



# Introduction: EIC Science an experimental review...

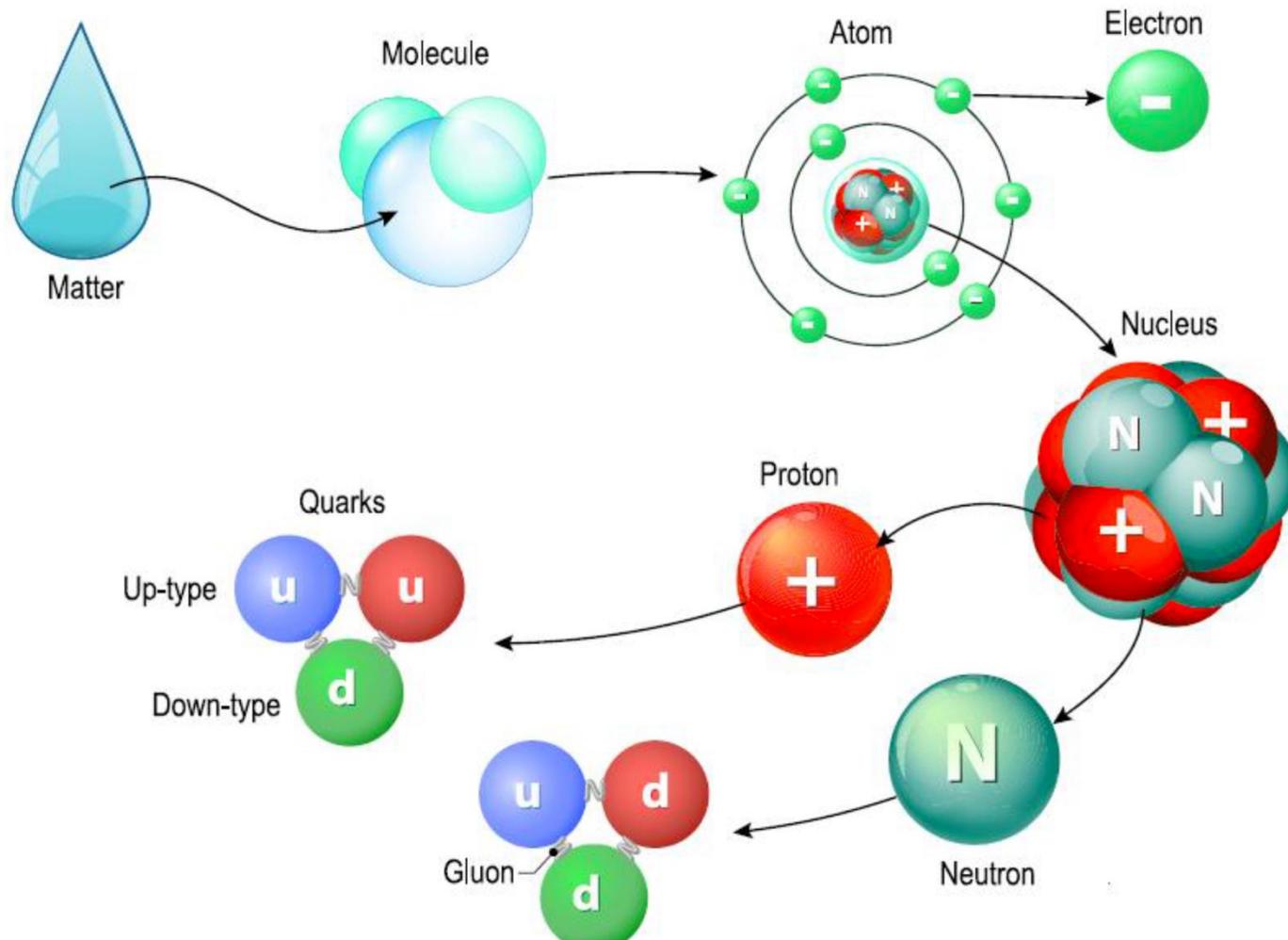
Abhay Deshpande

Lecture 1 of 3

EIC Introduction @ International School and Workshop on Probing Hadron Structure, IIT Bombay, India

February 8-15, 2026

# Quest for the fundamental structure of matter



What's in there?

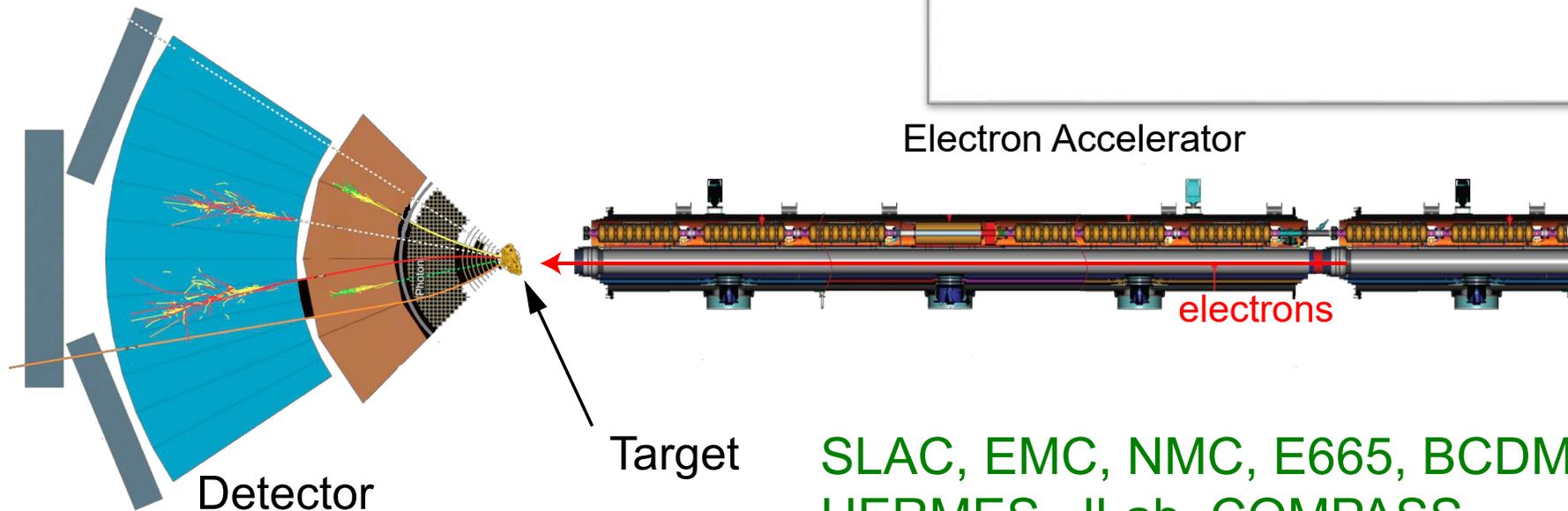
What are we made up of?

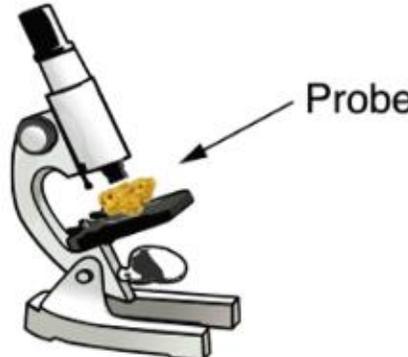
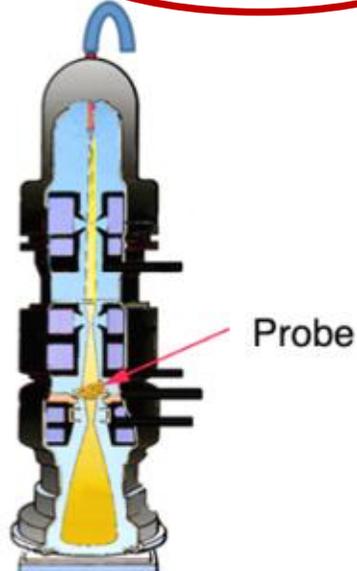
What is the "smallest"?

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

# Studying smaller and smaller things...

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



<p>Light Microscope Wave length: 380-740 nm Resolution: <math>&gt; 200</math> nm</p> 	<p>Electron Microscope Wave length: 0.002 nm (100 keV) Resolution: <math>&gt; 0.2</math> nm</p> 
--	---

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

# Many



1968: SLAC <b>u</b> up quark	1974: Brookhaven & SLAC <b>c</b> charm quark	1995: Fermilab <b>t</b> top quark	1979: DESY <b>g</b> gluon
1968: SLAC <b>d</b> down quark	1947: Manchester University <b>s</b> strange quark	1977: Fermilab <b>b</b> bottom quark	1923: Washington University* $\gamma$ photon
1956: Savannah River Plant $\nu_e$ electron neutrino	1962: Brookhaven $\nu_\mu$ muon neutrino	2000: Fermilab $\nu_\tau$ tau neutrino	1983: CERN <b>W</b> W boson
1897: Cavendish Laboratory <b>e</b> electron	1937: Caltech and Harvard $\mu$ muon	1976: SLAC $\tau$ tau	1983: CERN <b>Z</b> Z boson

1968: SLAC <b>u</b> up quark	1974: Brookhaven & SLAC <b>c</b> charm quark	1995: Fermilab <b>t</b> top quark	1979: DESY <b>g</b> gluon <b>Not Detectable</b>
1968: SLAC <b>d</b> down quark	1947: Manchester University <b>s</b> strange quark	1977: Fermilab <b>b</b> bottom quark	1923: Washington University* $\gamma$ photon <b>Not detectable</b>
1956: Savannah River Plant $\nu_e$ electron neutrino	1962: Brookhaven $\nu_\mu$ muon neutrino	2000: Fermilab $\nu_\tau$ tau neutrino	1983: CERN <b>W</b> W boson <b>Absorption length <math>\approx</math> 10 light years</b> <b>Hardly interact with matter</b>
1897: Cavendish Laboratory <b>e</b> electron	1937: Caltech and Harvard $\mu$ muon	1976: SLAC $\tau$ tau <b>Unstable</b>	1983: CERN <b>Z</b> Z boson <b>Unstable</b>

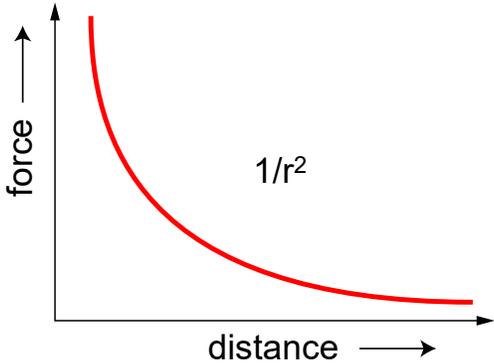
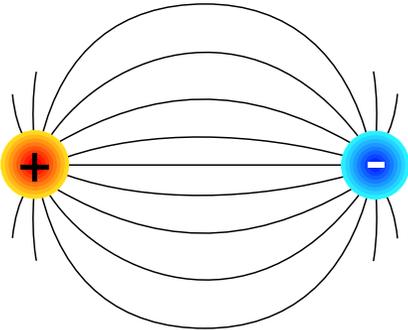
# H

# H

# Quantum Electrodynamics (QED)

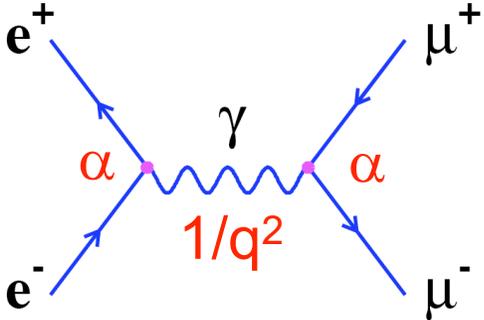
## Theory of electromagnetic interactions

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



$$V(r) = -\frac{q_1 q_2}{4\pi\epsilon_0 r} = -\frac{\alpha_{em}}{r}$$

### Example Feynman Diagram: $e^+e^-$ annihilation



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

# Quantum Chromodynamics (QCD)

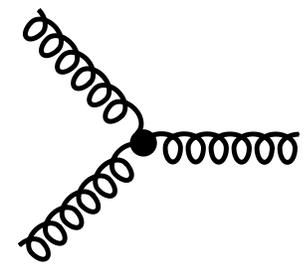
Quantum Chromo Dynamics is the “nearly perfect” fundamental theory of the strong interactions

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

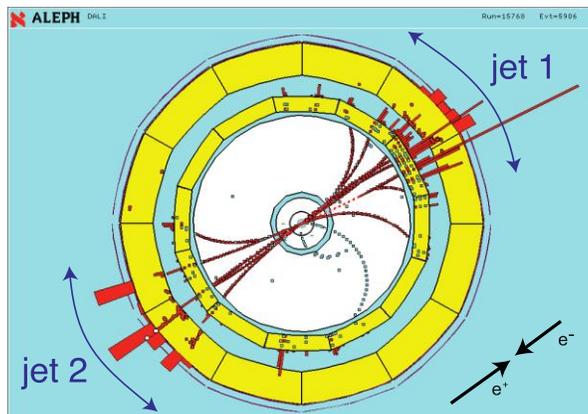
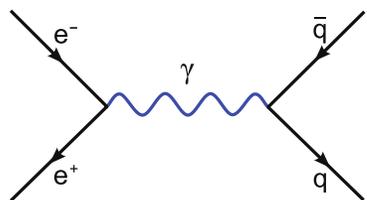
- Flux is confined:  $V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr$   
 $\sim 1/r$  at short range      long range  $\sim r$

Long range aspect  $\Rightarrow$  quark confinement and existence of nucleons

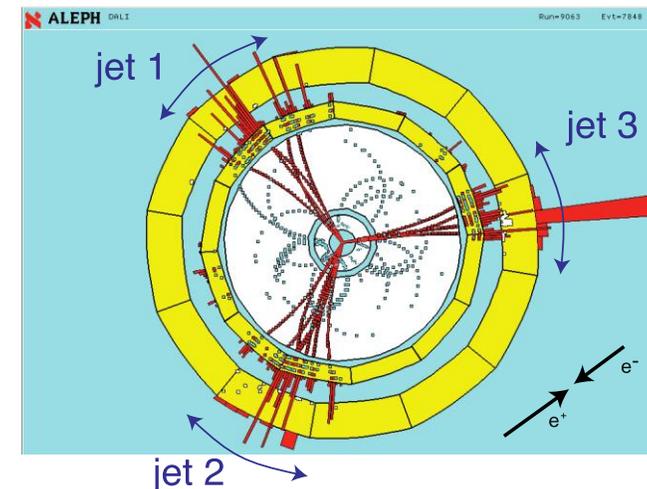
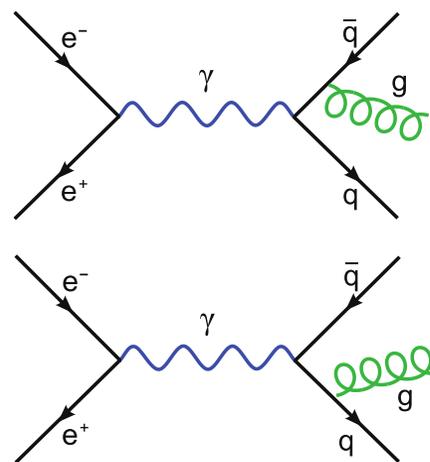
# Gluons!

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

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



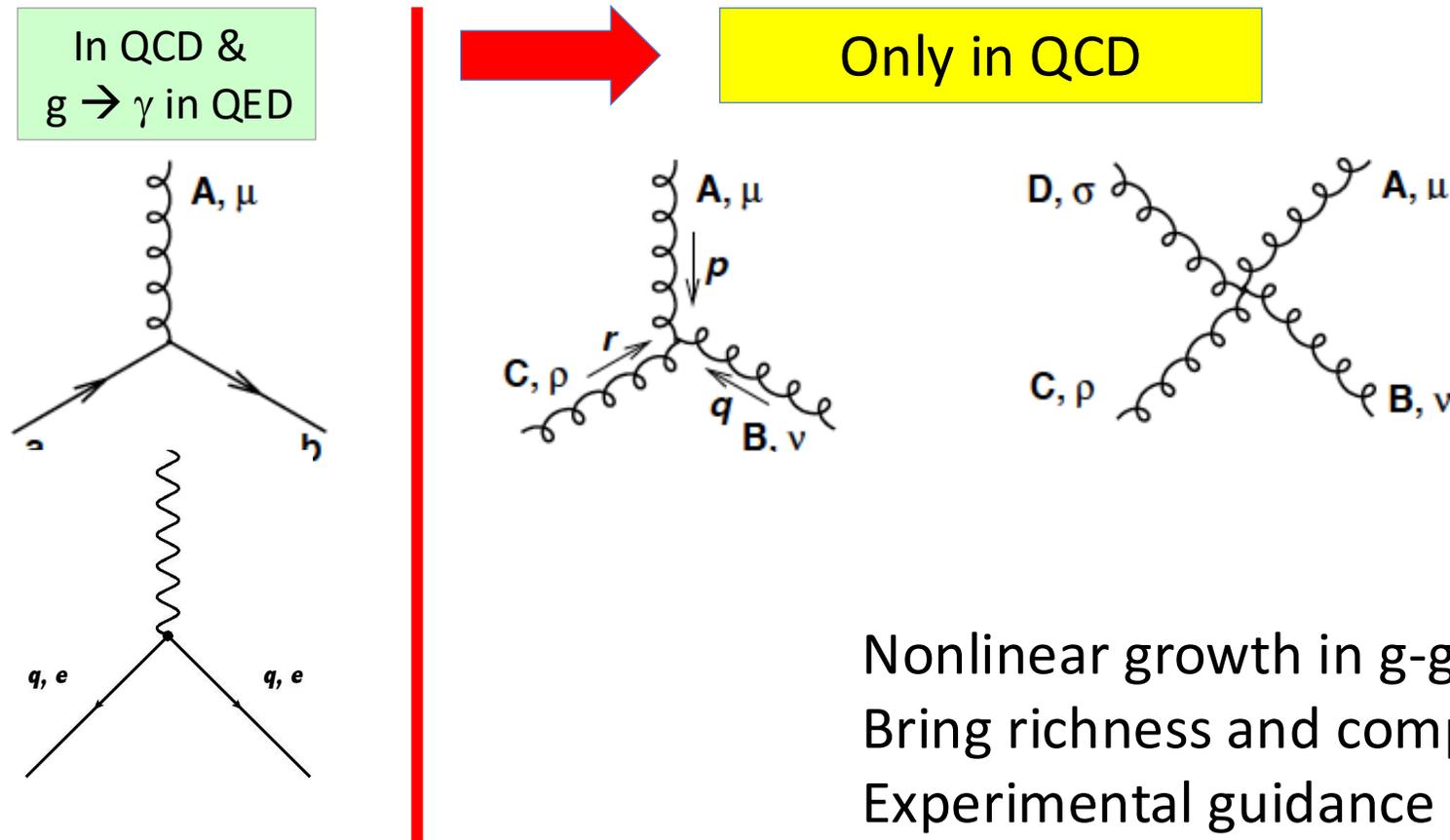
- $e^+ e^- \rightarrow q \bar{q} g \rightarrow 3\text{-jets}$



# What distinguishes QCD from QED?

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

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



# Introduction to EIC – three lectures

- Hour 1: Scientific history of “EIC Science”
  - ❖ Science drivers: Past & current experiments:
  - ❖ Their limitations
- Lecture 2: EIC Science
  - ❖ How EIC will overcome the limitations
- Lecture 3: EIC realization
  - ❖ Realization, a dream come through & the status
  - ❖ “Can I participate?” – Yes, you can!

# Deep Inelastic Scattering (DIS)

# Study of internal structure of a watermelon:



A-A (RHIC/LHC)

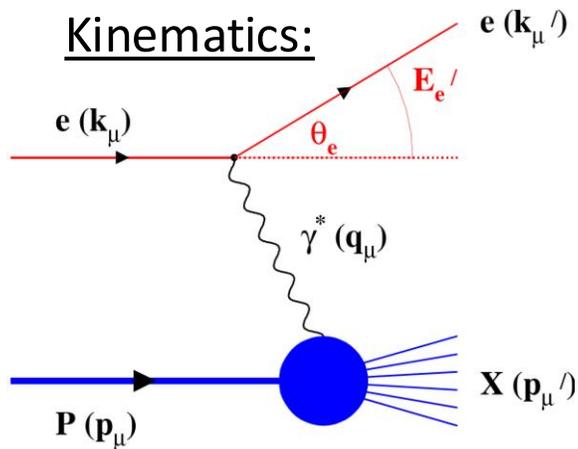
1) Violent collision of melons



2) Cutting the watermelon with a knife

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

# Deep Inelastic Scattering: Precision and control



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e (1 - \cos \Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\Theta'_e}{2} \right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

**Hadron :**

$$z = \frac{E_h}{\nu}; p_t \quad \text{with respect to } \gamma^*$$

$$s = 4 E_h E_e$$

**Exclusive DIS**

detect & identify everything  $e+p/A \rightarrow e'+h(\pi,K,p,jet)+\dots$

**Semi-inclusive events:**

$e+p/A \rightarrow e'+h(\pi,K,p,jet)+X$

detect the scattered lepton in coincidence with identified hadrons/jets

**Inclusive events:**

$e+p/A \rightarrow e'+X$

detect only the scattered lepton in the detector

High lumi & acceptance



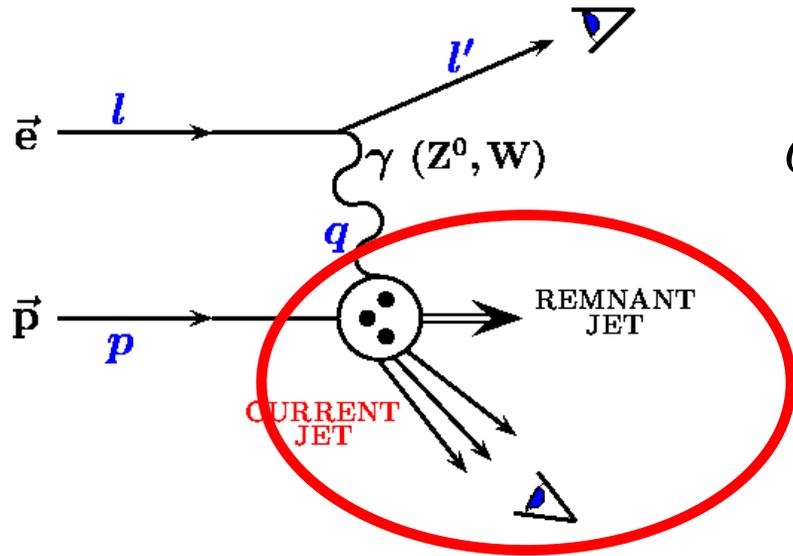
Low lumi & acceptance

# Some times scattered electron can't be measured....

## Reason:

- 1) Scattering angle so small that it is too close to the beam pipe
- 2) Radiative correction too large, i.e. electron lost its energy due to Initial State Radiation or Brehmstrahlung through material -- So the kinematic reconstruction unreliable.

*What to do? Then see if we can reconstruct the hadronic final state?*



$$y = \frac{E_j}{2E_e}(1 - \cos\theta_j)$$

$$Q^2 = E_j^2 \sin^2\theta_j / (1 - y)$$

$$x = \frac{E_j}{2E_p}(1 + \cos\theta_j) / (1 - y)$$

$$E_j = yE_e + x(1 - y)E_p$$

$$\cos\theta_j = \frac{-yE_e + (1 - y)xE_p}{yE_e + (1 - y)xE_p}$$

$$E_j^2 \sin^2\theta_j = 4xy(1 - y)E_eE_p = Q^2(1 - y)$$

$$y_{JB} = \frac{1}{2E_e} \sum_h (E_h - p_{Zh})$$

$$Q_{JB}^2 = \frac{(\sum_h p_{Xh})^2 + (\sum_h p_{Yh})^2}{1 - y_{JB}}$$

$$x_{JB} = Q_{JB}^2 / (y_{JB}s)$$

# Complete set of variables for DIS e-p:

<https://core.ac.uk/download/pdf/25211047.pdf>

We will use some of these more often than others, you should know them all.

$E_p$	proton beam energy
$E_e$	electron beam energy
$p = (0, 0, E_p, E_p)$	four momentum of incoming proton with mass $m_p$
$e = (0, 0, -E_e, E_e)$	four momentum of incoming electron
$e' = (E'_e \sin\theta'_e, 0, E'_e \cos\theta'_e, E'_e)$	four momentum of scattered electron
$s = (e + p)^2 = 4E_p E_e$	square of total ep c.m. energy
$q^2 = (e - e')^2 = -Q^2$	mass squared of exchanged current $J$ = square of four momentum transfer
$\nu = q \cdot p / m_p$	energy transfer by $J$ in p rest system
$\nu_{max} = s / (2m_p)$	maximum energy transfer
$y = (q \cdot p) / (e \cdot p) = \nu / \nu_{max}$	fraction of energy transfer
$x = Q^2 / (2q \cdot p) = Q^2 / (ys)$	Bjorken scaling variable
$q_c = x \cdot p + (e - e')$	four momentum of current quark
$M^2 = (e' + q_c)^2 = x \cdot s$	mass squared of electron - current quark system.

# Unpolarized e-p/A DIS

# DIS without Spin:

See A. Cooper-Sarkar's set  
of lectures.

## Inclusive Cross-Section:

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

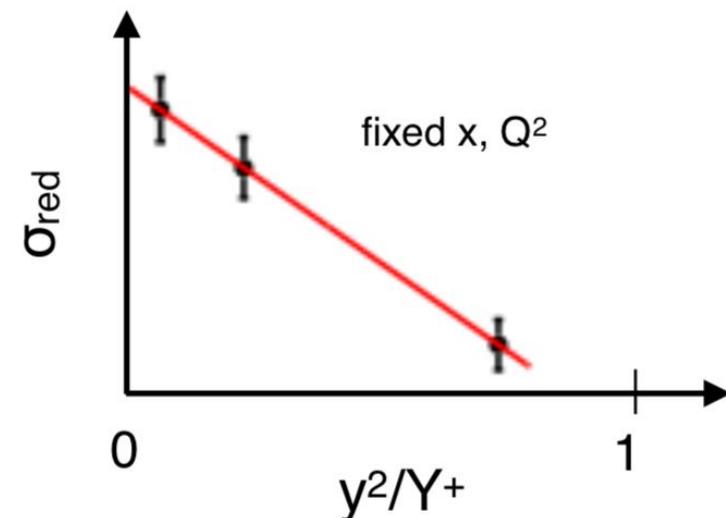
## Reduced Cross-Section:

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

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

## Rosenbluth Separation:

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



$$(CME)^2 = S = 4 E_e E_p$$

## Early experiments: fixed target

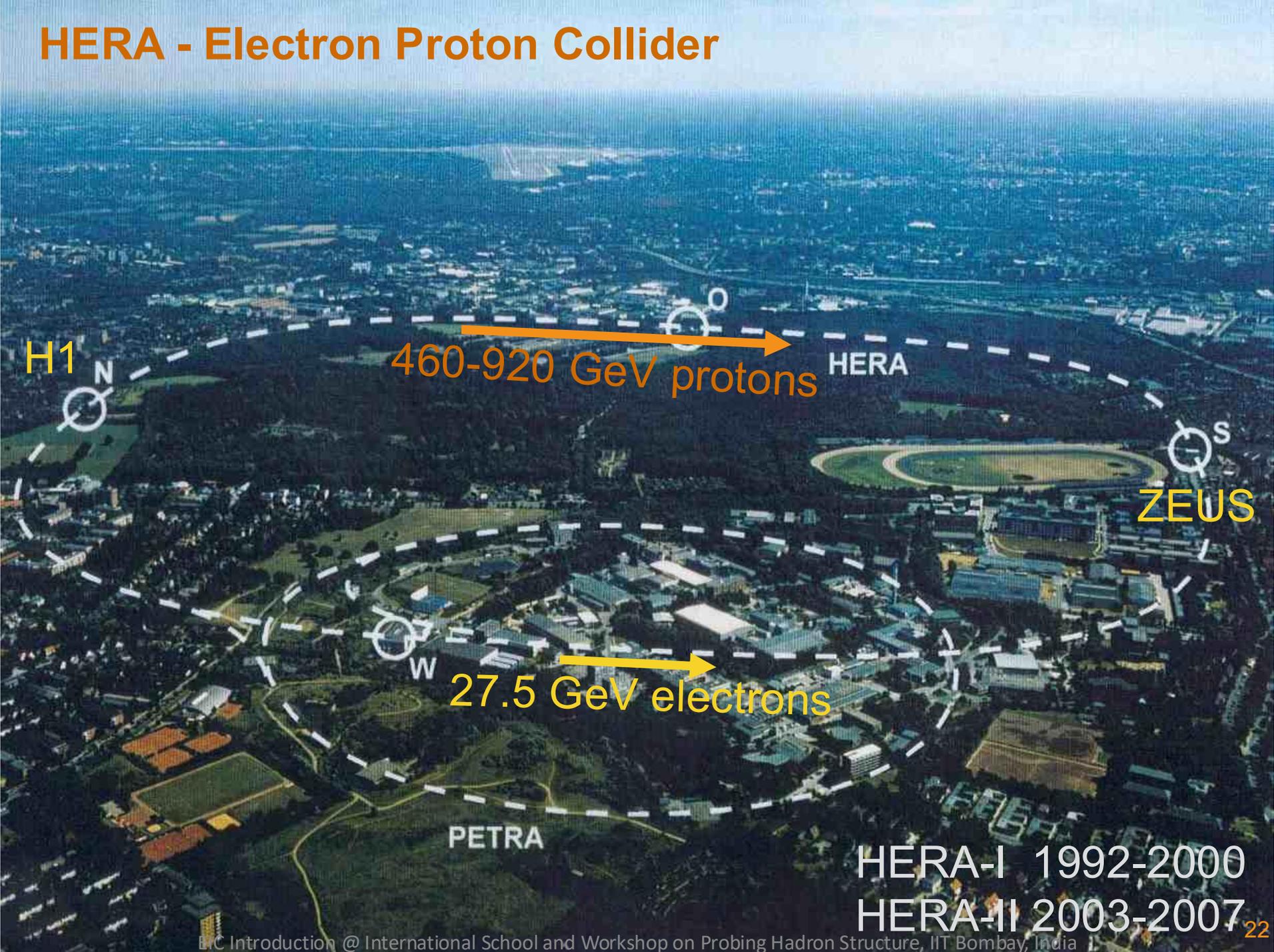
With electron (3-20 GeV) and muon (up to 240 GeV) beams

Range of Center of Mass Energies (CME)

## HERA the first e-p collider:

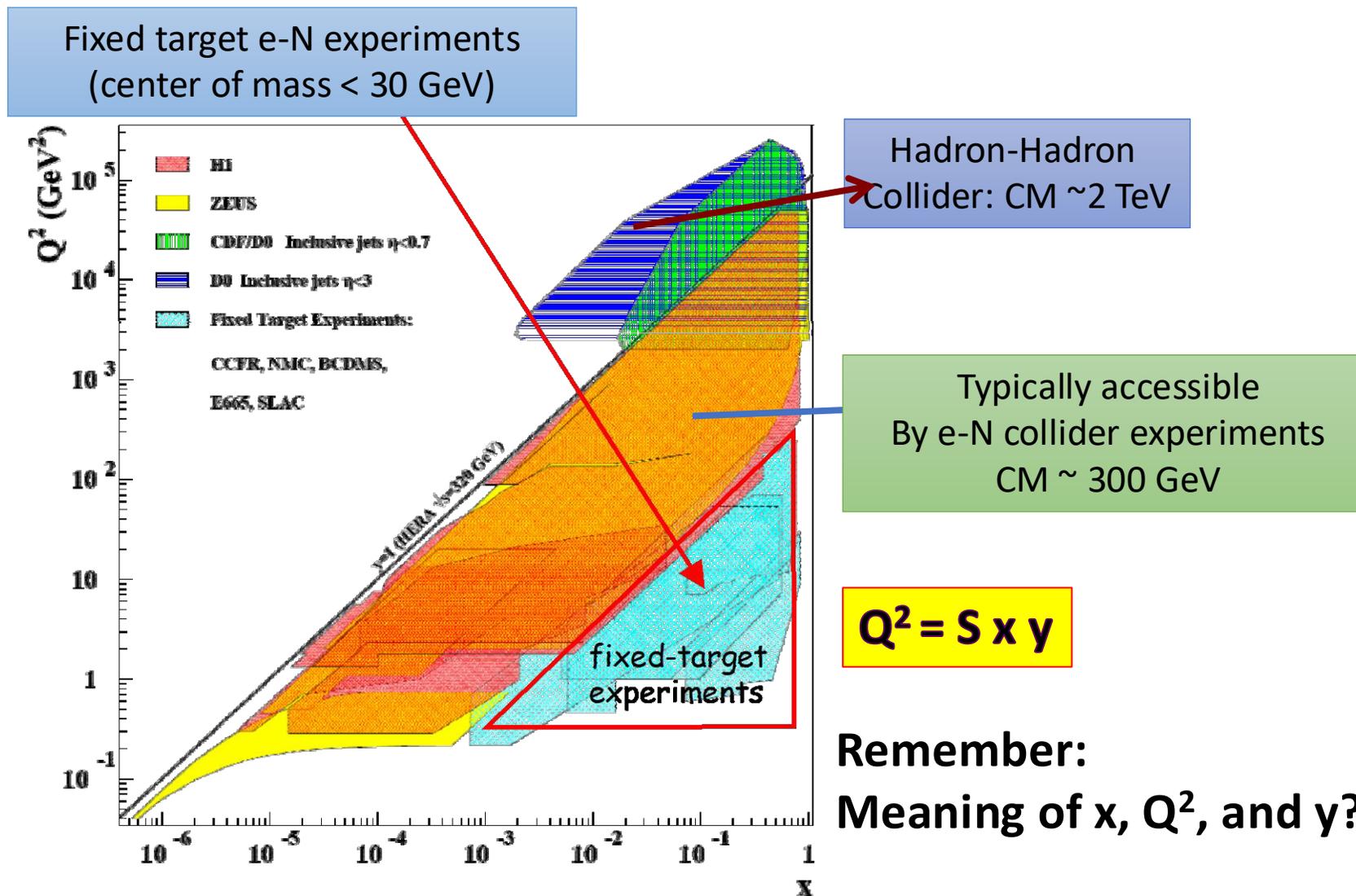
~300 GeV Center of Mass: 820 GeV p x 27 GeV e

# HERA - Electron Proton Collider

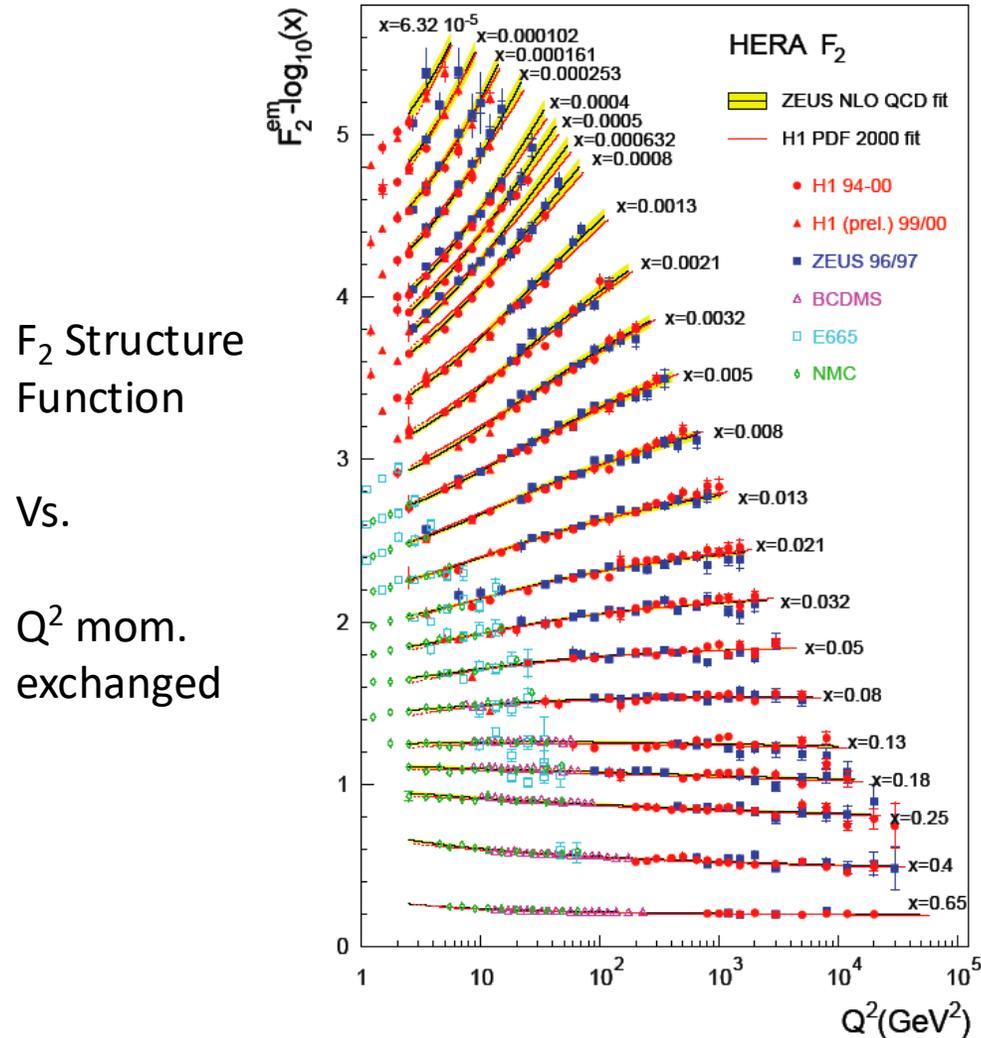


HERA-I 1992-2000  
HERA-II 2003-2007

# Perspective on $x, Q^2$ , Center of Mass



# Measurement of unpolarized glue at HERA



$F_2$  Structure Function

Vs.

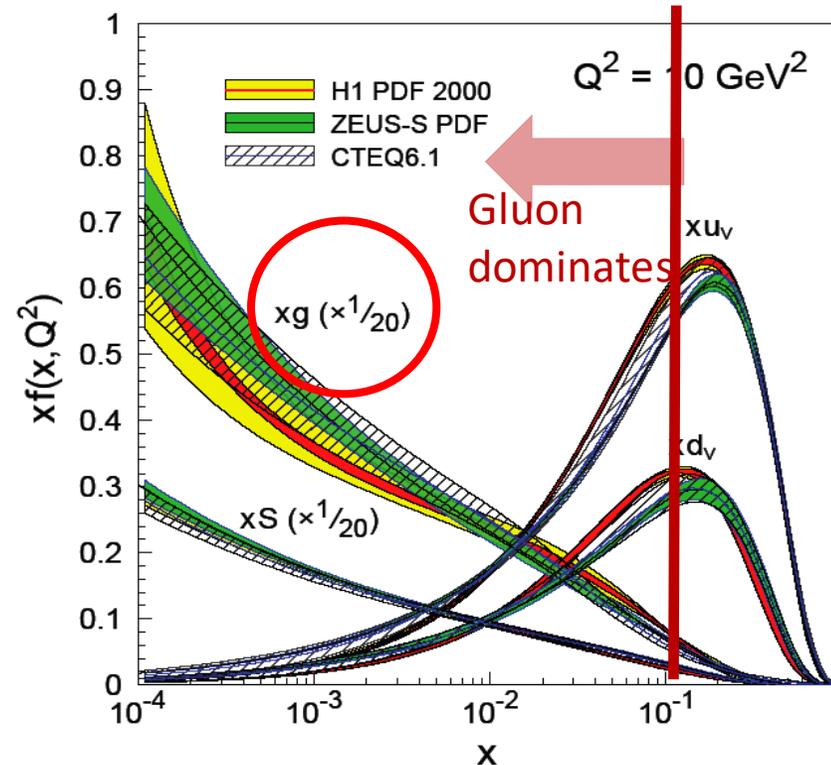
$Q^2$  mom. exchanged

\*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

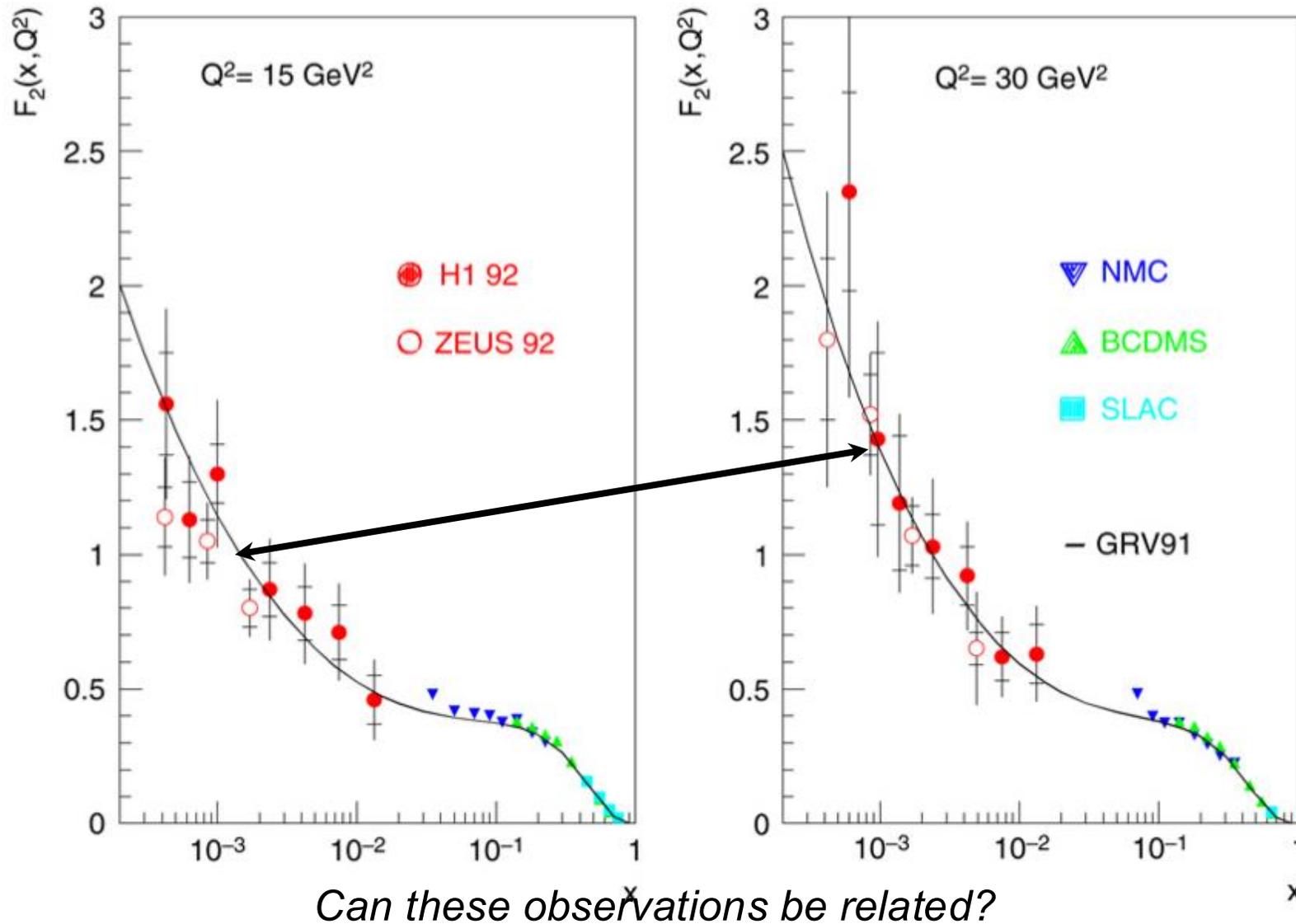
- Scaling violations of  $F_2(x, Q^2)$

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

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



# HERA - Early Measurements

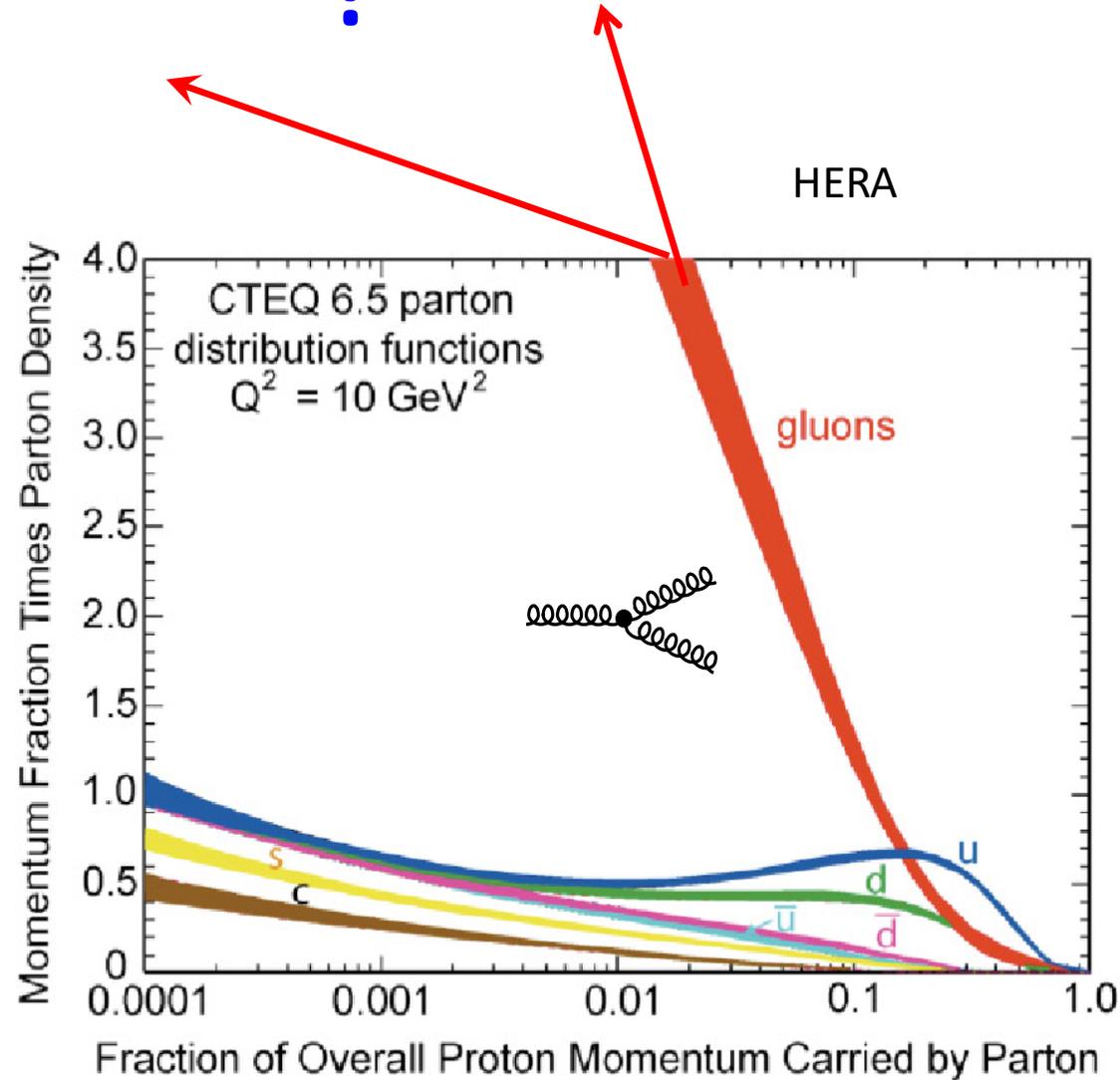


Yes! Through  
QCD evolution!  
At the heart of it  
are gluons

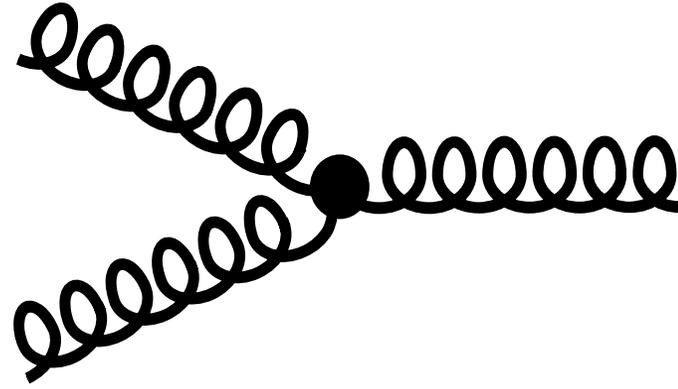
*Can these observations be related?*

?

Low x rise  
of the gluon  
distribution



What could  
tame the  
low-x rise?



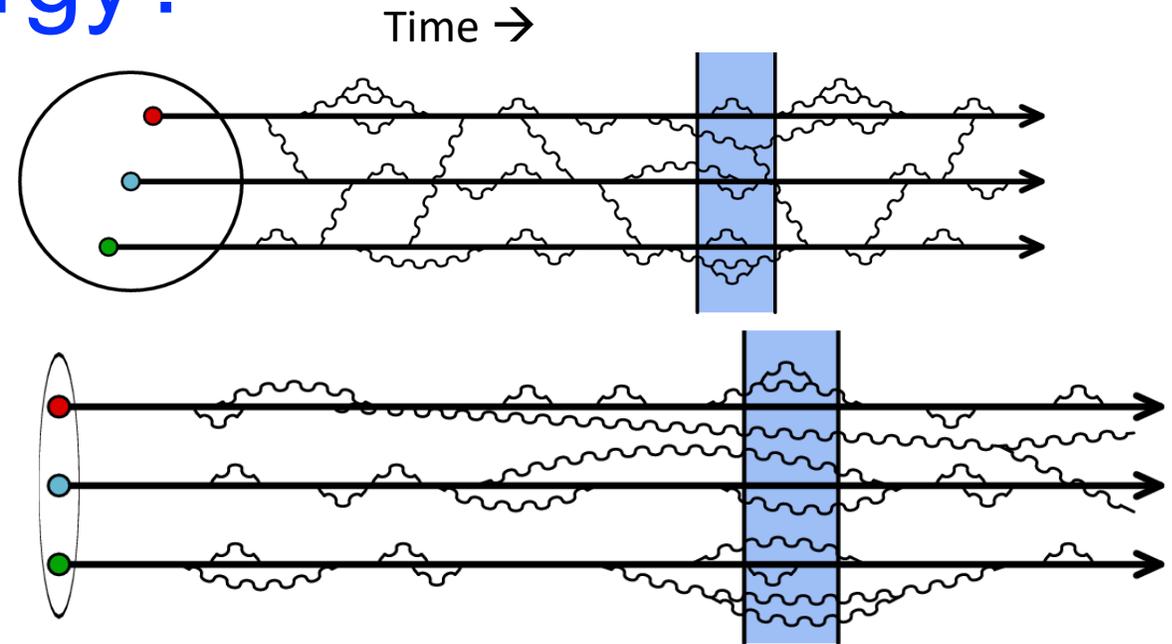
# Consequence of gluon self interactions → non-linear GDLAP evolution... ?

Particularly at high energy → low-x

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

Low energy: High  $x$   
Regime of fixed target exp.

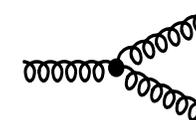
High energy: Low-  $x$   
Regime of a Collider



Cartoon of boosted proton

## At high energy:

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



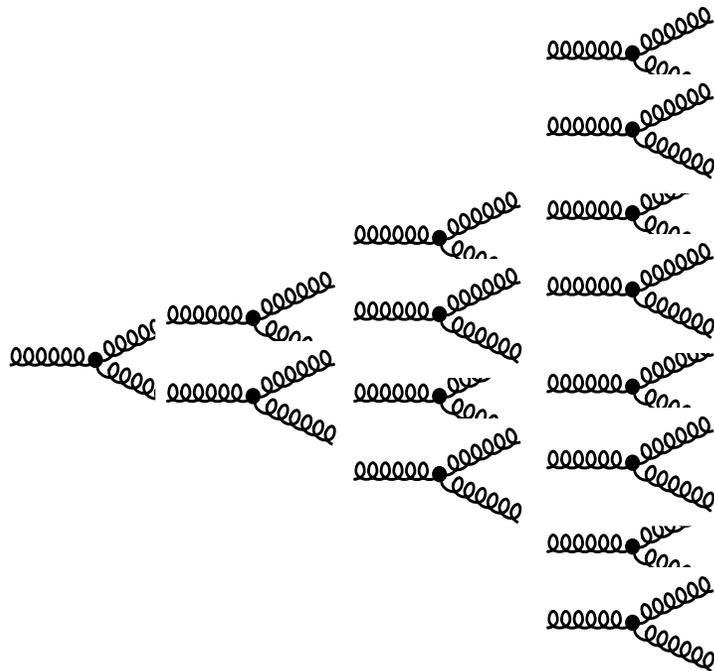
Gluon splitting

# 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*

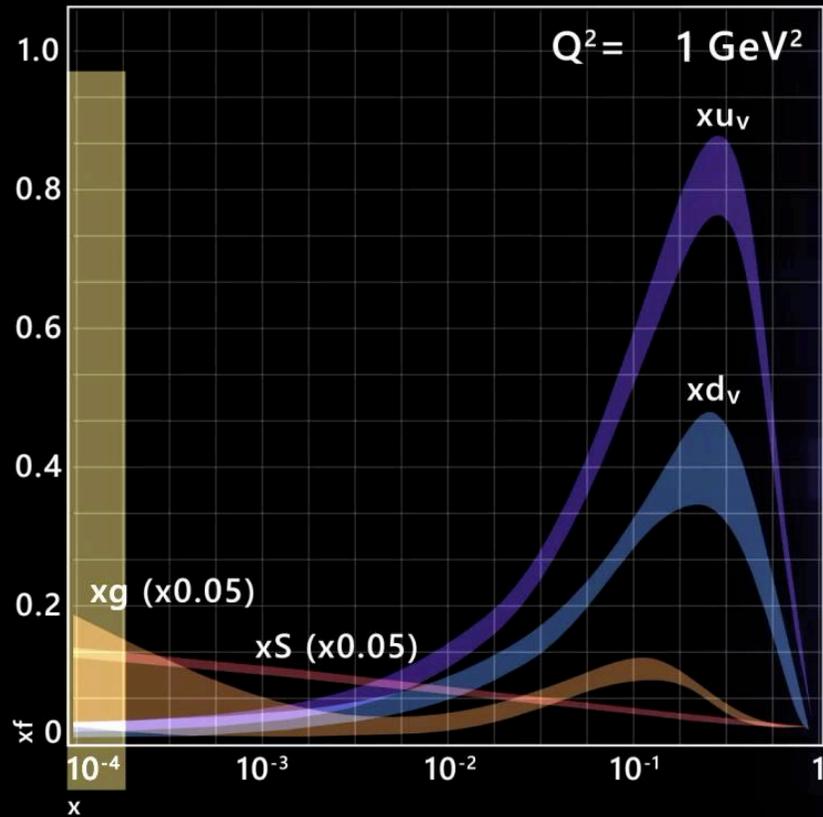


? Infinity?  
**No!**



# Proton Structure - Artistic Visualization

Compare two "resolution" scenarios:  $Q^2 = 1, 200 \text{ GeV}^2$   
Size of the boxes on the right



SPUTNIK  
ANIMATION

Jefferson Lab  
Thomas Jefferson National Accelerator Facility

ARTS  
CENTER FOR ART,  
SCIENCE & TECHNOLOGY  
AT MIT

Let's switch gears...  
Another QCD puzzle emerged  
in the 1990's

“Proton Spin” Crisis -- Puzzle

# 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.

“*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)*

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

Quark Spin.
Quark Ang. Mom.
Gluon Spin.
Gluon Ang. Mom

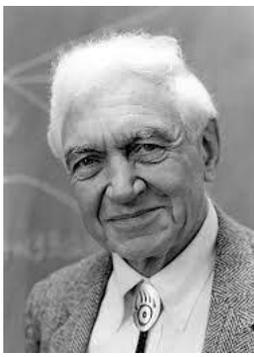
# Proton Spin Crisis

Adeva et al, Phys. Rev. D **58**, 112001 (1998) Spin asymmetry measurements

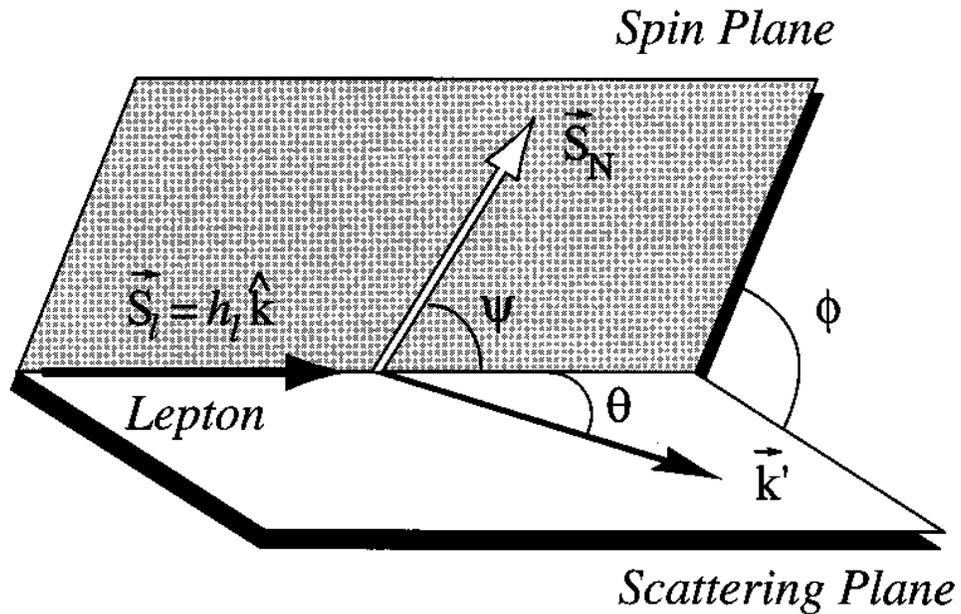
Adeva et al. Phys. Rev. D **58**, 112002 (1998) NLO calculations and global fits using the world Sample of data in 1998

Aidala et al. Rev. Mod. Phys. **85**, 655 (2013)

# Lepton-nucleon cross section...with spin



V. W. Hughes  
1922-2003



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

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

For high energy scattering  $\gamma$  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....

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

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

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

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

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

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

# First Moments of SPIN Structure Functions

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

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

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

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 Sum Rule

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

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

Assuming  $SU(3)_f$  &  $\Delta s = 0$ ,

J.Ellis and R.L.Jaffe, Phys.Rev.D9(1974), D10 (1974) 1669

$$\Gamma_1^p = 0.170 \pm 0.004$$

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

Low 8-20 GeV electron beam on fixed target

Did not reach low enough  $x \rightarrow x_{\min} \sim 10^{-2}$

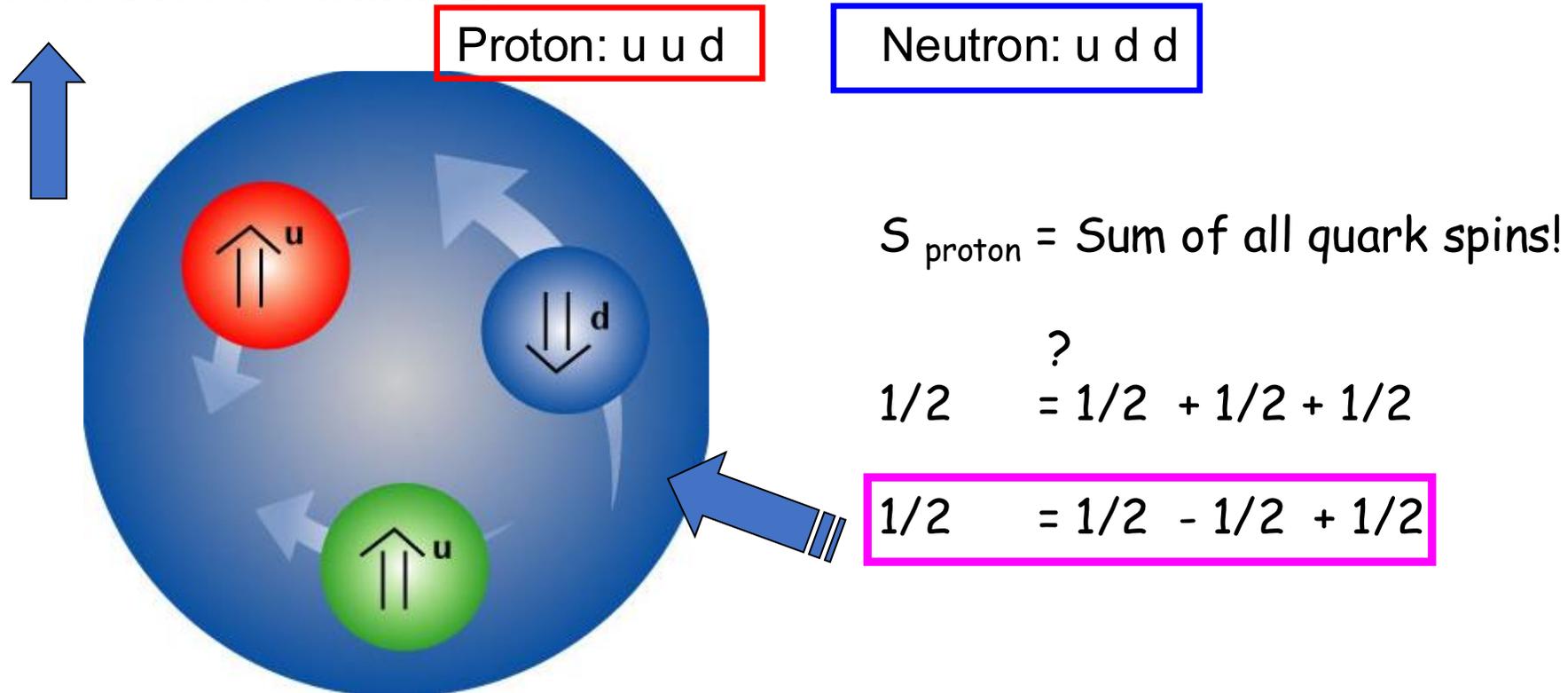
Found consistency of data and E-J sum rule above

But higher energy  
muon beam exposed  
something important  
and unexpected!

# The measurement and surprises...

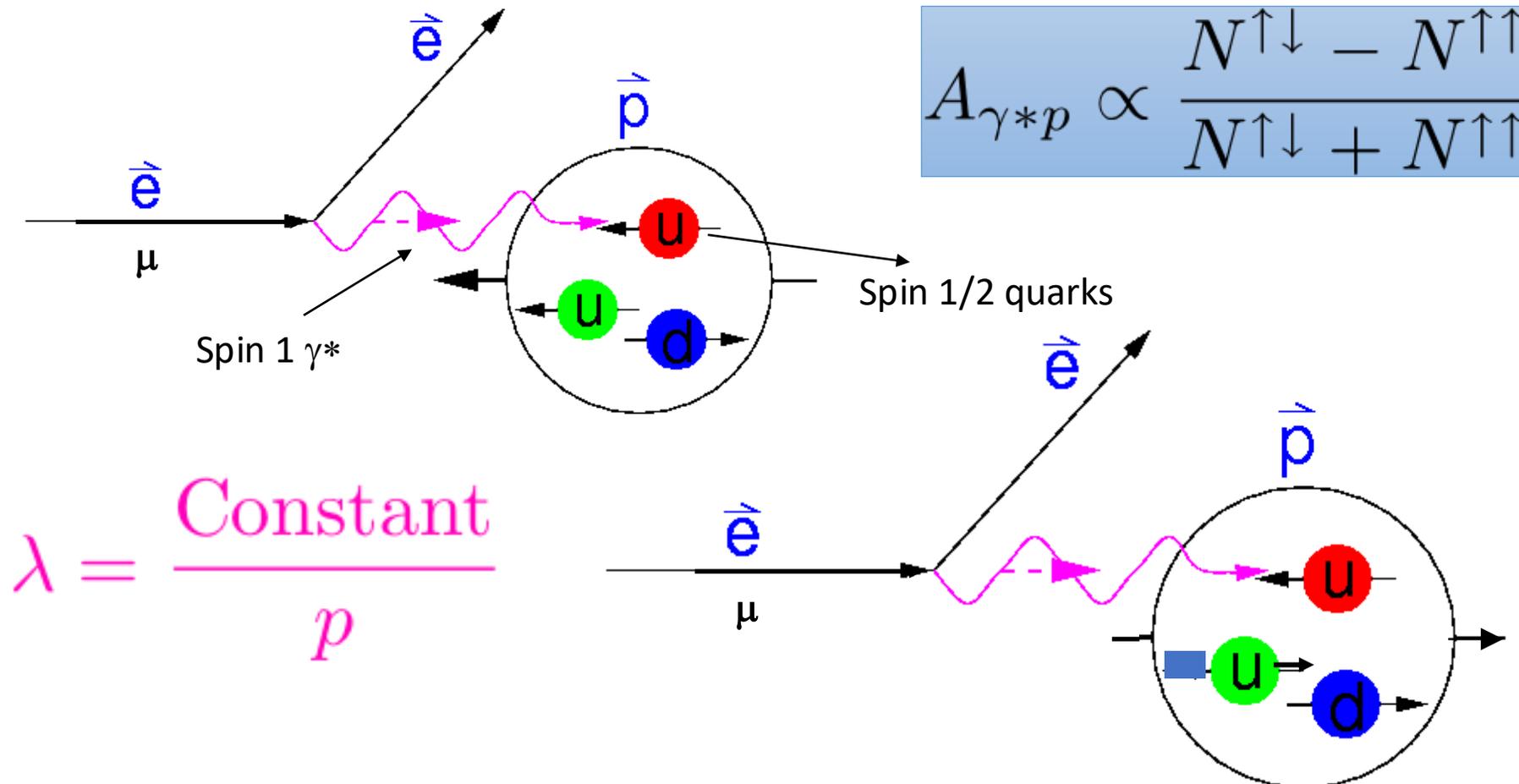
# Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects... now, illustration only, but historically taken seriously)

- 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



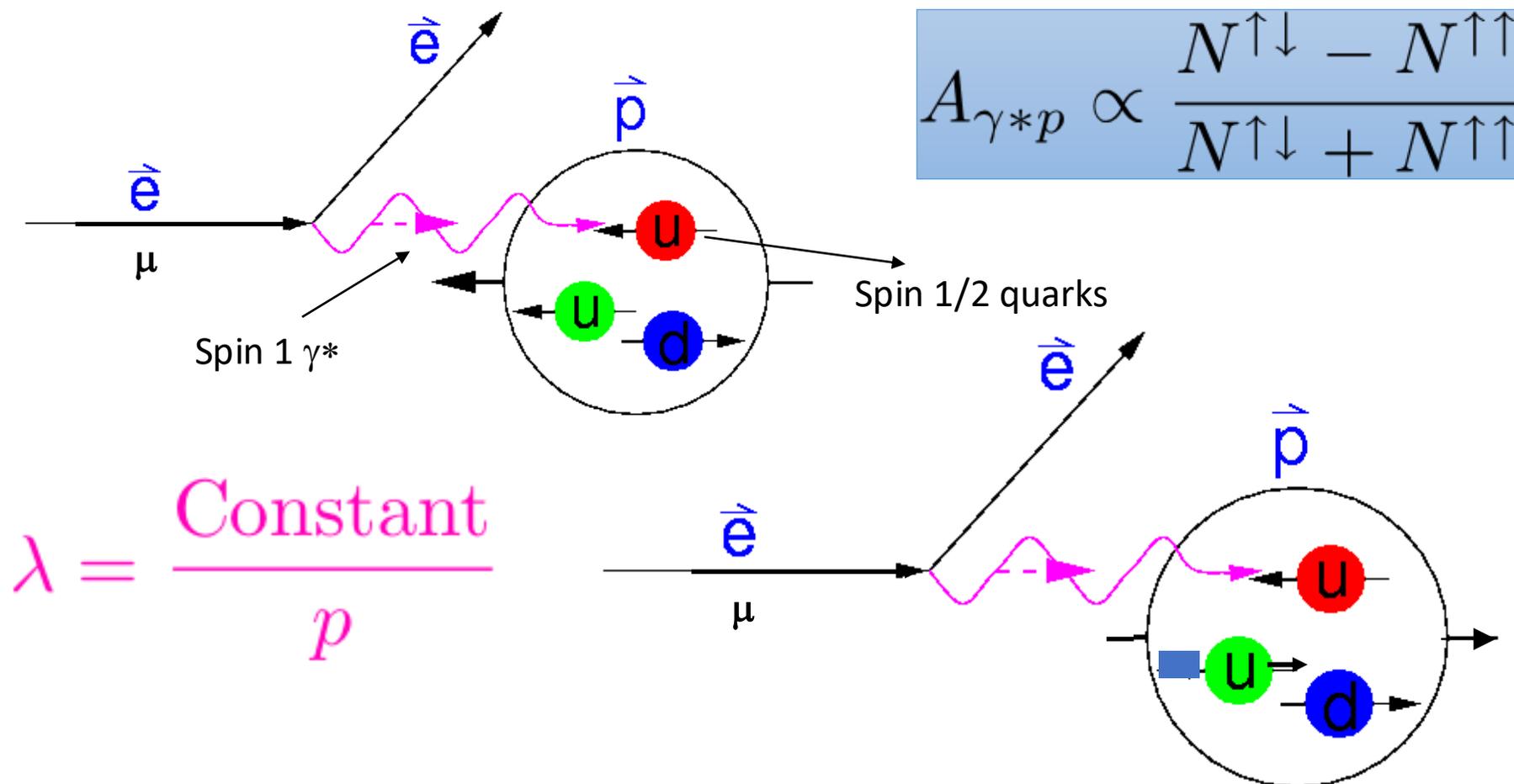
# How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

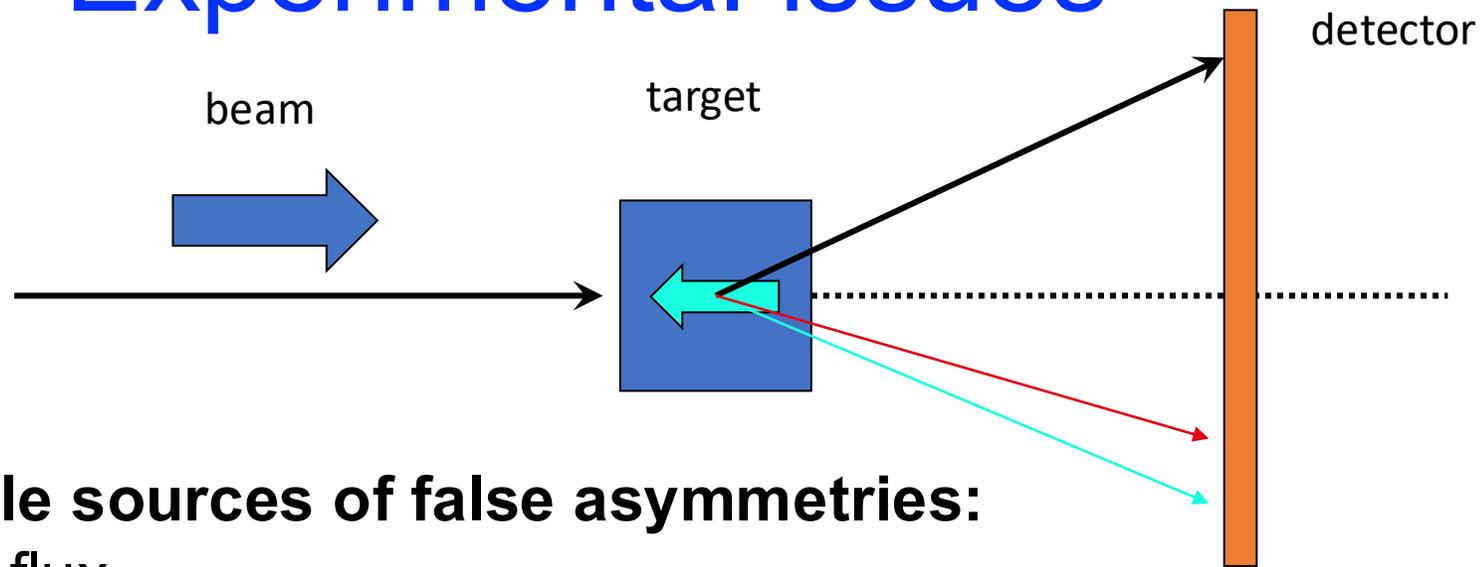


# How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

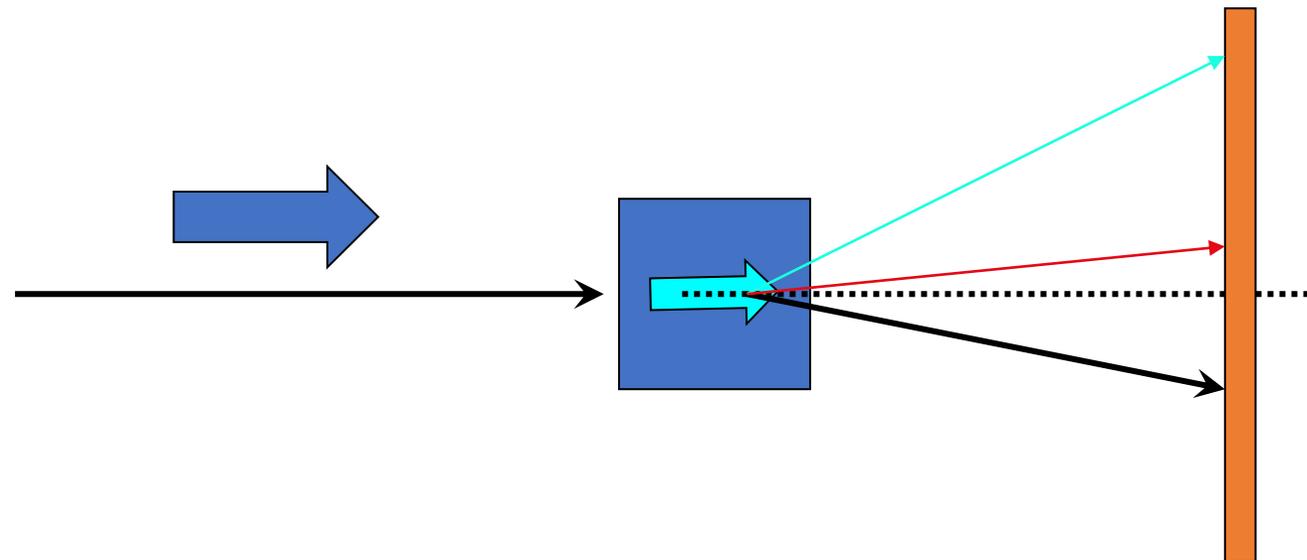


# Experimental issues



## Possible sources of false asymmetries:

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



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

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

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

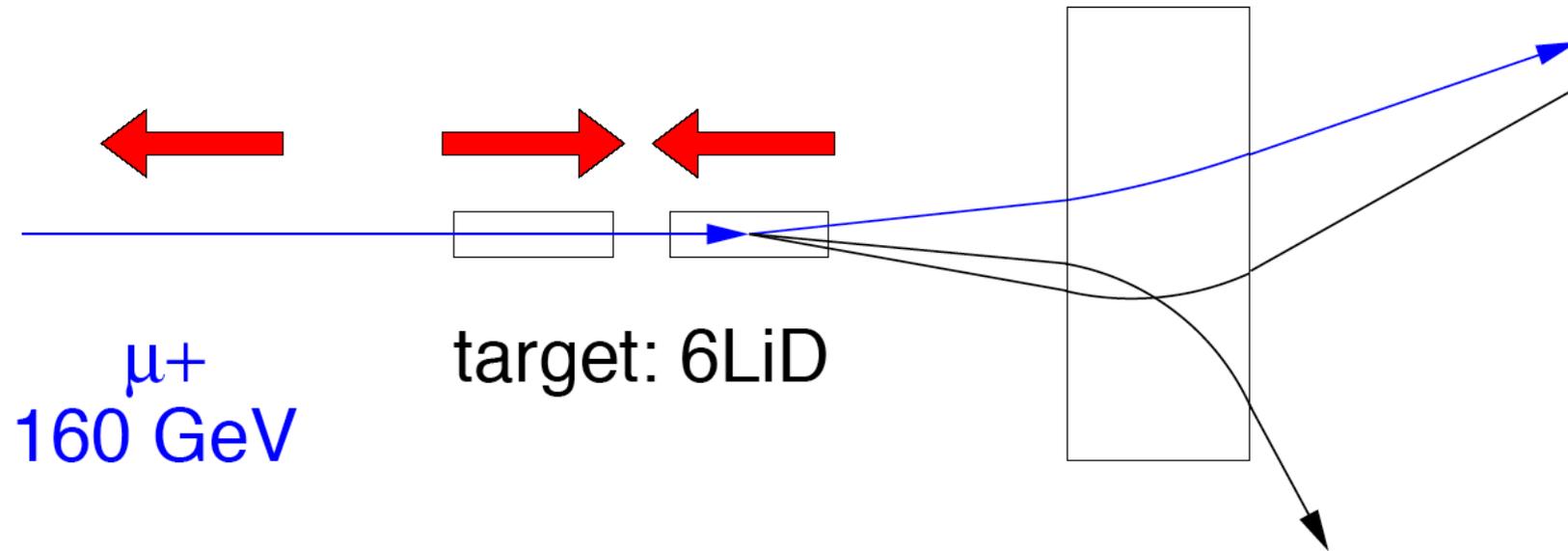
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

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

# Experimental Needs in DIS

## **Polarized target, polarized beam**

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

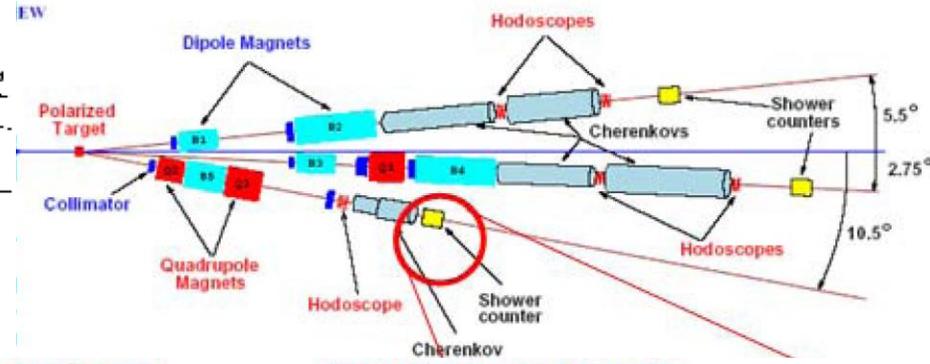
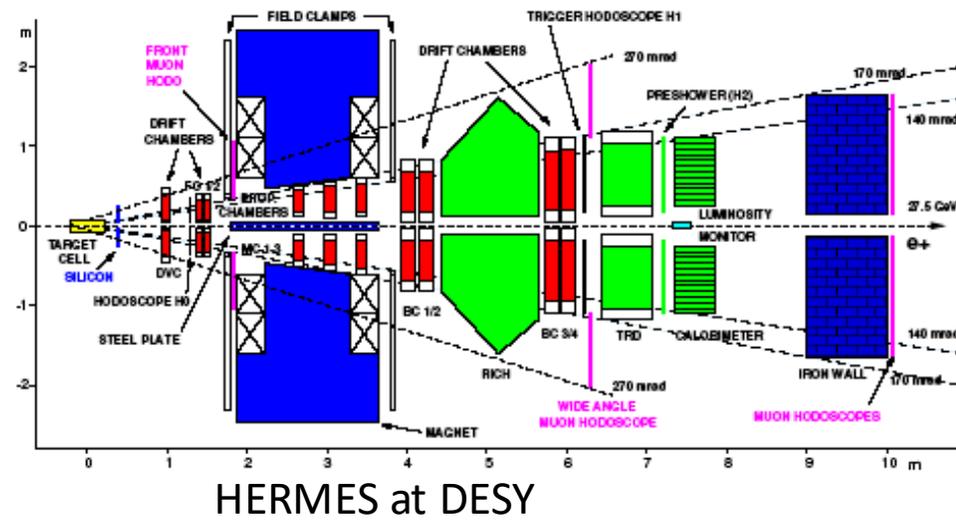
## **Determine the kinematics: measure with high accuracy:**

- 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.)**

# Experiments

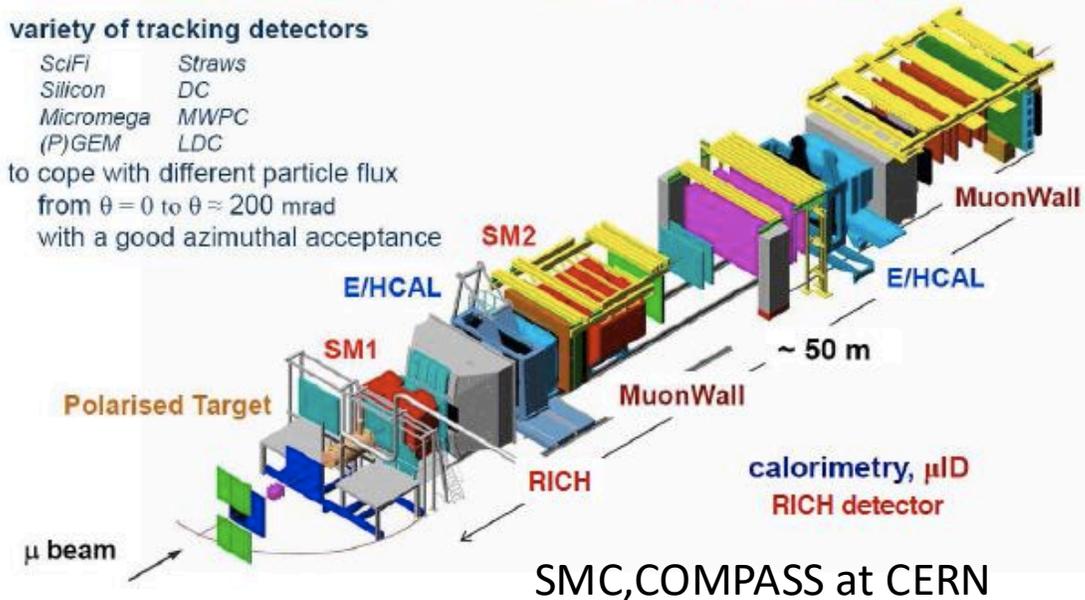
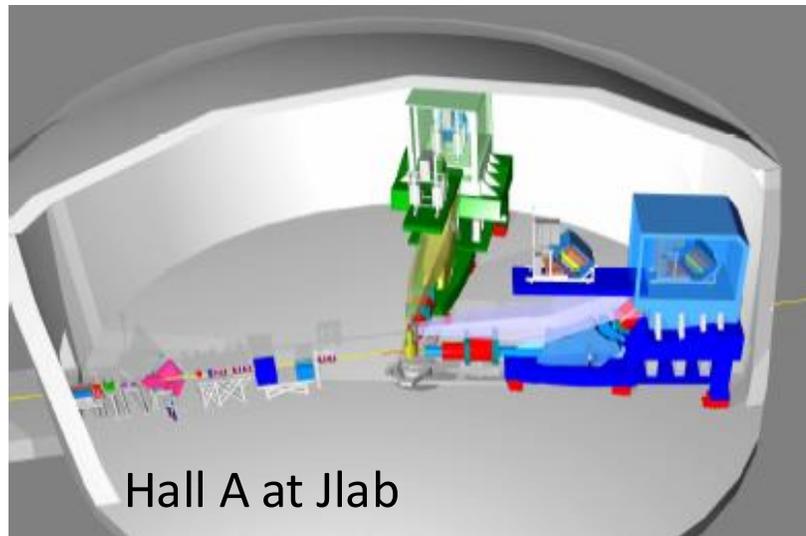


- high energy beams
- large angular acceptance
- broad kinematical range

### variety of tracking detectors

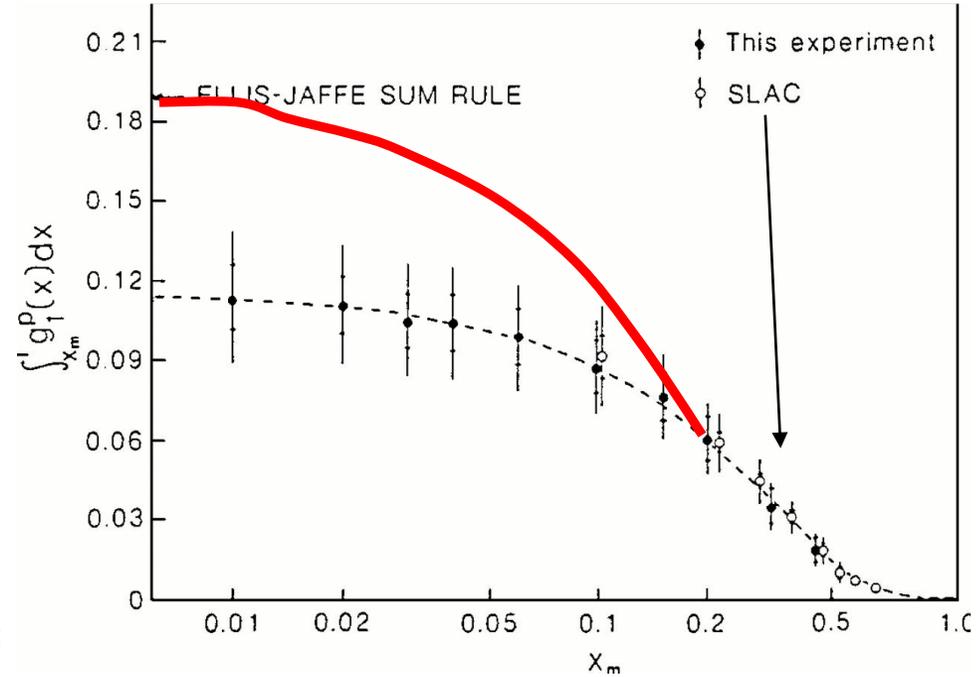
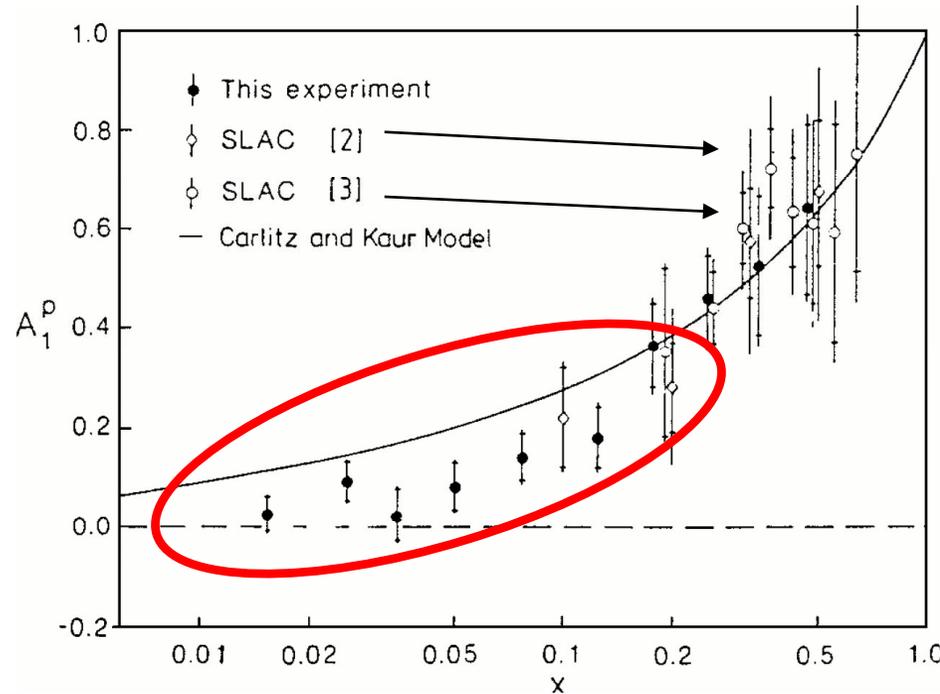
SciFi	Straws
Silicon	DC
Micromega	MWPC
(P)GEM	LDC

to cope with different particle flux  
from  $\theta = 0$  to  $\theta \approx 200$  mrad  
with a good azimuthal acceptance



# Proton Spin Crisis (1989)!

*EMC experiment at CERN: high energy muon beam – reached lower x*



$$\Delta\Sigma / 2 = (0.12) \pm (0.17) \text{ (EMC, 1989)}$$

$$\Delta\Sigma / 2 = 0.58 \text{ expected from E-J sum rule....}$$

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

# Proton spin puzzle

- EMC & SMC experiment at CERN along with experiments at SLAC established without any doubt that quarks do NOT explain the proton's spin quantum number.
- Ellis-Jaffe spin sum rule is violated.
- $\Delta\Sigma = 0.25 \rightarrow$  Quark's contribution is  $\frac{1}{2} (DS) = 0.12$  out of proton's spin  $\frac{1}{2}$
- Where is the remaining SPIN?

