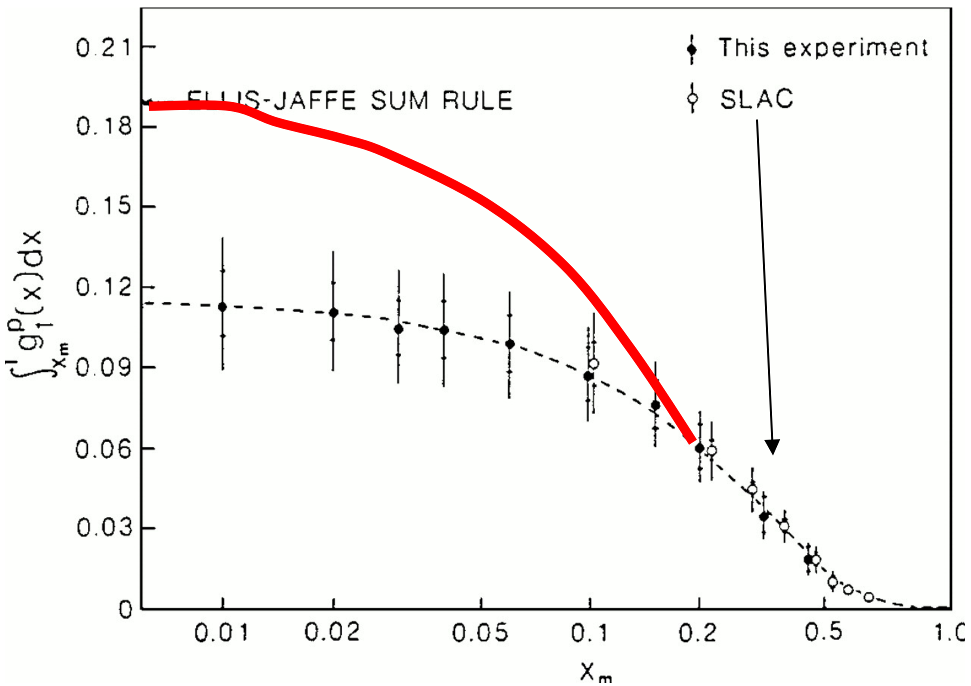
- Experiment setup (EMC, SMC, COMPASS@CERN)



- 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

Proton Spin Crisis (1989)!



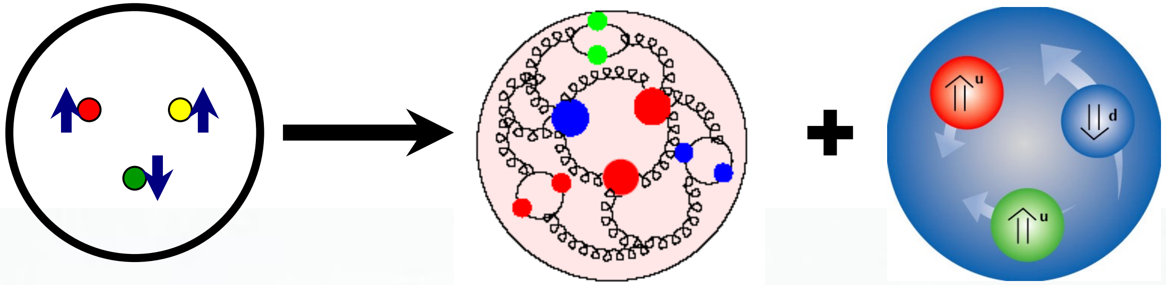


$\Delta\Sigma/2 = (0.12)$ +/- (0.17) (EMC, 1989)

$\Delta\Sigma/2 = 0.58$ 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

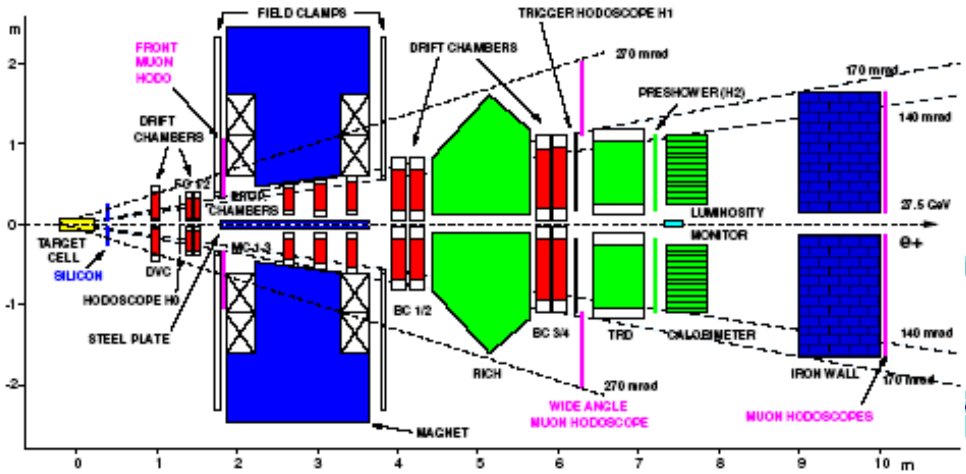
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma /2 \ = 0.12 +/- 0.17$

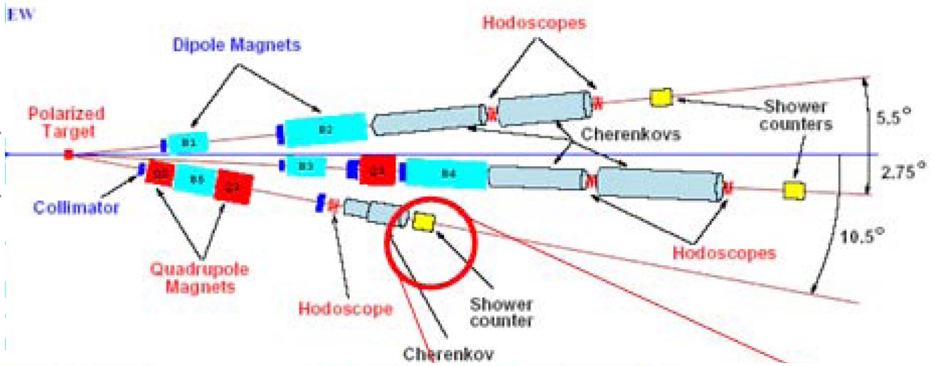
Need information about transverse dimensions of the proton

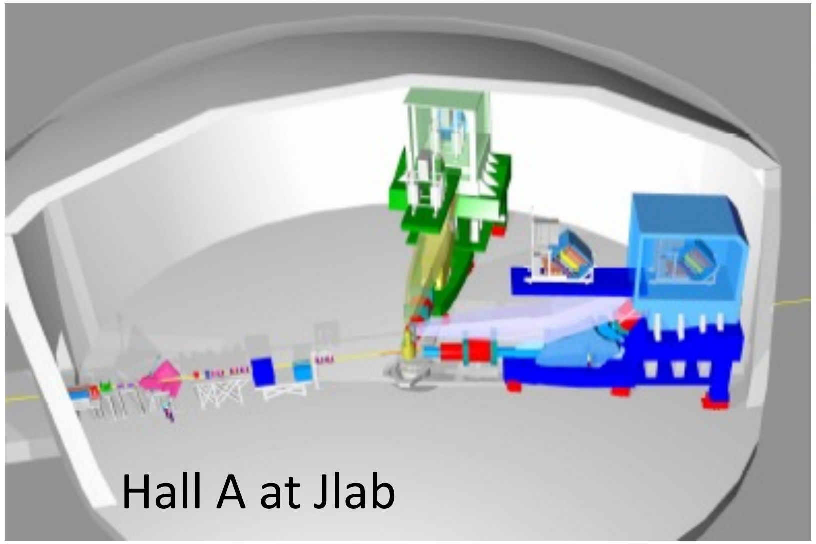
Spin discovered a problem…. What now? Need precision and investigations of gluons….

Experiments

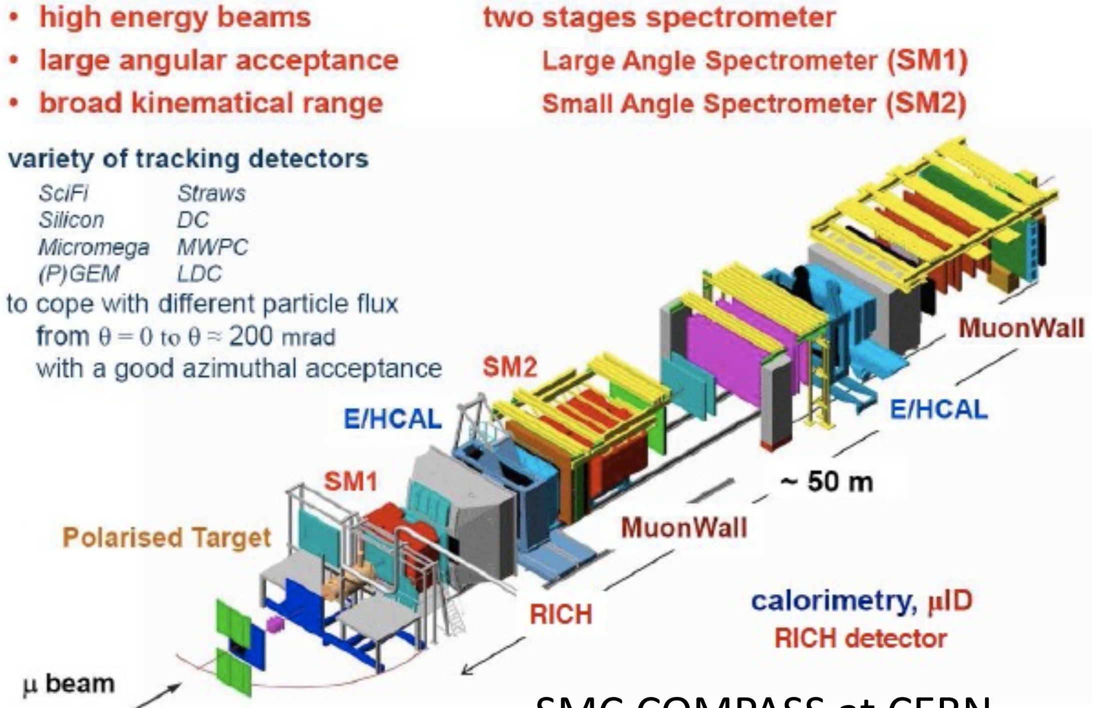


HERMES at DESY



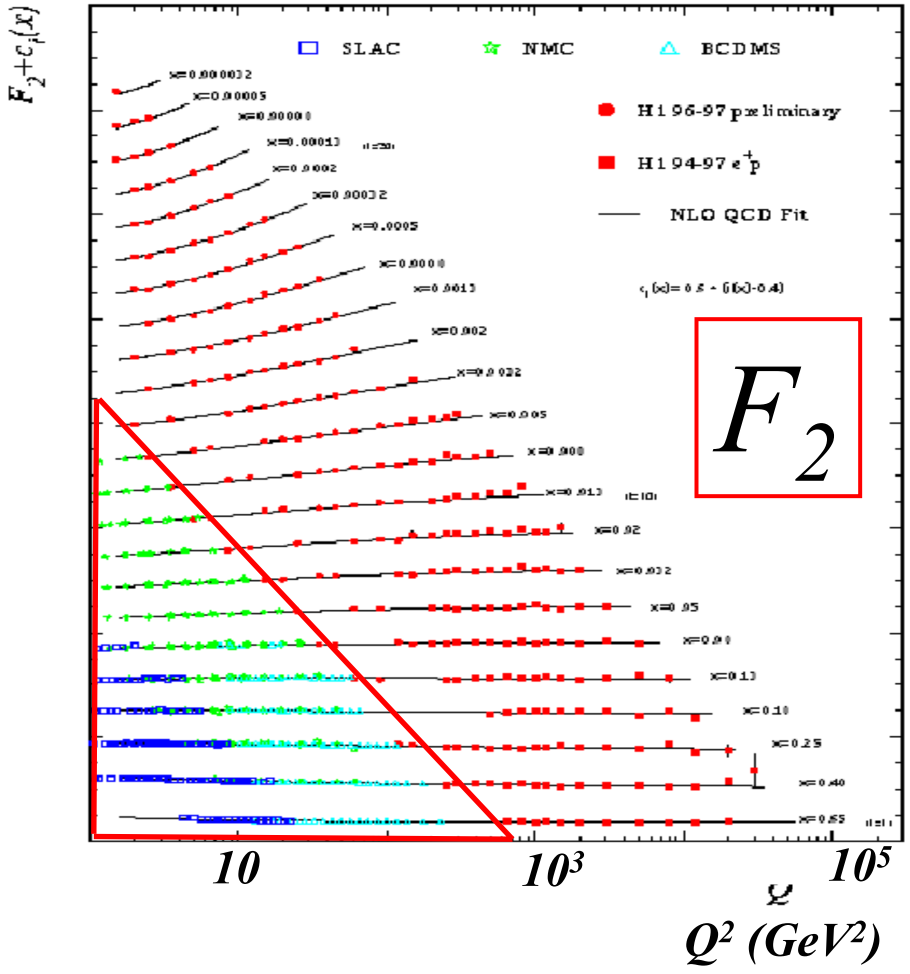


Hall A at Jlab

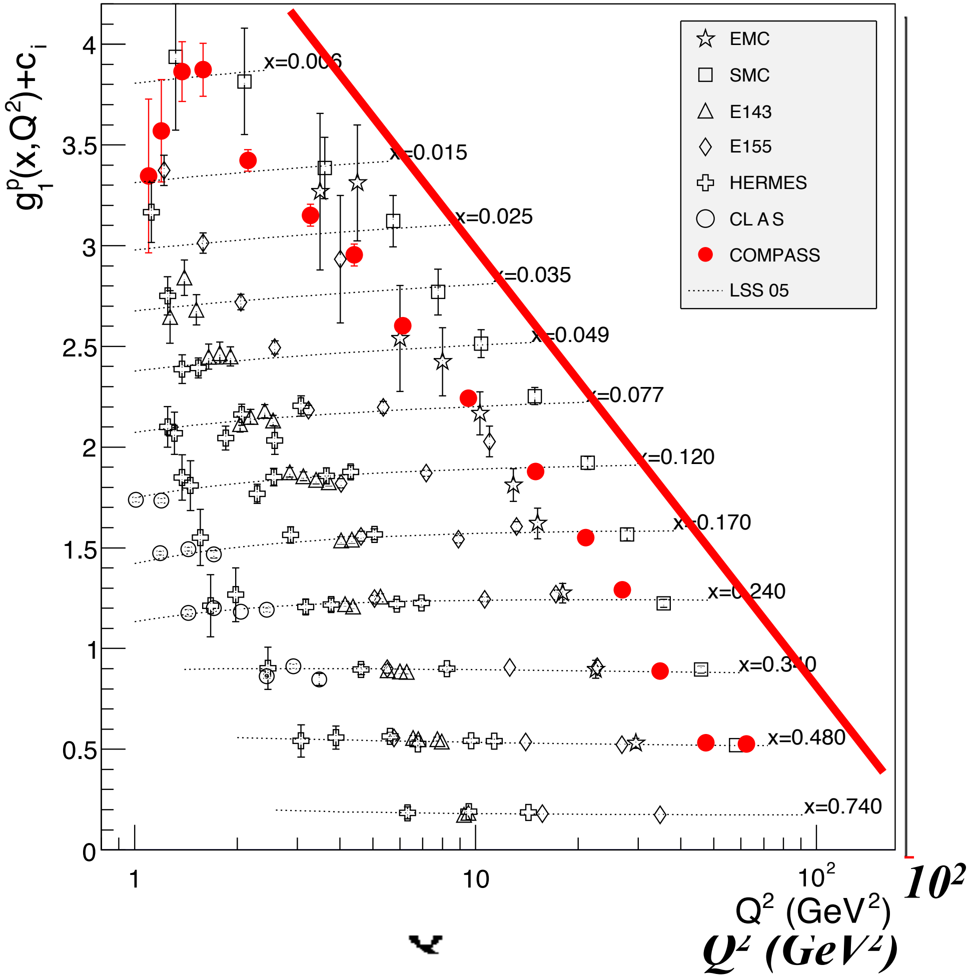


SMC,COMPASS at CERN

F_2 vs. g_1 structure function measurements



Aidala et al.1209.2803v2

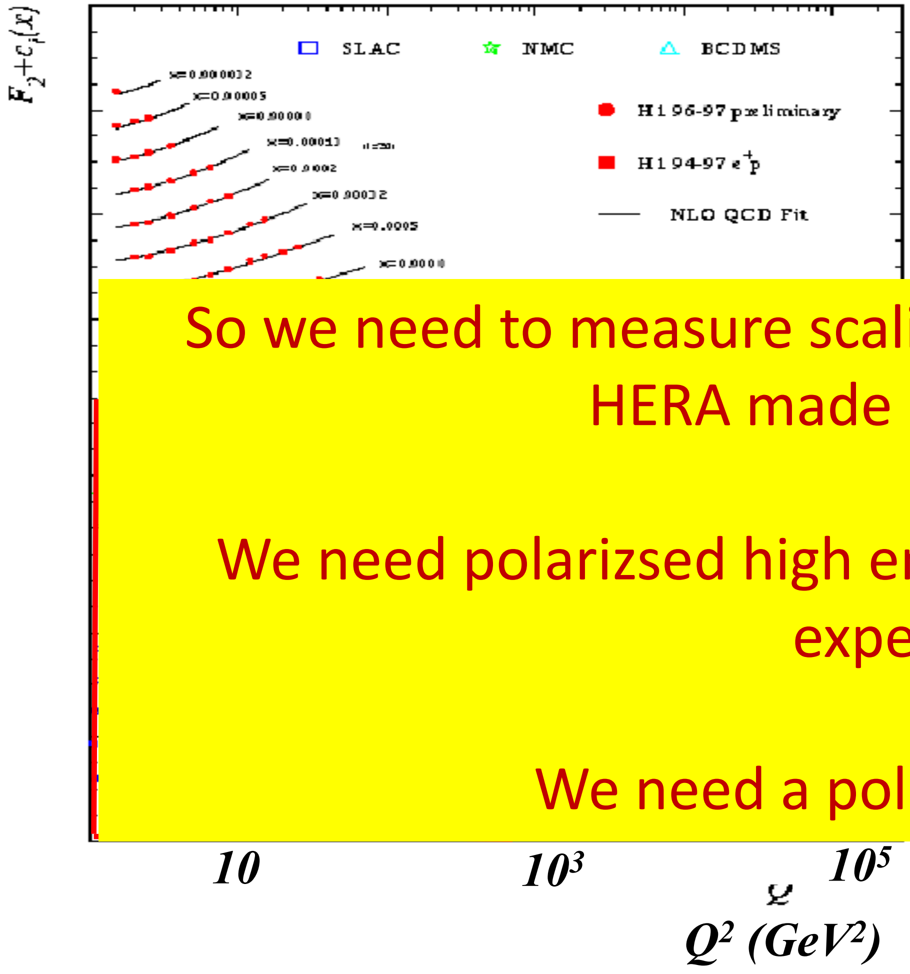


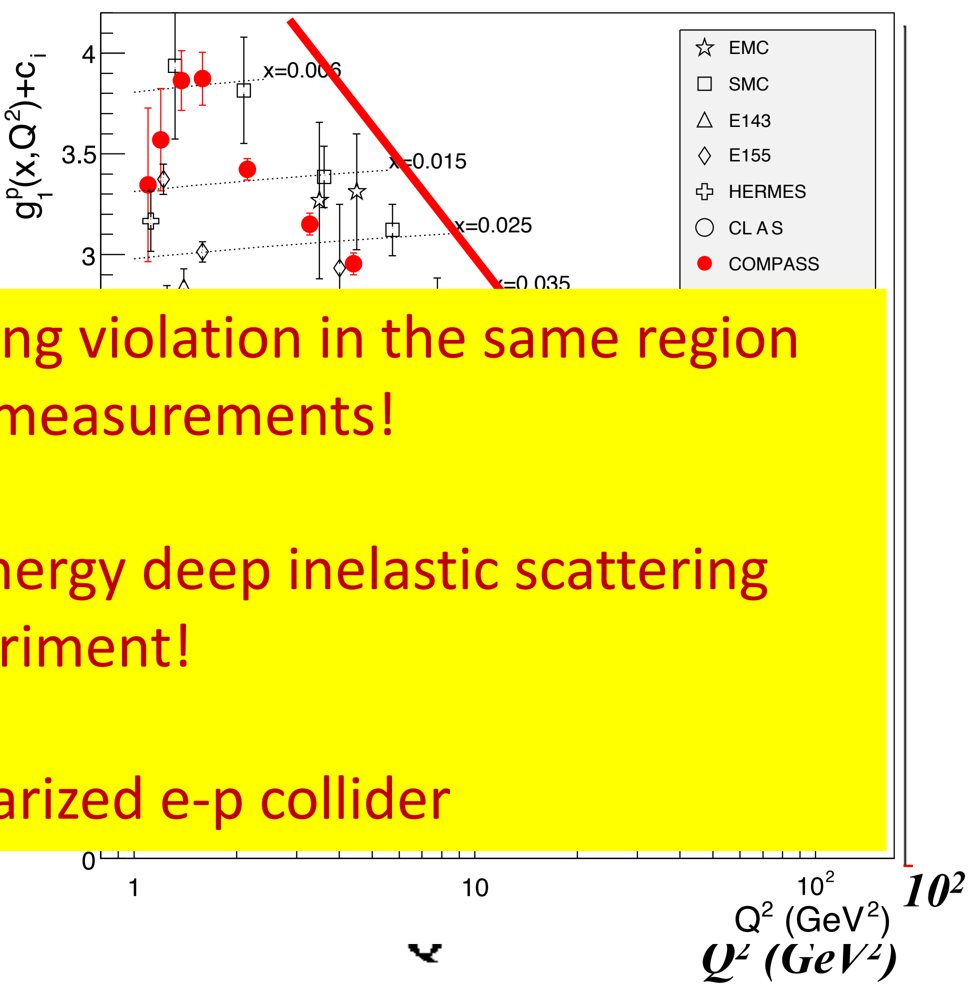
Large amount of polarized data since 1998… but not in NEW kinematic region!

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

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

Consequence:

- Quark + Anti-Quark contribution to nucleon spin is definitely small:

$$\text{Quark's contribution to nucleon spin} \rightarrow \frac{1}{2}\Delta\Sigma = 0.15 \pm 0.03$$

- Is this smallness due to some cancellation between quark+anti-quark polarization

- The gluon's contribution seemed to be large! $\Delta G = 1 \pm 1.5$

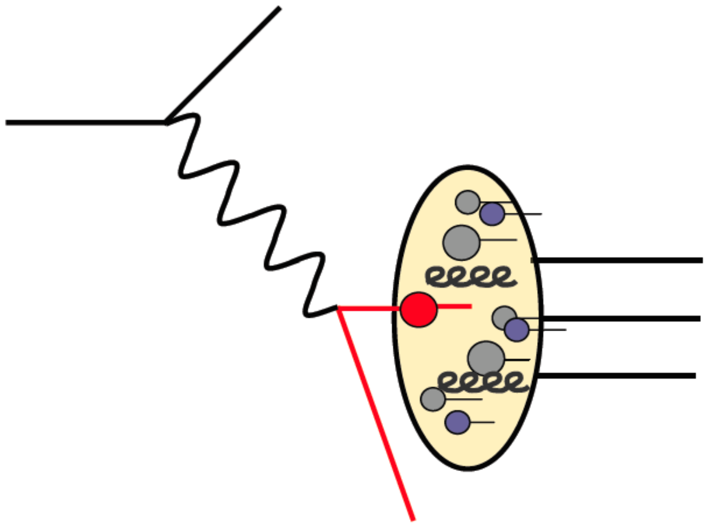
- Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
  - Direct measurement of gluon spin with other probes warranted.
  - Seeded the RHIC Spin program ➔ Lecture 2

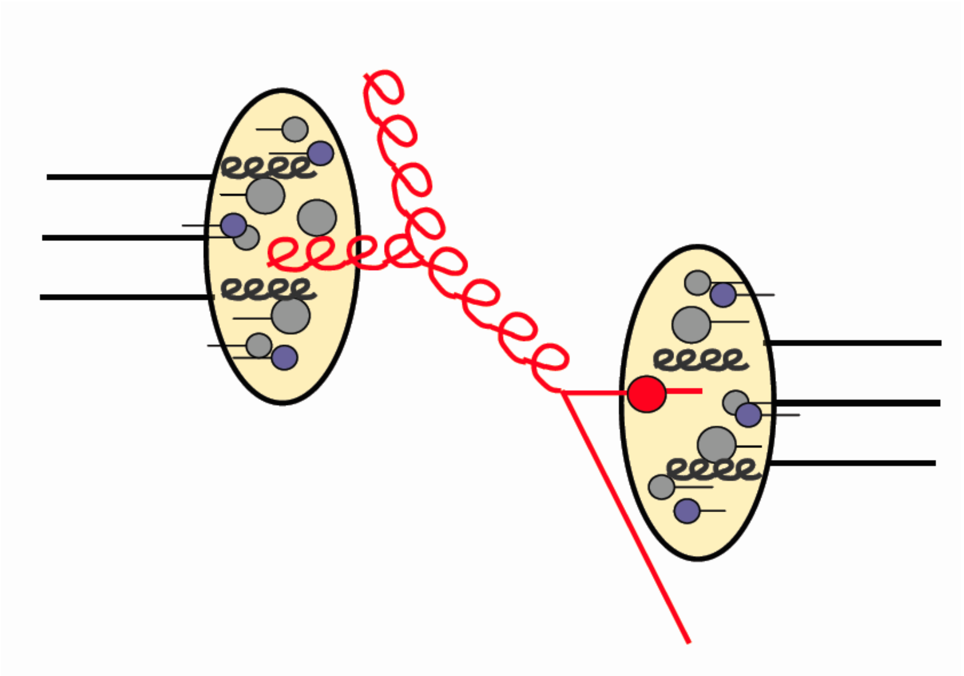
RHIC Spin program and the Transverse Spin puzzle

Pre-cursor to a polarized e-p collider

EIC lecture 1 A

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 ?

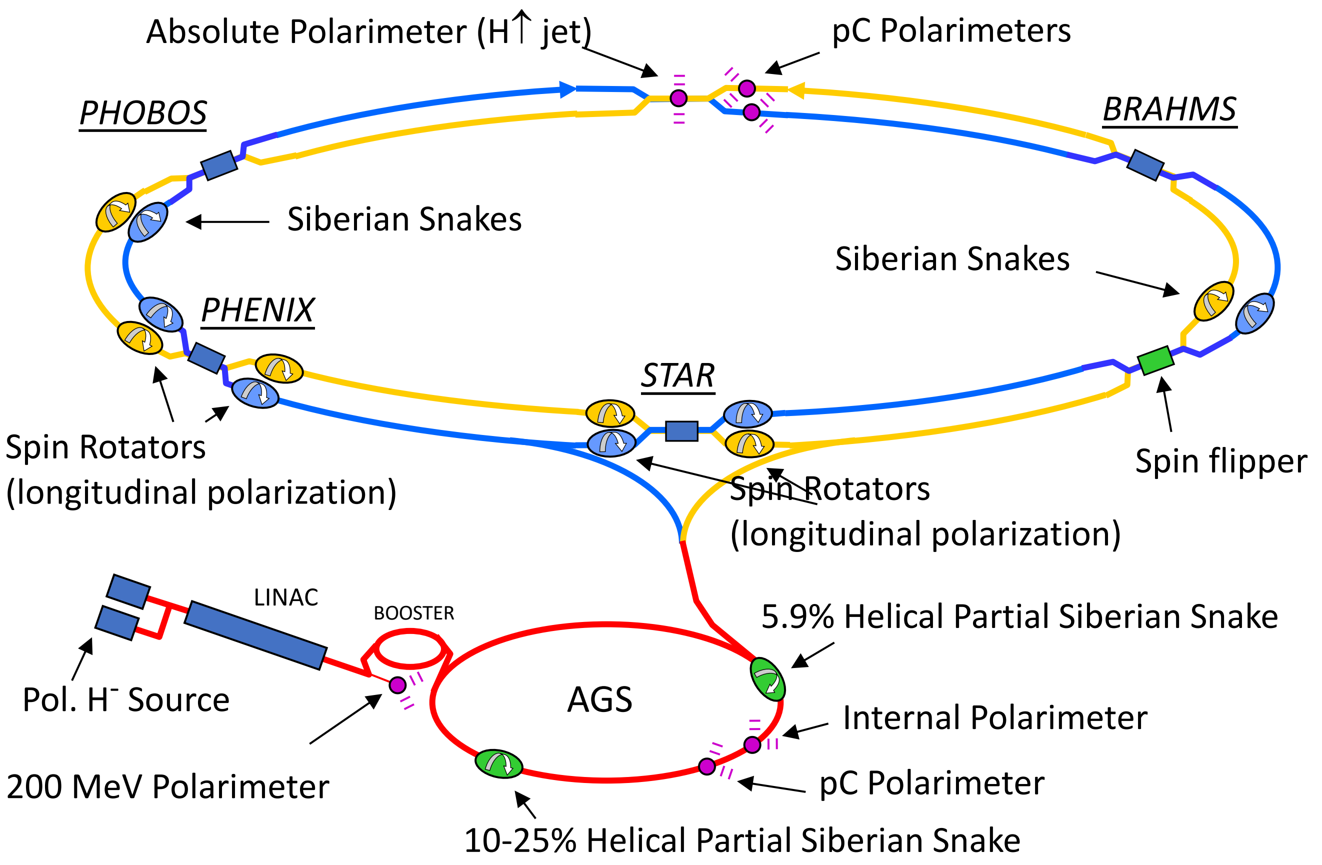
Seeds for RHIC Spin program:

- ❖Hadrons are almost full of gluons…. So if one wants to study gluon's spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton p-p collisions instead of e-p?***

- ❖Curious and bothersome transverse spin asymmetries in p-p scattering persistent in every experiment performed…. US physicists heavily involved… decided to investigate further

- ❖**Technical know-how of polarizing proton beams at high energy became available!**

RHIC as a Polarized Proton Collider

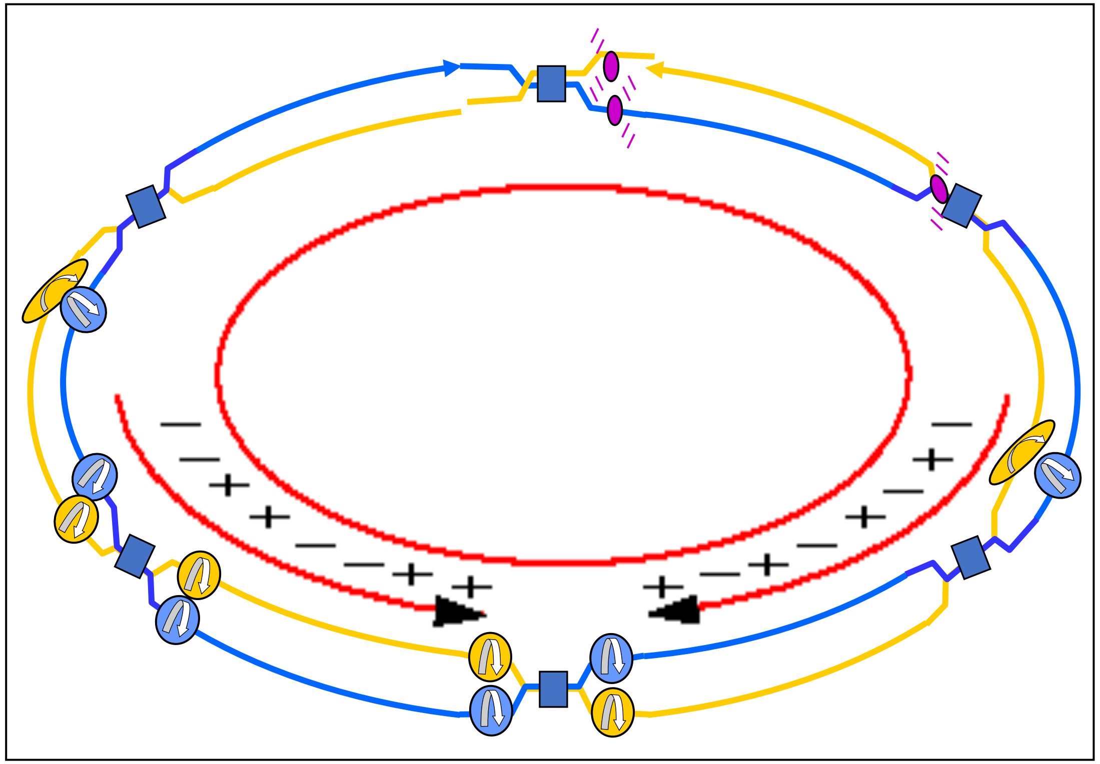


Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

Measuring A_{LL}

Longitudinal Spin Asymmetry using polarized proton bunches in the RHIC ring

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



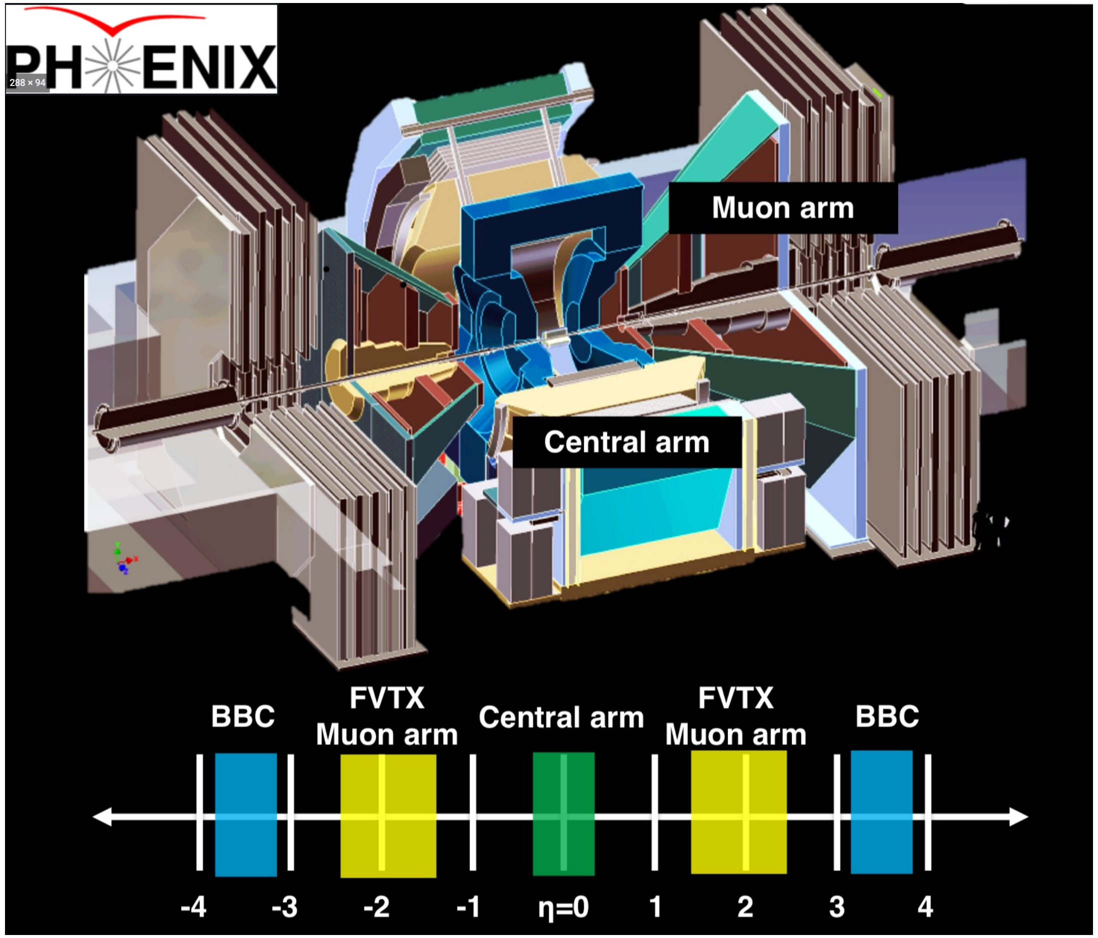
(N) Yield
(R) Relative Luminosity
(P) Polarization

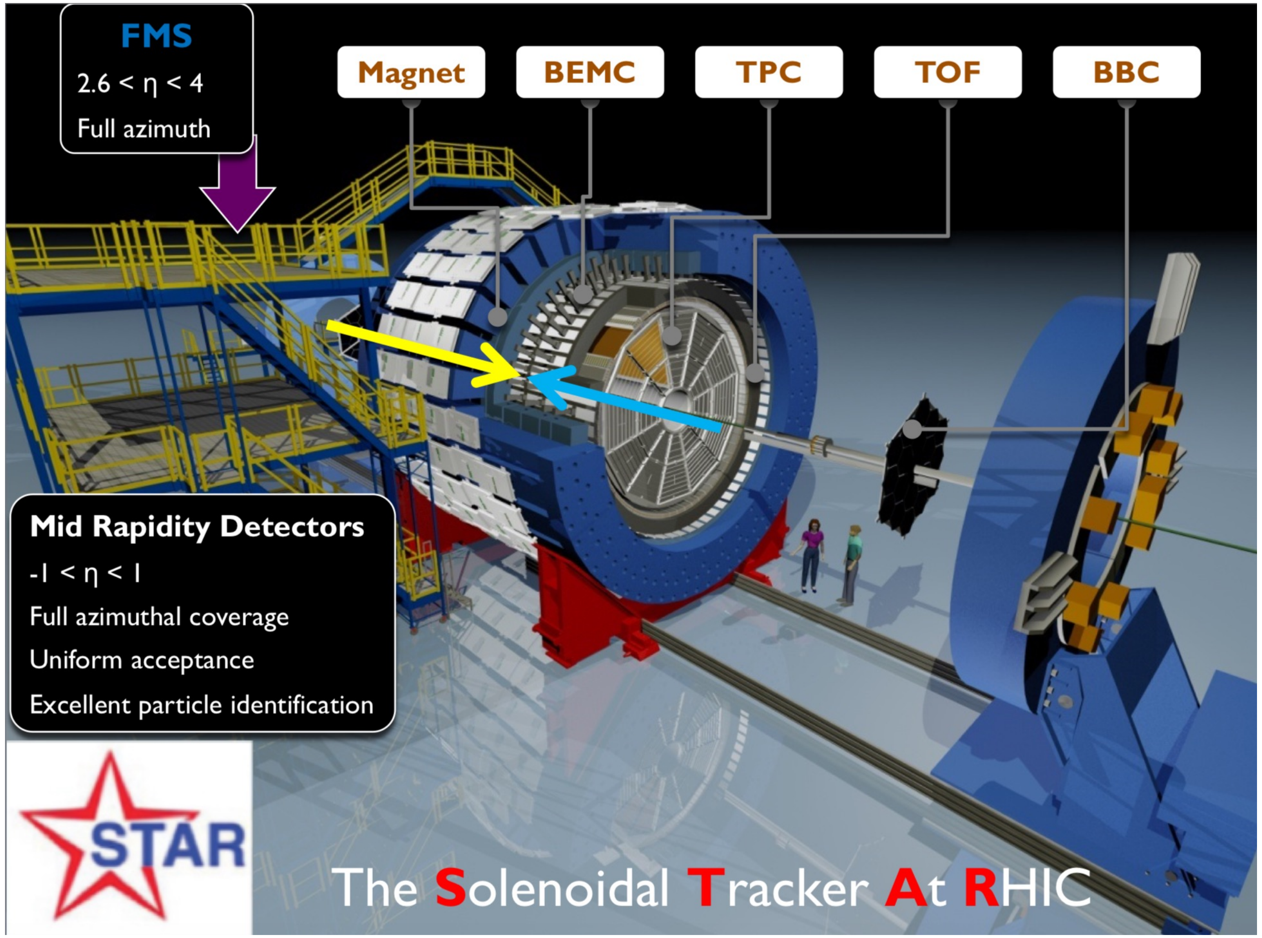
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

- ✓ 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

Two main detectors for spin studies

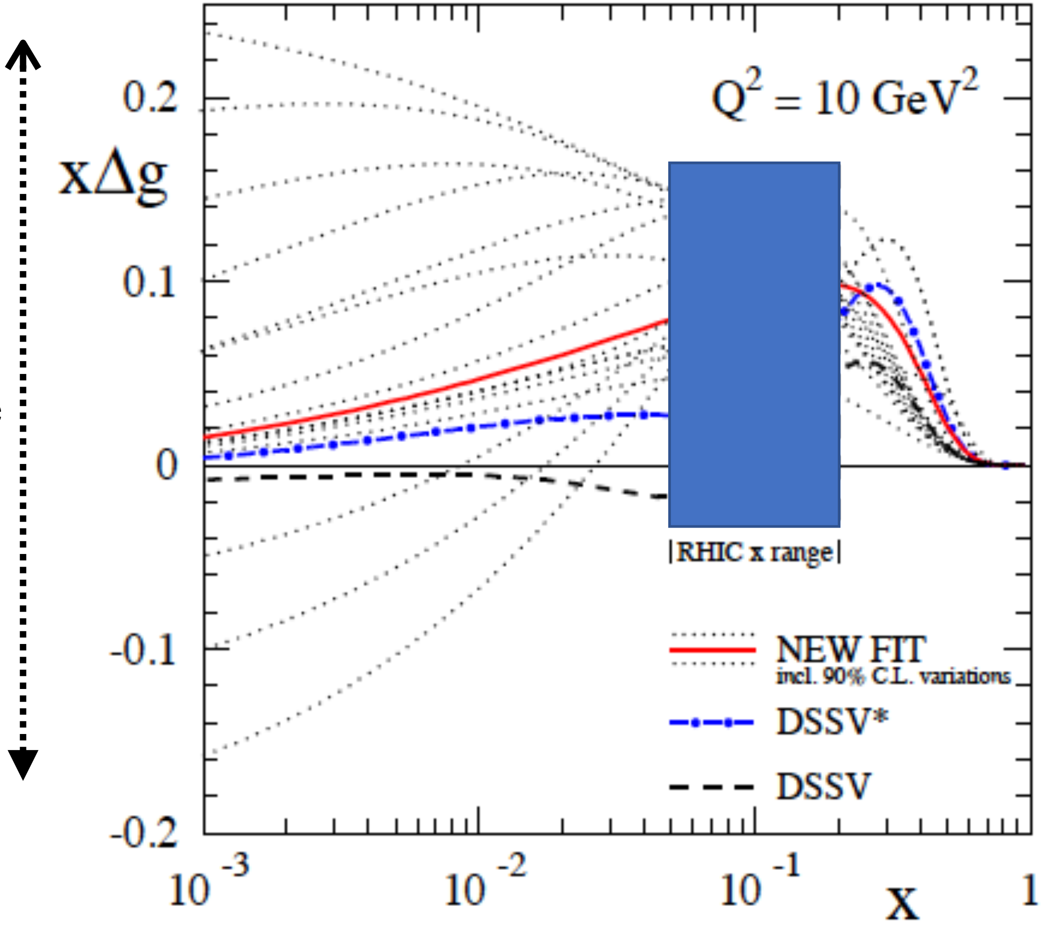




Recent global analysis: DSSV

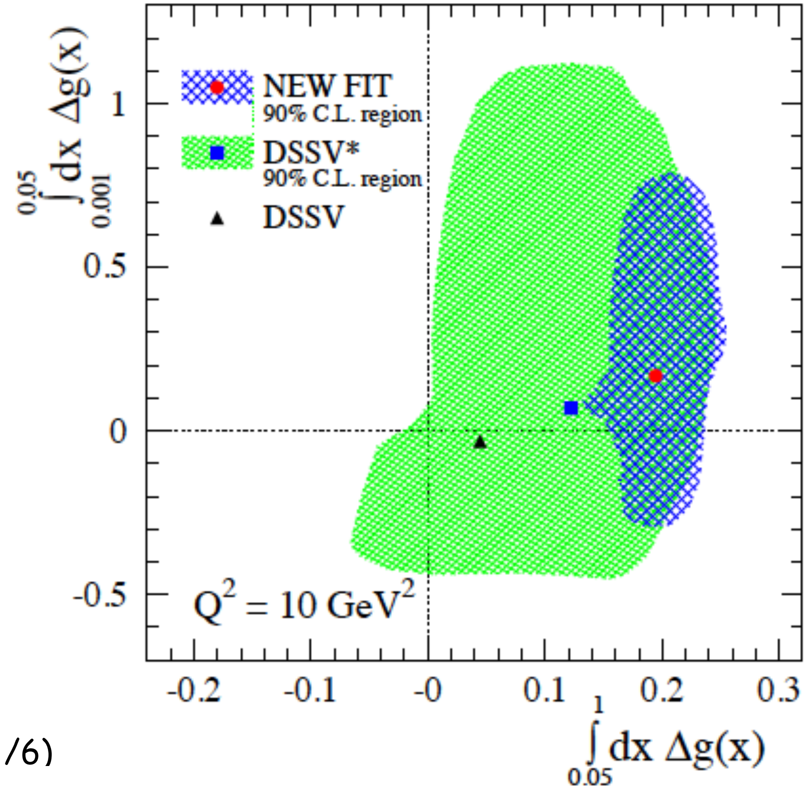
D. deFlorian et al., arXiv:1404.4293

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



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

/6)

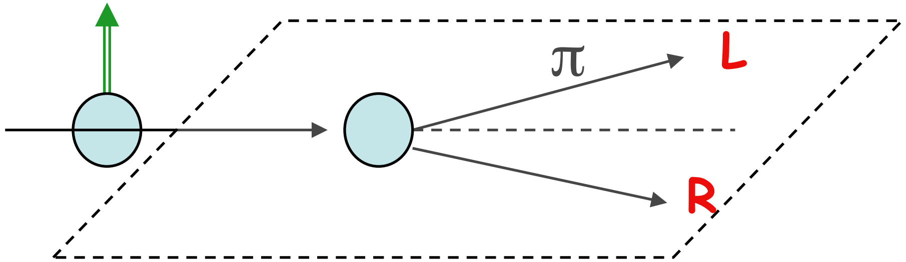


While RHIC made a huge impact on ΔG

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

Transverse Spin effects in p-p observed but ignored for 40+ years

Transverse spin introduction



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

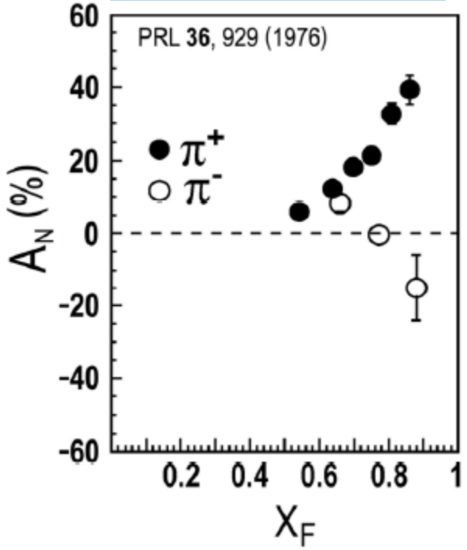
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

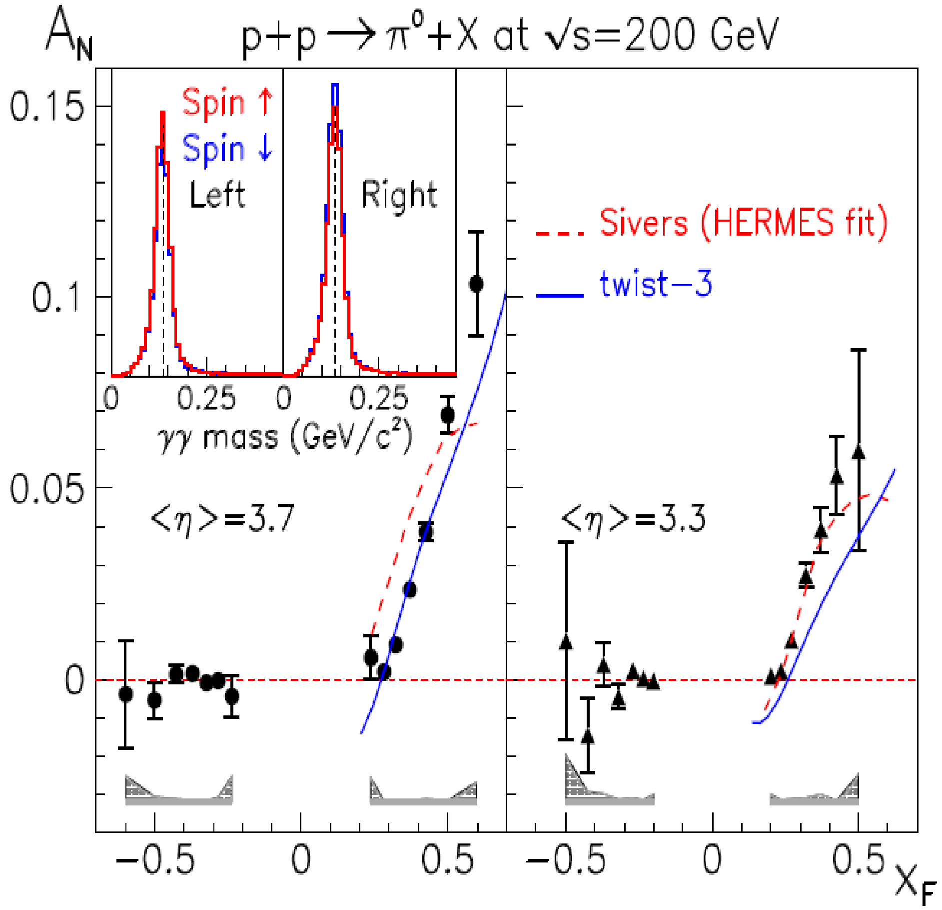
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people focused at high p_T to interpret them in pQCD frameworks, this (expected small effect) was "neglected However….
- Pion production in single transverse spin collisions showed us something different….

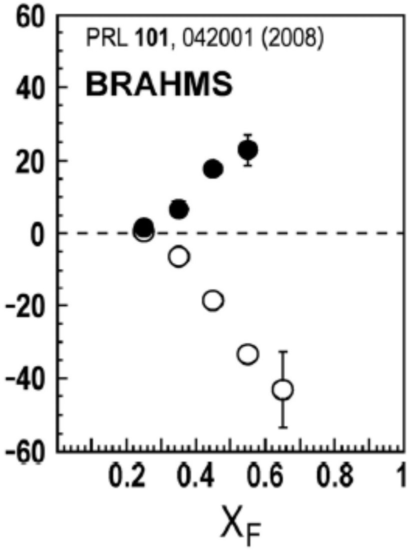
Pion asymmetries: at broad range in CM energies!

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

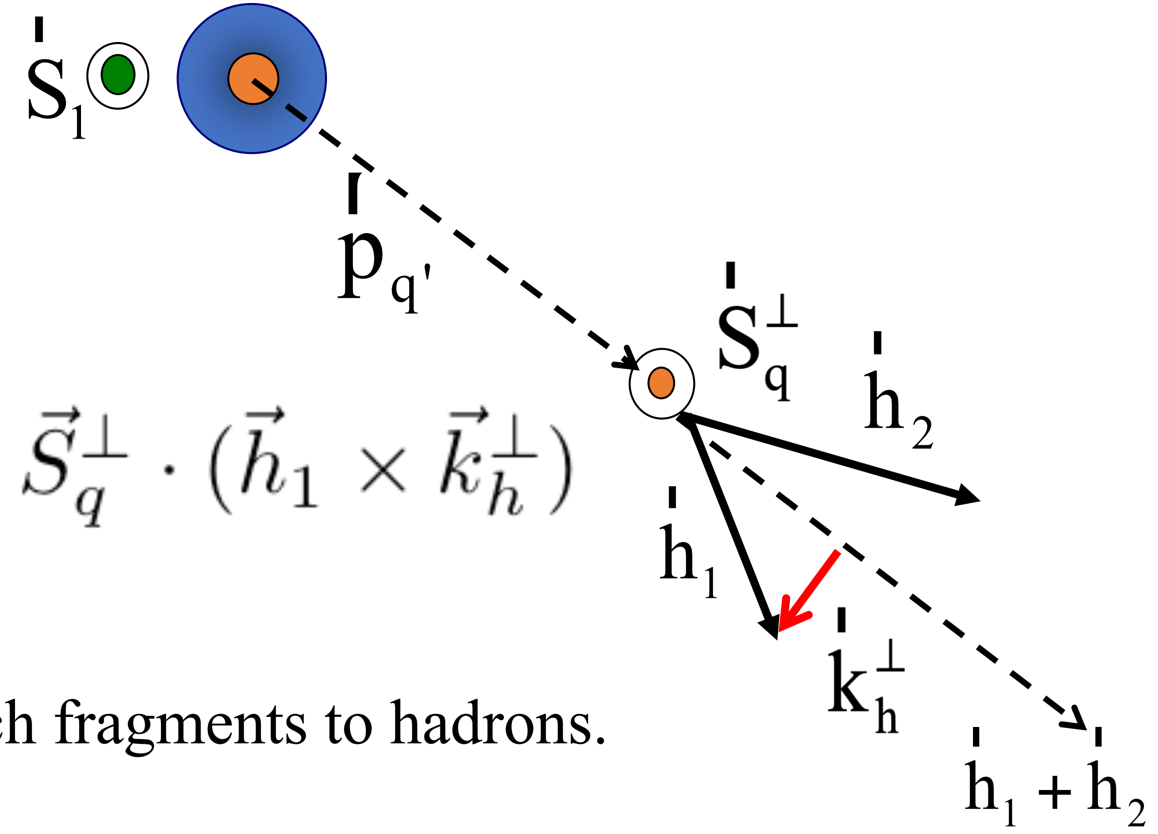


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well ➔ **0.001 expected 0.2-0.6 observed at all Center of Mass Energies**

What could be the origin of such effect?
Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

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

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

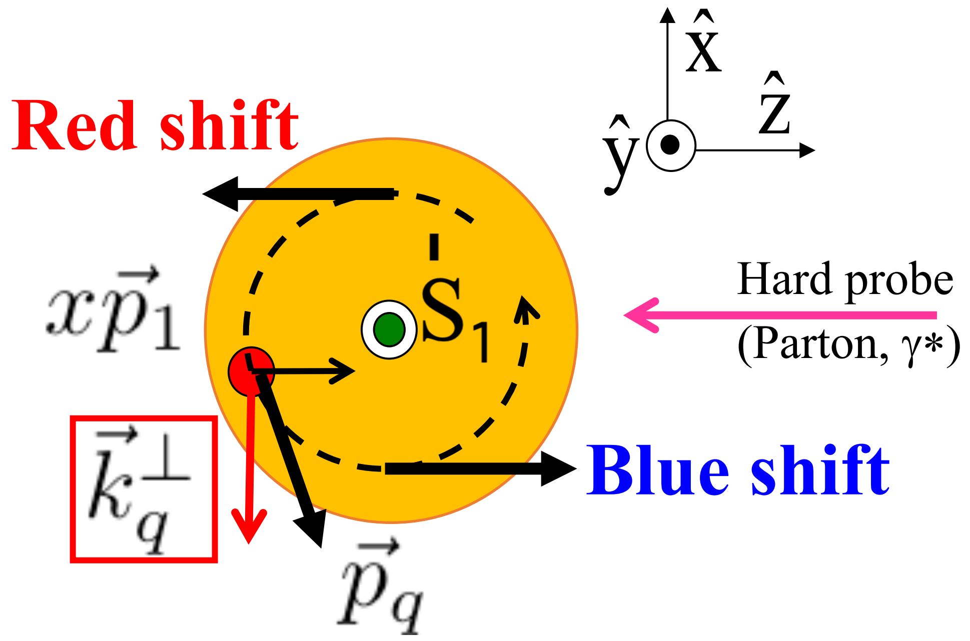


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

Other possibility: 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 **F**unctions

PRD59 (1999) 014013

Lessons learned:

- Proton and neutrons spin not just alignment of quarks and gluons….
    - Proton's spin is complex: alignment of quarks, gluons and possibly orbital motion
- To fully understand proton structure (including the partonic dynamics) one needs to explore over a **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:** Precise measurements of gluons critical.

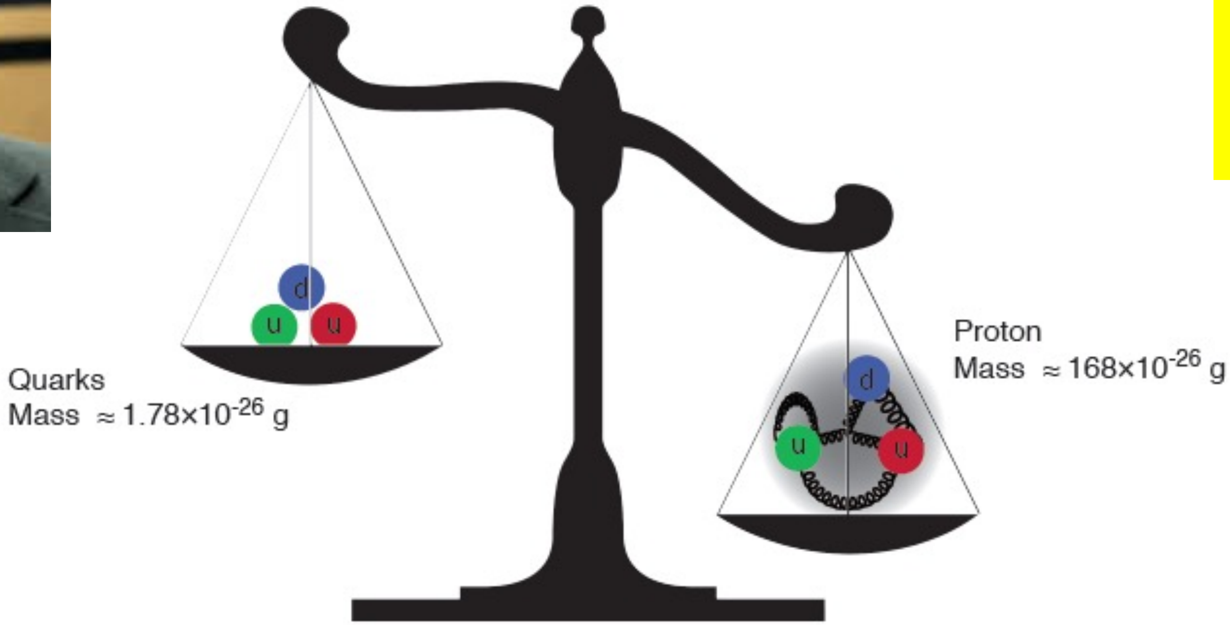
We need a new polarized e-p collider….

Proton mass puzzle

Peter Higgs

It is like saying:

1 + 1 + 1 = 300



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

But the proton's mass (which is made of 3 dominant quarks and massless gluons) is 168×10^{-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?