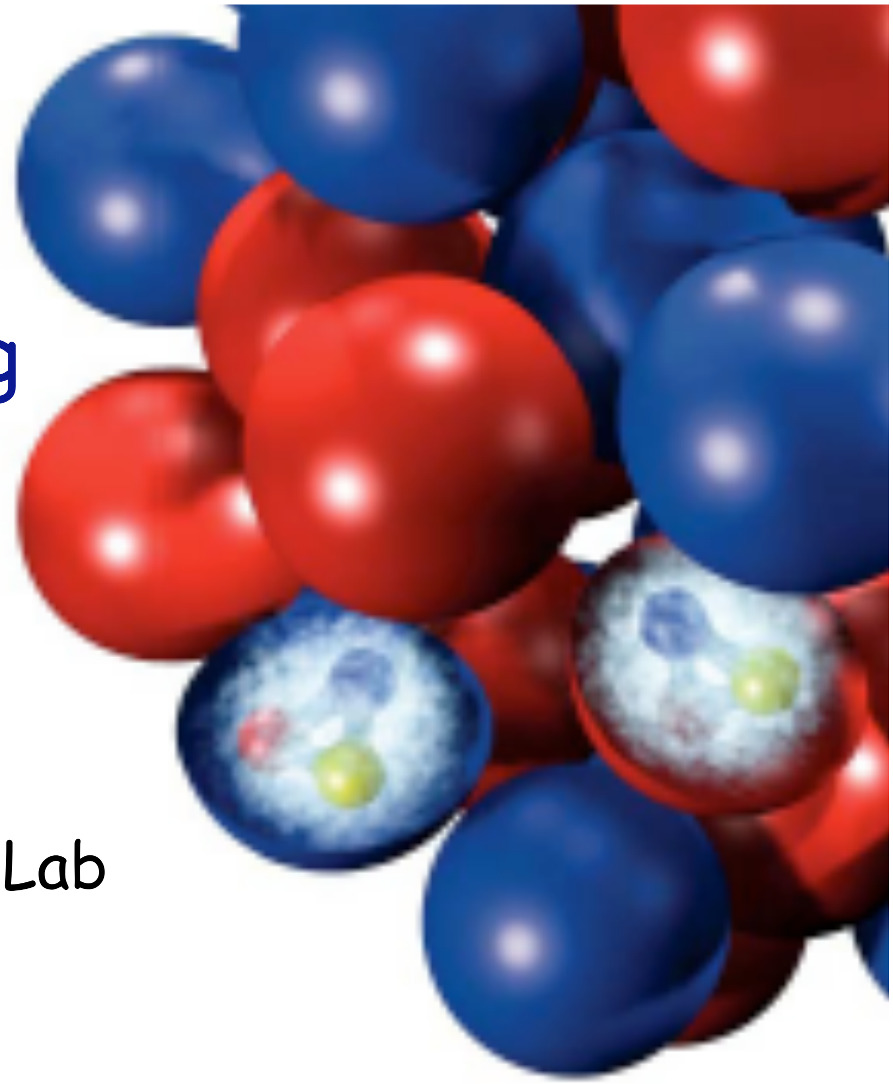
Deep Inelastic Scattering

CTEQ Summer School

Madison, WI, July 2011



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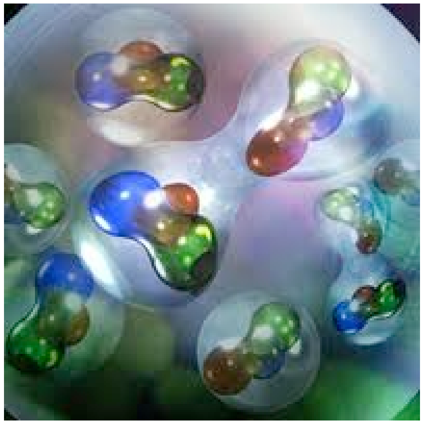
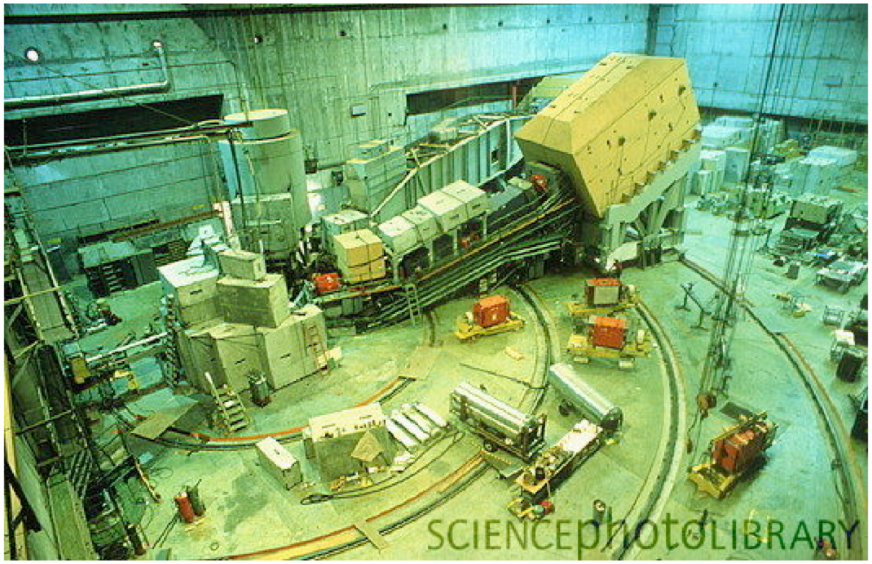


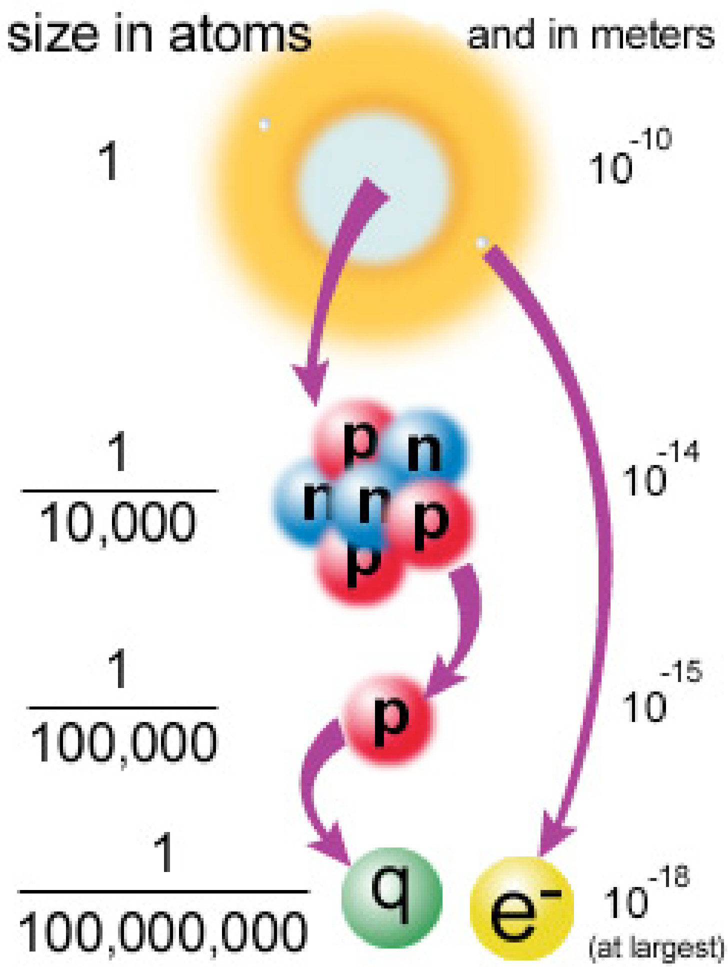
40 years of physics

Maybe 100 experiments

...in an hour.....



How to probe the nucleon / quarks?



large momentum -> short distance
(Uncertainty Principle at work!)

- Scatter high-energy lepton off a proton:

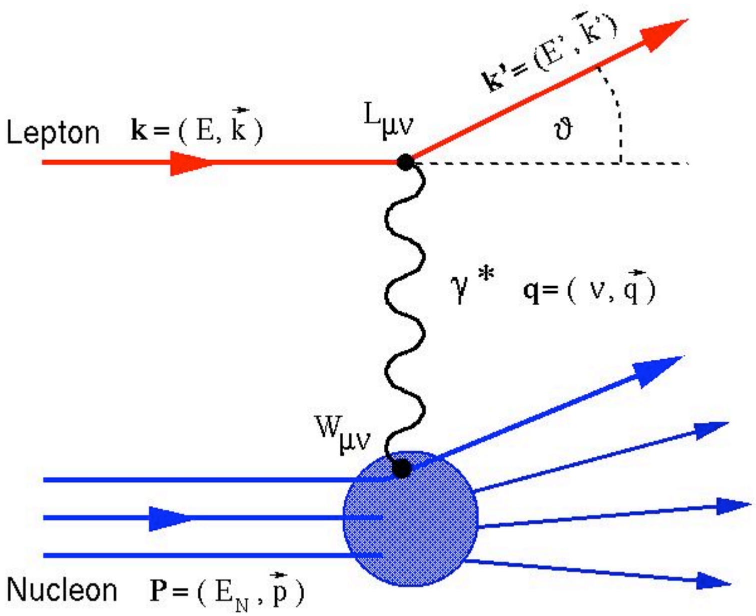
Deep-Inelastic Scattering (DIS)

- In DIS experiments point-like leptons + EM interactions which are well understood are used to probe hadronic structure (which isn't).

- Relevant scales:

$$d_{probed} \propto \lambda\!\!\!^{-} = \frac{\hbar}{p} \approx 10^{-18}\ \mathrm{m}$$

DIS Kinematics



$L_{\mu\nu}$: lepton tensor

$W_{\mu\nu}$: hadron tensor

*a virtual photon of four-momentum **q** is able to resolve structures of the order ℏ/√ q²*

- Four-momentum transfer:

$$q^2 = (E - E')^2 - (\vec{k} - \vec{k}') \cdot (\vec{k} - \vec{k}') =$$
$$= m_e^2 + m_{e'}^2 - 2(EE' - |\vec{k}||\vec{k}'|\cos\theta) =$$
$$\approx \; -4EE'\sin^2\tfrac{\theta}{2} \equiv -Q^2$$

- Mott Cross Section ($\hbar c = 1$):

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4\alpha^2 E'^2}{Q^4}\cos^2\frac{\theta}{2} \cdot \frac{E'}{E}$$
$$= \frac{4\alpha^2 E'^2}{16E^2E'^2\sin^4\frac{\theta}{2}}\cos^2\frac{\theta}{2} \cdot \frac{1}{1+\frac{E}{M}(1-\cos\theta)}$$
$$= \frac{\alpha^2\cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}} \cdot \frac{1}{1+\frac{E}{M}(2\sin^2\frac{\theta}{2})}$$

Electron scattering of a spinless point particle

Electron-Proton Scattering

- Effect of proton spin:
  - Mott cross section:

$$\sigma_{Mott} = \frac{4\alpha^2 E'^2}{Q^4}\cos^2\frac{\theta}{2}\cdot\frac{E'}{E} \equiv \sigma_{Ruth}\cos^2\frac{\theta}{2}$$

  - Effect proton spin $\Rightarrow$
    - helicity conservation
    - 0 deg.: σ_{ep}(magnetic) $\rightarrow$ 0
    - 180 deg.: spin-flip!

      $\sigma_{magn} \sim \sigma_{Ruth}\ \sin^2(\theta/2)$

      $\sim \sigma_{Mott}\ \tan^2(\theta/2)$

$$\sigma_{e-spin-\frac{1}{2}} \propto \sigma_{Mott}\cdot[1 + 2\tau\tan^2\frac{\theta}{2}]$$

- with $\tau = \frac{Q^2}{4M^2c^2}$

Mass of target = proton

- Nucleon form factors:

$$\sigma_{ep} = \sigma_{Mott}[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}]$$

with:

$$A(Q^2) = \frac{G_E^2 + \tau G_M^2}{1+\tau} \quad \text{and} \quad B(Q^2) = 2\tau G_M^2$$

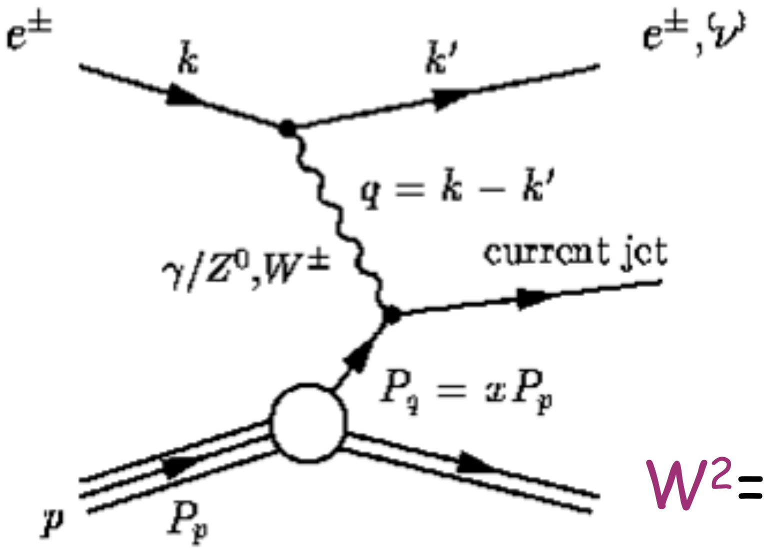
$$G_E^p(0) = 1 \quad \text{and} \quad G_M^p(0) = \tfrac{g_p}{2}\mu_N = 2.79\mu_N$$

$$G_E^n(0) = 0 \quad \text{and} \quad G_M^n(0) = \tfrac{g_n}{2}\mu_N = \text{-}1.91\mu_N$$

- The proton form factors have a substantial Q^2 dependence.

Measurement kinematics…

ep collision



Final electron energy

Initial electron energy

$$Q^2=-q^2=-(k-k')^2=2E_eE'_e(1+\cos\theta_e)$$

Electron scattering angle

$$W^2=(q+P_p)^2=M^2+2M(E_e-E'_e)-Q^2$$

= invariant mass of final state hadronic system

Everything we need can be reconstructed from the measurement of Ee, E'_e and θ_e. (in principle) ->

try a measurement!….

Excited states of the nucleon

- Scatter 4.9 GeV electrons from a hydrogen target. At 10 degrees, measure ENERGY of scattered electrons
- Evaluate invariant energy of virtual-photon proton system

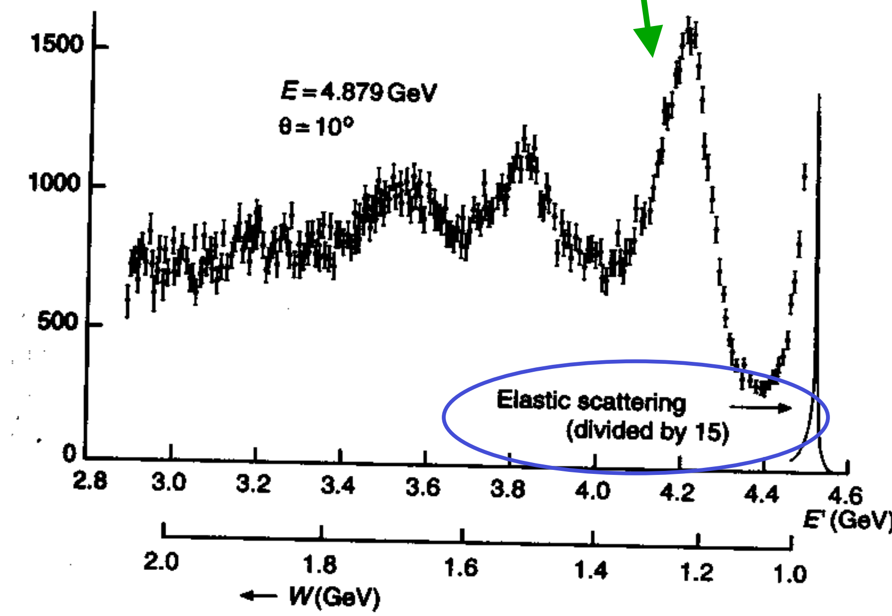
  $W^2 = 10.06 - 2.03 E'_e$ *
- In the lab-frame: $P = (m_p, 0) \rightarrow$

$$W^2 = (P_p + q)^2 = P^2 + 2Pq + q^2$$

$$W^2 = m_p^2 + 2m_p\nu - Q^2$$

* Convince yourself of this!

Δ(1232)



- Observe excited resonance states:

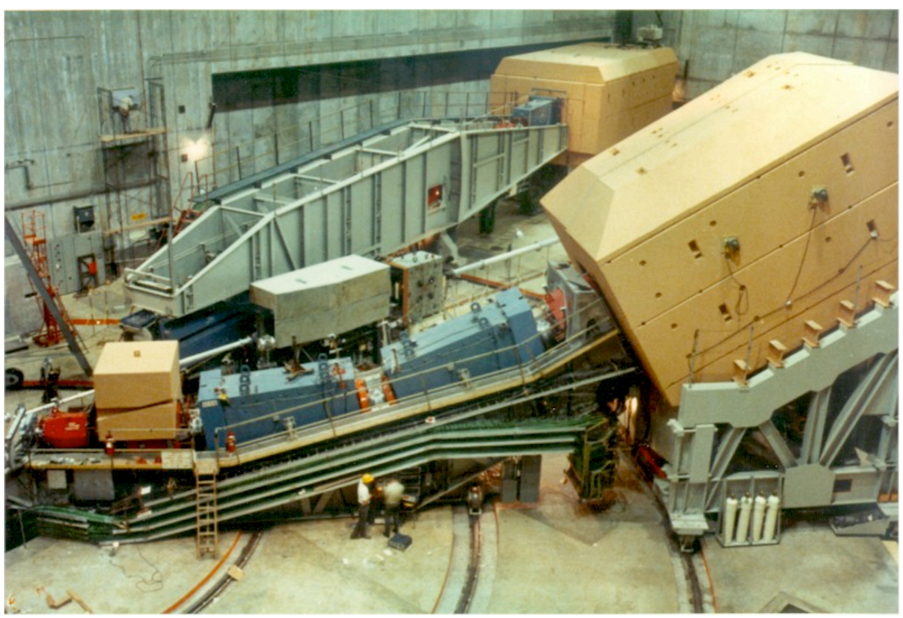
Nucleons are composite

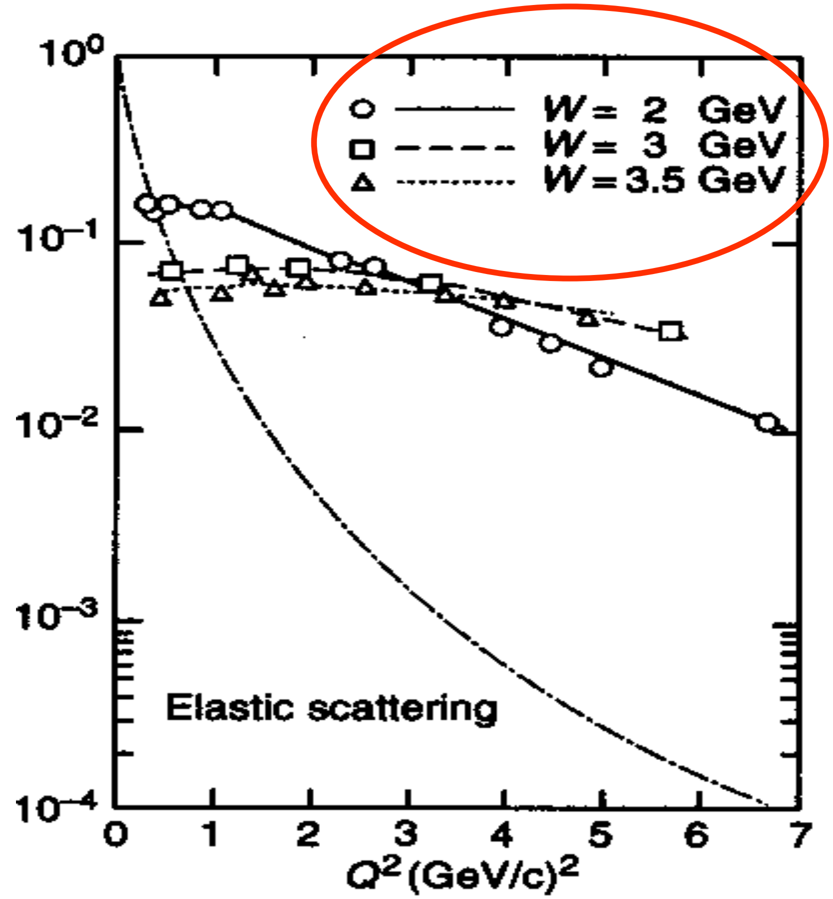
→ What do we see in the data for $W > 2$ GeV ?

- First SLAC experiment ('69):
  - expected from proton form factor:

$$\frac{d\sigma / dE' d\Omega}{(d\sigma / d\Omega)_{\mathrm{Mott}}} = \left(\frac{1}{(1+Q^2/0.71)^2} \right)^2 \propto Q^{-8}$$

- First data show big surprise:
  - very weak Q^2-dependence
  - form factor -> 1!
  - scattering off point-like objects?

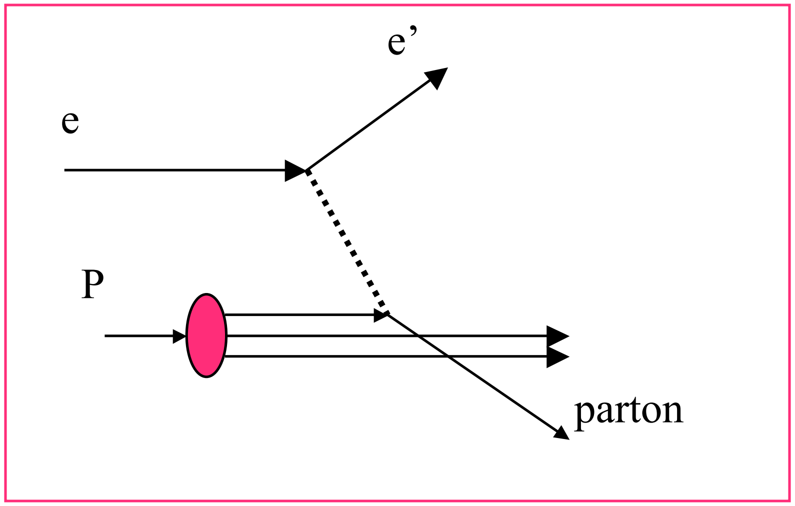




.... introduce a clever model!

The Quark-Parton Model

- Assumptions:
  - Proton constituent = Parton
  - Elastic scattering from a quasi-free spin-1/2 quark in the proton
  - Neglect masses and p_T's, "infinite momentum frame"



- Lets assume: $p_{quark} = xP_{proton}$

$$(xP+q)^2 = p'^2_{quark} = m^2_{quark} \approx 0$$

  - Since $xP^2 \leq M^2 << Q^2$ it follows:

$$2xP \cdot q + q^2 \approx 0 \Rightarrow x = \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu}$$

$\nu = (q \cdot p)/M = E_e\text{-}E_e'$

Definition Bjorken scaling variable

- Check limiting case:

$$W^2 = M_p^2 + 2M_p\nu - Q^2 \xrightarrow{x \to 1} M_p^2$$

- Therefore:

$x = 1$: elastic scattering

and $0 < x < 1$

Structure Functions F_1, F_2

- Introduce dimensionless structure functions:

$$F_1 = MW_1 \text{ and } F_2 = \nu W_2 \Rightarrow \frac{d\sigma}{dE' d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \frac{1}{\nu}\left[F_2(x) + \frac{2\nu}{M} F_1(x) \tan^2(\theta/2)\right]$$

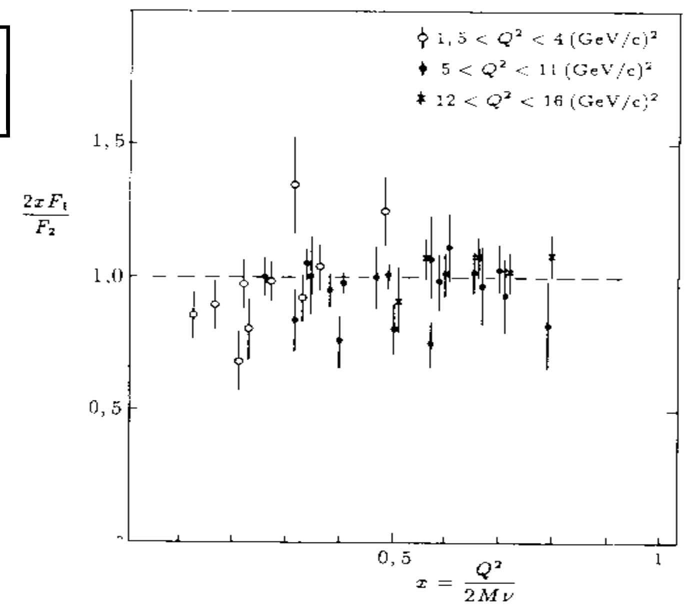
- Rewrite this in terms of : $\tau = Q^2 / 4m_{quark}^2$ (elastic e-q scatt.: $2m_q\nu = Q^2$)

$$\frac{d\sigma}{dE' d\Omega} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_M = \frac{1}{\nu}\left[F_2(x) + 2\frac{Q^2}{4m_q^2}\frac{4m_q^2}{Q^2}\frac{\nu}{M} F_1(x) \tan^2(\theta/2)\right] =$$

$$= \frac{1}{\nu}\left[F_2(x) + 2\tau \cdot 2x F_1(x) \tan^2(\theta/2)\right]$$

if $F_2(x) = 2xF_1(x)$

$$= \frac{1}{\nu} F_2(x)\left[1 + 2\tau \tan^2(\theta/2)\right]$$



- Experimental data for $2xF_1(x) / F_2(x)$

  → *quarks have spin 1/2*

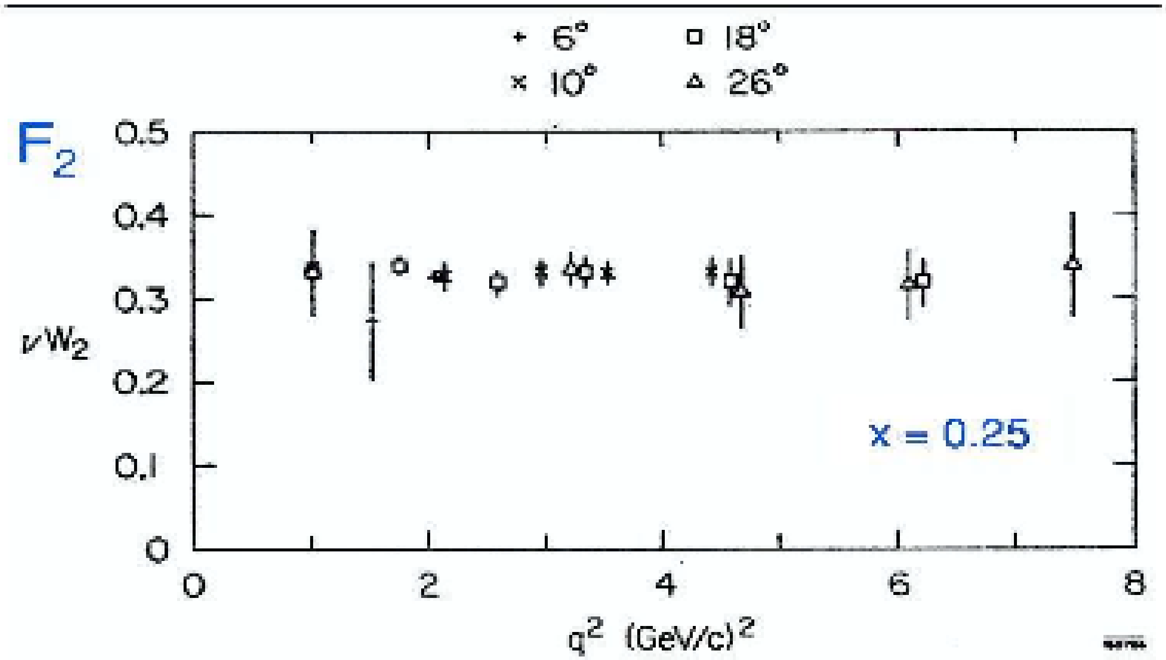
  (if bosons: no spin-flip $\Rightarrow F_1(x) = 0$)

Interpretation of $F_1(x)$ and $F_2(x)$

- In the quark-parton model:

Quark momentum distribution

$$F_1(x) = \sum_f \tfrac{1}{2} z_f^2 [q_f(x) + \overline{q}_f(x)]$$



J.T.Friedman + H.W.Kendall, Ann. Rev. Nucl. Sci. **22** (1972) 203

The quark structure of nucleons

- Quark quantum numbers:
  - Spin: ½ ⇒ $S_{p,n} = (\uparrow\uparrow\downarrow) = ½$
  - Isopin: ½ ⇒ $I_{p,n} = (\uparrow\uparrow\downarrow) = ½$
- Why fractional charges?
  - Extreme baryons: $Z = (-1,+2)$

$$-1 \le 3z_q \le +2 \;\Rightarrow\; -\tfrac{1}{3} \le z_q \le +\tfrac{2}{3}$$

  - Assign: $z_{up} = +\,2/3,\; z_{down} = -\,1/3$
- Three families:

$$\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}\begin{pmatrix}t\\b\end{pmatrix} \quad \begin{matrix}\Rightarrow z = +\frac{2}{3};\; m_u \ll m_{c\,(\approx 1.5\,\mathrm{GeV})} \ll m_t \\ \Rightarrow z = -\frac{1}{3};\; m_d \ll m_{s\,(\approx 0.3\,\mathrm{GeV})} \ll m_b\end{matrix}$$

  - $m_{c,b,t} >> m_{u,d,s}$: no role in p,n

- Structure functions:

$$F_2^p = x[\tfrac{1}{9}(d_v^p + d_s^p + \bar{d}_s^p) + \tfrac{4}{9}(u_v^p + u_s^p + \bar{u}_s^p) + \tfrac{1}{9}(s_s + \bar{s}_s)]$$
$$F_2^n = x[\tfrac{1}{9}(d_v^n + d_s^n + \bar{d}_s^n) + \tfrac{4}{9}(u_v^n + u_s^n + \bar{u}_s^n) + \tfrac{1}{9}(s_s + \bar{s}_s)]$$

  - Isospin symmetry:

$$u_v^n = d_v^p,\; d_v^n = u_v^p,\; \bar{u}_s^n = \bar{d}_s^n = \bar{u}_s^p = \bar{d}_s^p$$

  - 'Average' nucleon $F_2(x)$ with $q(x) = q_v(x) + q_s(x)$ etc.

$$F_2^N = \tfrac{1}{2}(F_2^p + F_2^n) = \tfrac{5}{18}x\cdot\sum_{u,d}(q(x)+\bar{q}(x)) + \tfrac{1}{9}x\cdot[s_s(x) + \bar{s}_s(x)]$$

- Neutrinos:

$$F_2^\nu = x[(d_v + d_s + \bar{d}_s) + (u_v + u_s + \bar{u}_s) + (s_s + \bar{s}_s)]$$
$$= x[(d + u + s) + (\bar{d}_s + \bar{u}_s + \bar{s}_s)] = x\sum_{u,d,s}(q(x) + \bar{q}(x))$$

Fractional quark charges

- Neglect strange quarks $\Rightarrow$

$$\frac{F_2^{e,N}}{F_2^{\nu,N}} \approx \frac{5}{18}$$

  – Data confirm factor 5/18:

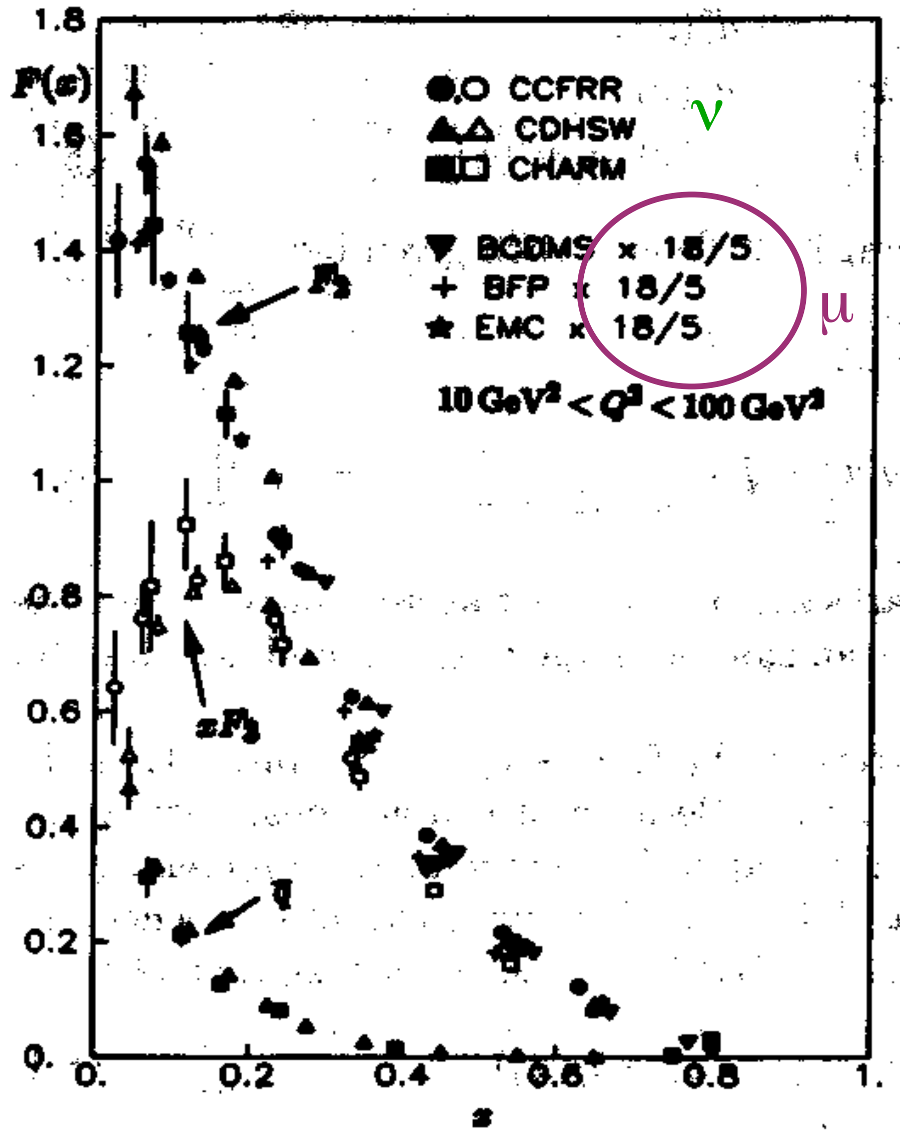
Evidence for fractional charges

- Fraction of proton momentum carried by quarks:

$$\int_0^1 F_2^{\nu,N}(x)dx = \tfrac{18}{5}\int_0^1 F_2^{e,N}(x)dx \approx 0.5$$

  – 50% of momentum due to non-electro-weak particles:

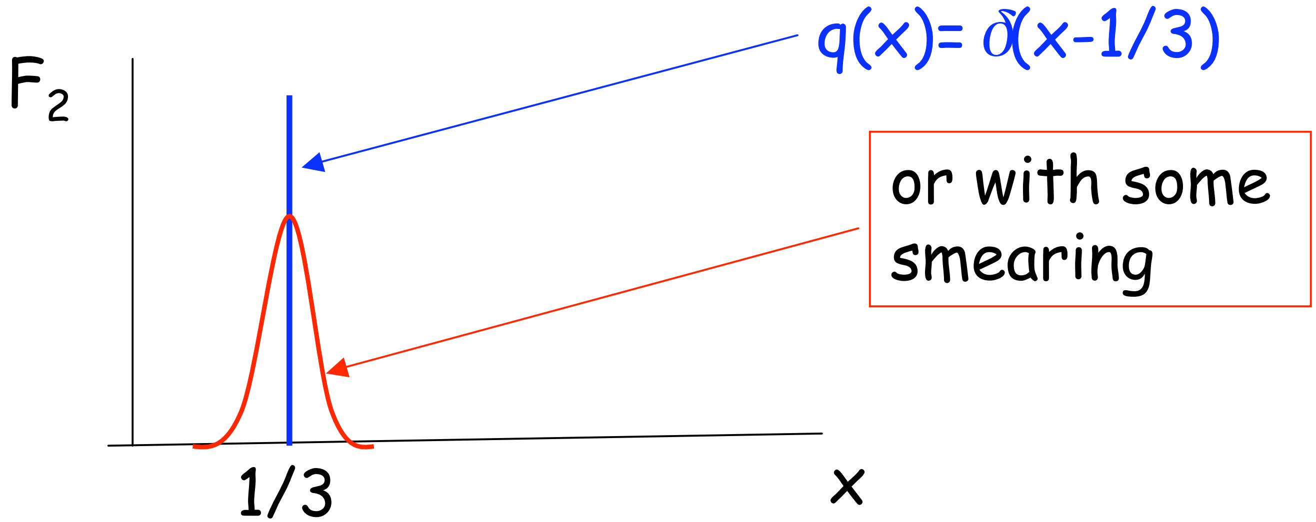
Evidence for gluons



IF, proton was made of 3 quarks each with 1/3 of proton's momentum:

no anti-quark!

$$F_2 = x\sum(q(x) + \bar{q}(x))\, e_q^2$$



The partons are point-like and incoherent then Q^2 shouldn't matter.

→ Bjorken scaling: F_2 has no Q^2 dependence.

Thus far, we've covered:

- Some history
- Some key results
- Basic predictions of the parton model

The parton model assumes:

- Non-interacting point-like particles

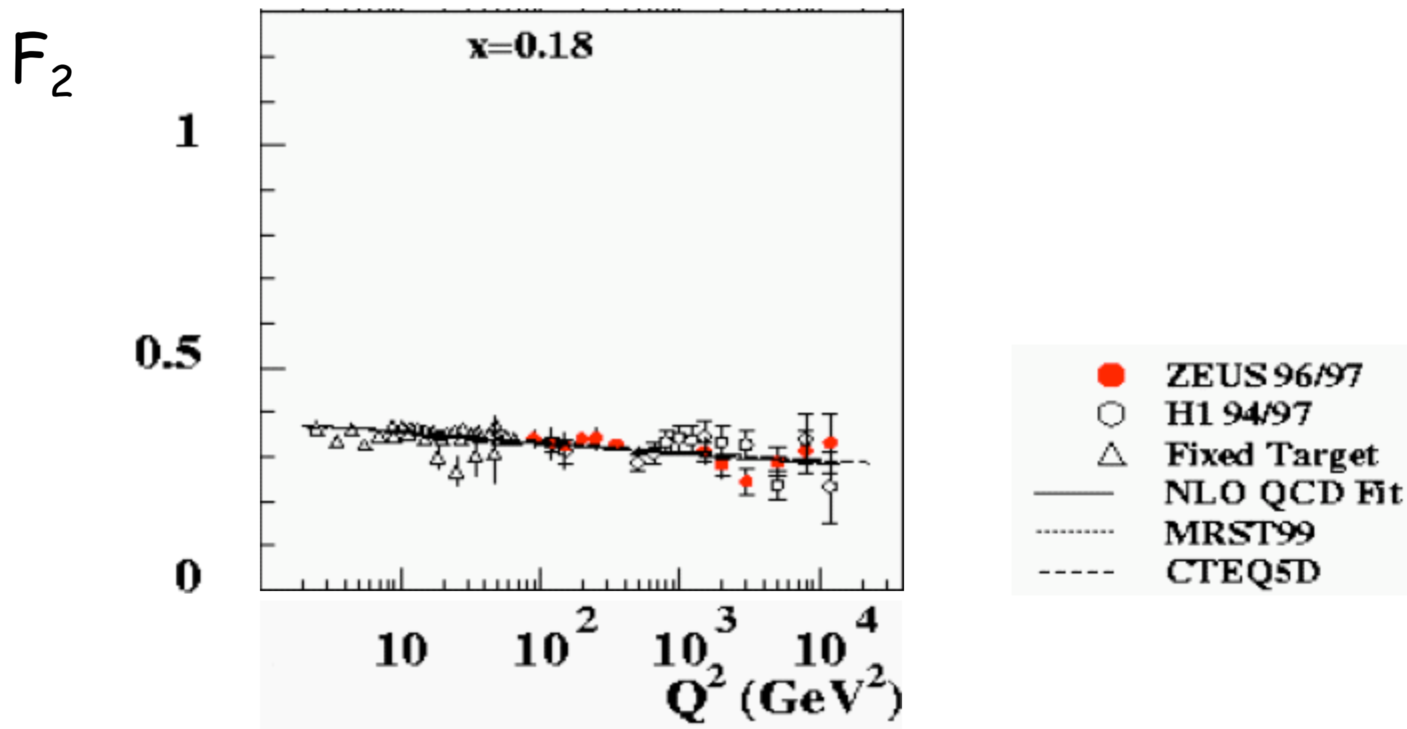
→ Bjorken scaling, i.e. $F_2(x,Q^2)=F_2(x)$

- Fractional charges (if partons=quarks)
- Spin 1/2
- Valence and sea quark structure (sum rules)

Makes key predictions that can be tested by experiment.....

Let's look at some data→

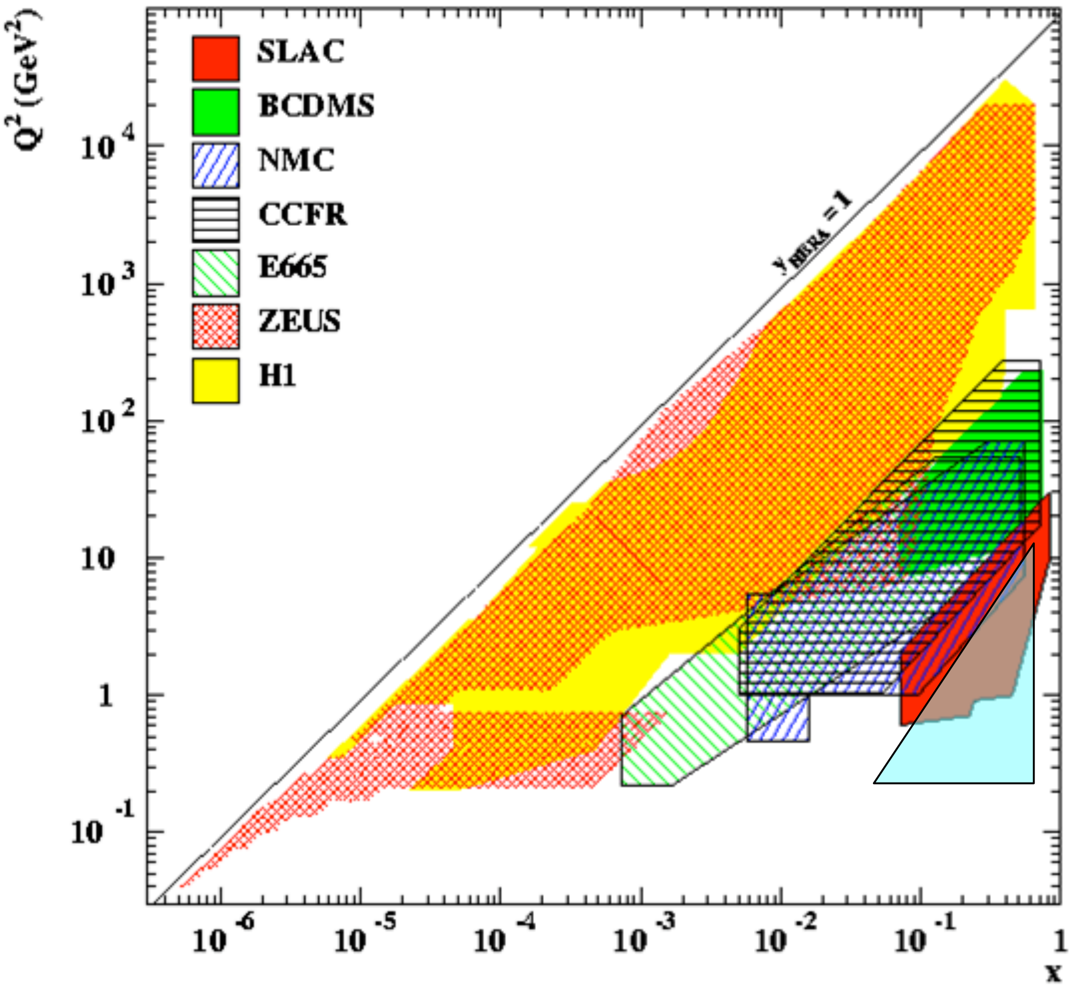
Proton Structure Function F_2



Seems to be.... ...uh oh...

Lovely movies are from R. Yoshida, CTEQ Summer School 2007

Deep Inelastic Scattering experiments

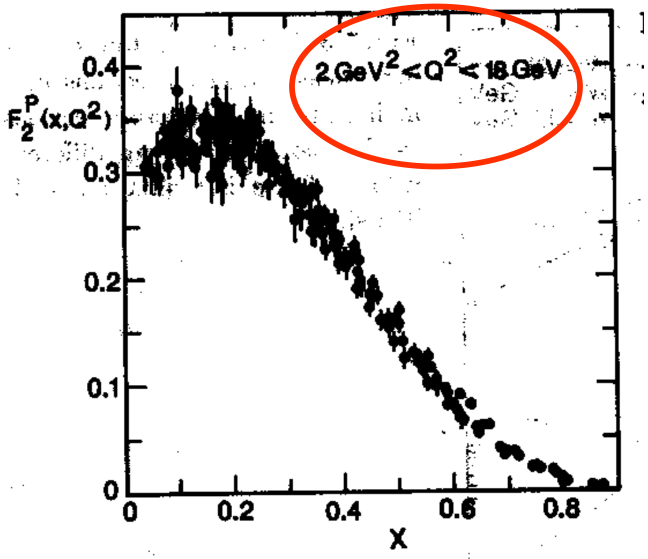


HERA collider: H1 and ZEUS experiments 1992 - 2007

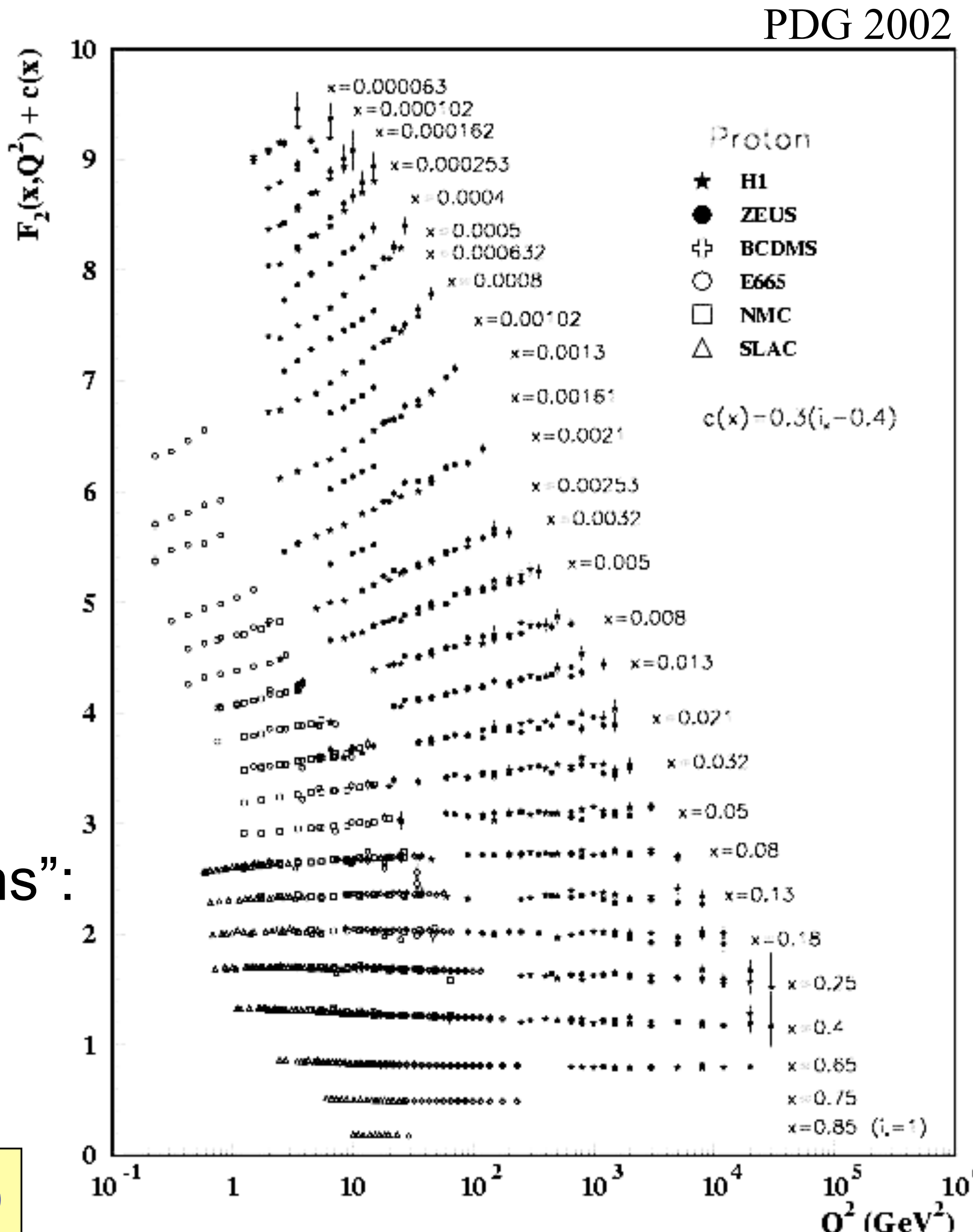
Fixed target DIS at SLAC, FNAL, CERN, now JLab

Modern data

- First data (1980):



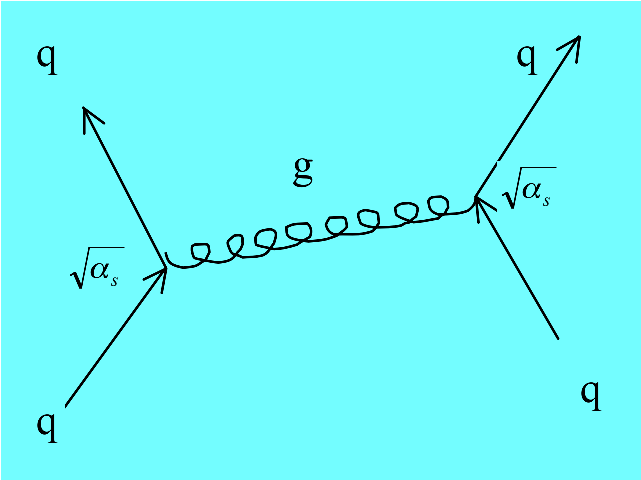
- Now..“Scaling violations”:
  - weak Q^2 dependence
  - rise at low x
  - what physics??



….. QCD

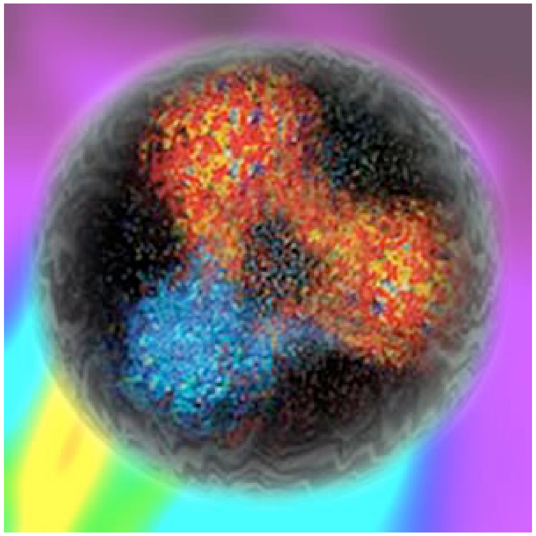
Quantum Chromodynamics (QCD)

- Field theory for strong interaction:
  - quarks interact by gluon exchange
  - quarks carry a ‘colour’ charge
  - exchange bosons (gluons) carry colour ⇒ self-interactions (cf. QED!)



- Hadrons are colour neutral:
  - $R\bar{R}$, $B\bar{B}$, $G\bar{G}$ or RGB
  - leads to confinement:

$$|q\rangle,\ |qq\rangle \ \text{or}\ |qq\bar{q}\rangle \quad \text{forbidden}$$



- Effective strength ~ #gluons exch.
  - low Q^2: more *g’s*: large eff. coupling
  - high Q^2: few *g’s*: small eff. coupling

The QCD Lagrangian

$$\mathsf{L}_{qcd} = i\sum_q \overline{\psi}_q^{\,j}\gamma^{\mu}(\mathsf{D}_{\mu})_{jk}\psi_q^{\,k} - \sum_q m_q \overline{\psi}_q^{\,j}\psi_q^{\,k} - \tfrac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}$$

(j,k = 1,2,3 refer to colour; q = u,d,s refers to flavour; a = 1,..,8 to gluon fields)

Covariant derivative:

$$\mathsf{D}_{\mu} = \partial_{\mu} + i\tfrac{1}{2}g_s\lambda_a G^a_{\mu}$$

Free quarks

$$G^a_{ìí} = \underbrace{\partial_{\mu}G^a_{\nu} - \partial_{\nu}G^a_{\mu}}_{\text{Gluon kinetic energy term}} - \underbrace{g_s f_{abc}G^a_{\mu}G^a_{\nu}}_{\text{Gluon self-interaction}}$$

qg-interactions
SU(3) generators:

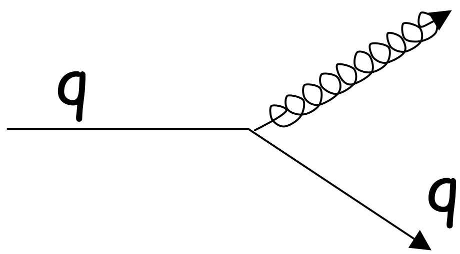
$$\lambda_1 = \begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}\quad \lambda_2 = \begin{pmatrix}0&-i&0\\i&0&0\\0&0&0\end{pmatrix}\quad \lambda_3 = \begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}\quad \lambda_4 = \begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$$

$([\lambda_a, \lambda_b] = i\tfrac{1}{2}f_{abc}\lambda_c)$

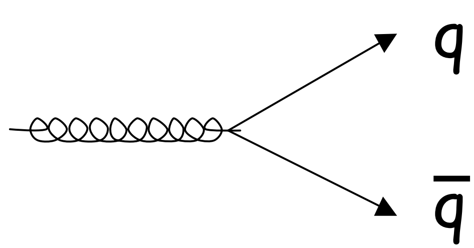
$$\lambda_5 = \begin{pmatrix}0&0&-i\\0&0&0\\i&0&0\end{pmatrix}\quad \lambda_6 = \begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}\quad \lambda_7 = \begin{pmatrix}0&0&0\\0&0&-i\\0&i&0\end{pmatrix}\quad \lambda_8 = \frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$$

So what does this mean..?

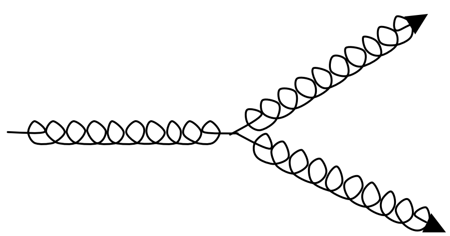
QCD brings new possibilities:



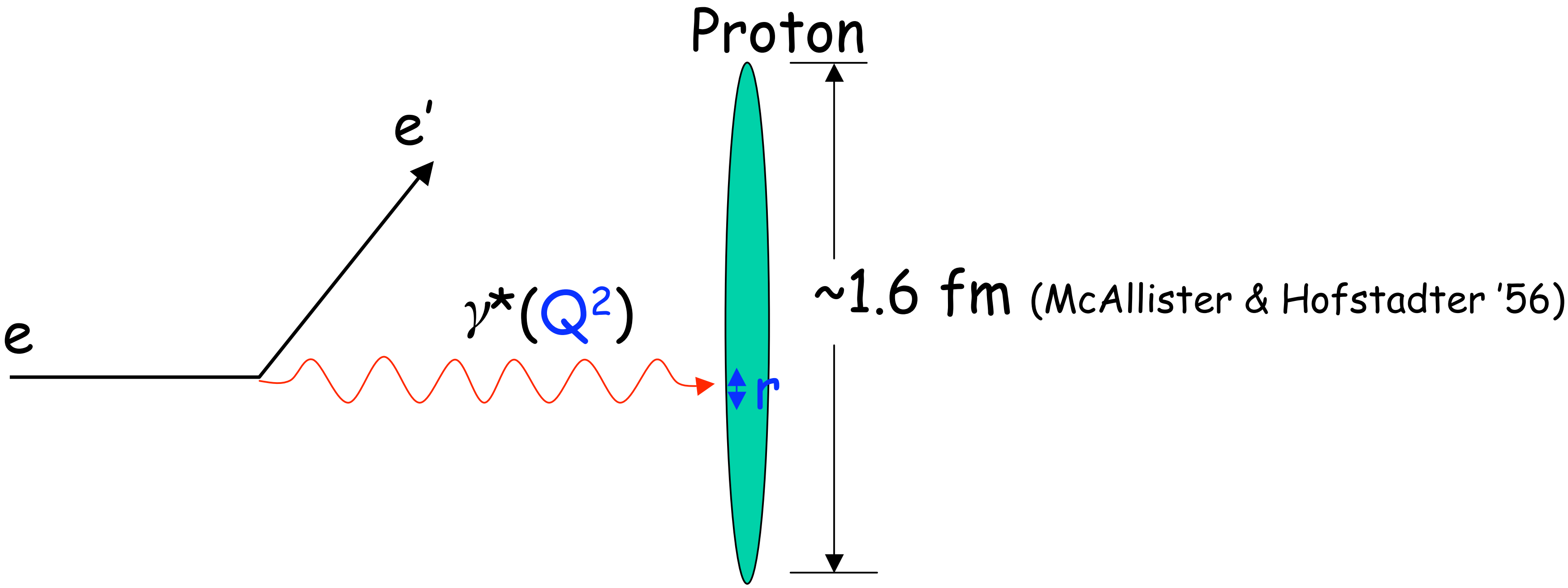
quarks can radiate gluons



gluons can produce $q\bar{q}$ pairs



gluons can radiate gluons!



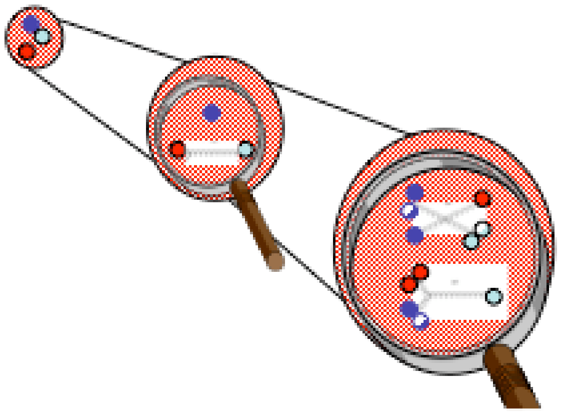
Virtuality (4-momentum transfer) Q gives the distance scale r at which the proton is probed.

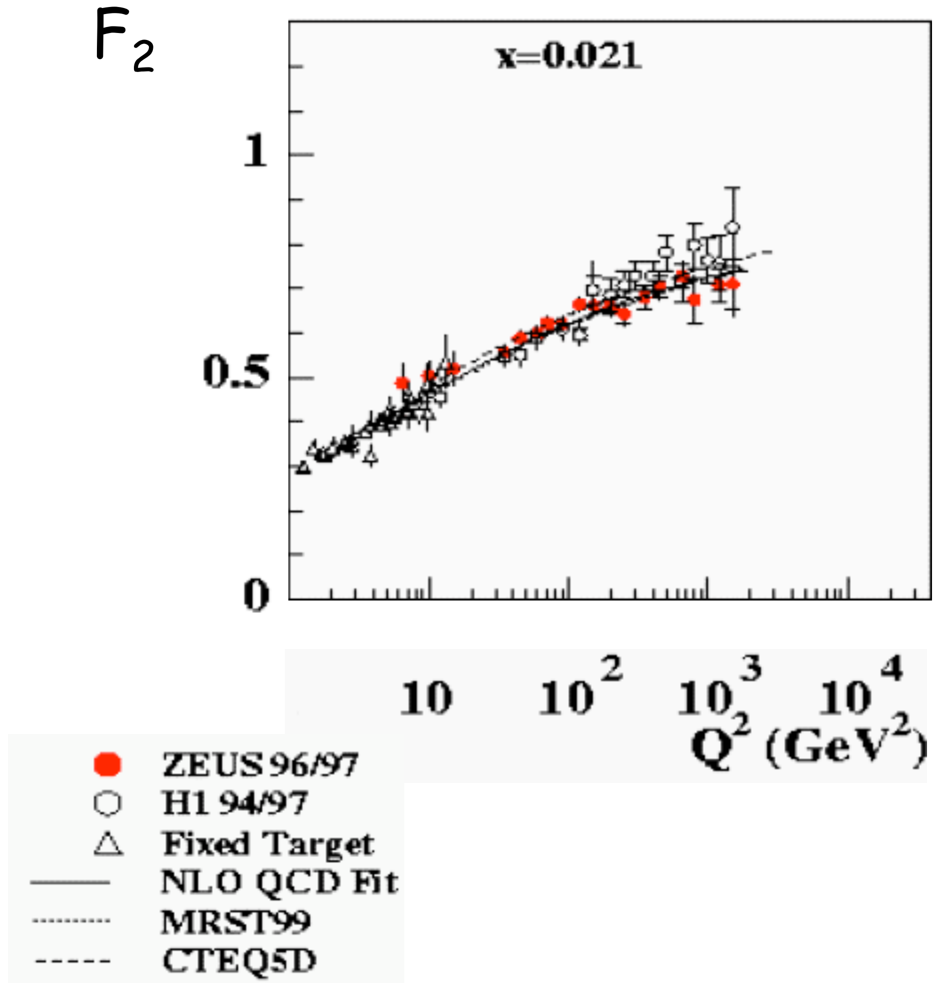
$r \approx \hbar c/Q = 0.2\text{fm}/Q[\text{GeV}]$

CERN, FNAL fixed target DIS:	$r_{min} \approx$ 1/100 proton dia.
HERA ep collider DIS:	$r_{min} \approx$ 1/1000 proton dia.

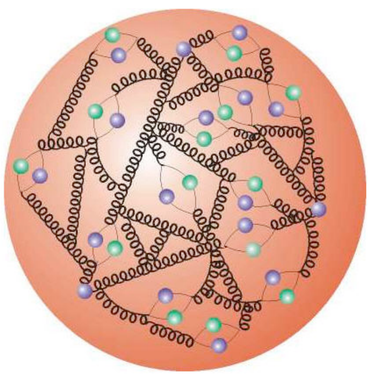
HERA: E_e=27.5 GeV, E_P=920 GeV

(Uncertainty Principle again)

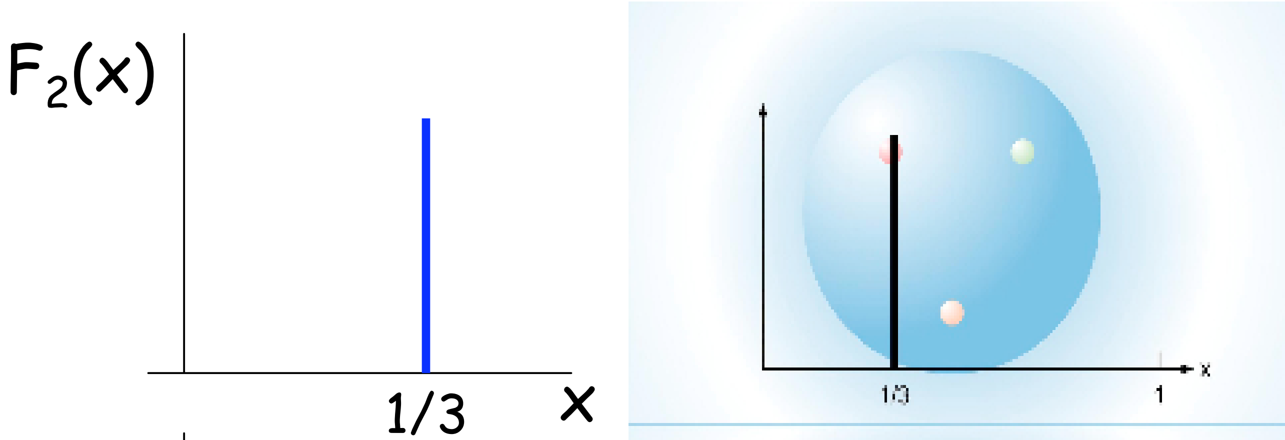




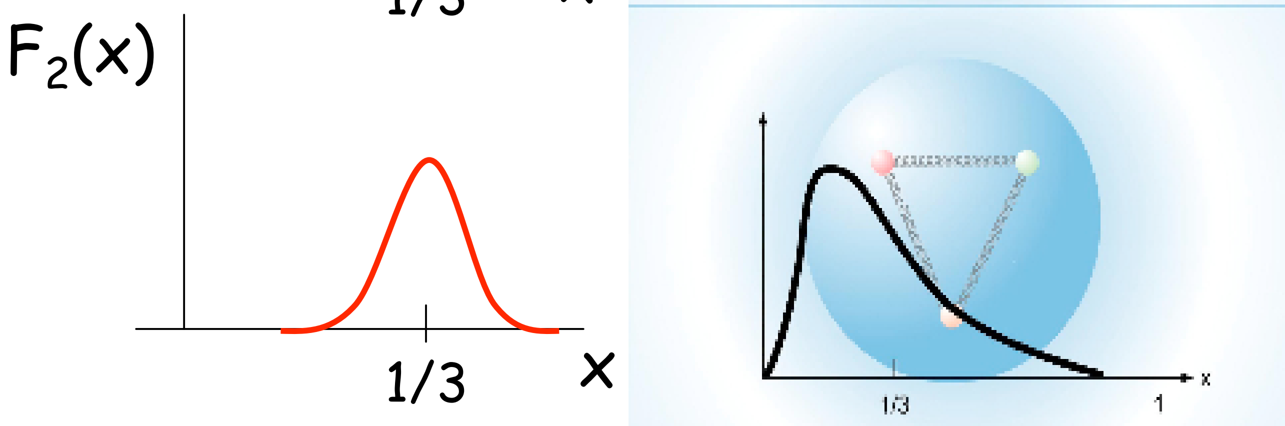
Higher the resolution (i.e. higher the Q^2) more low x partons we “see”.



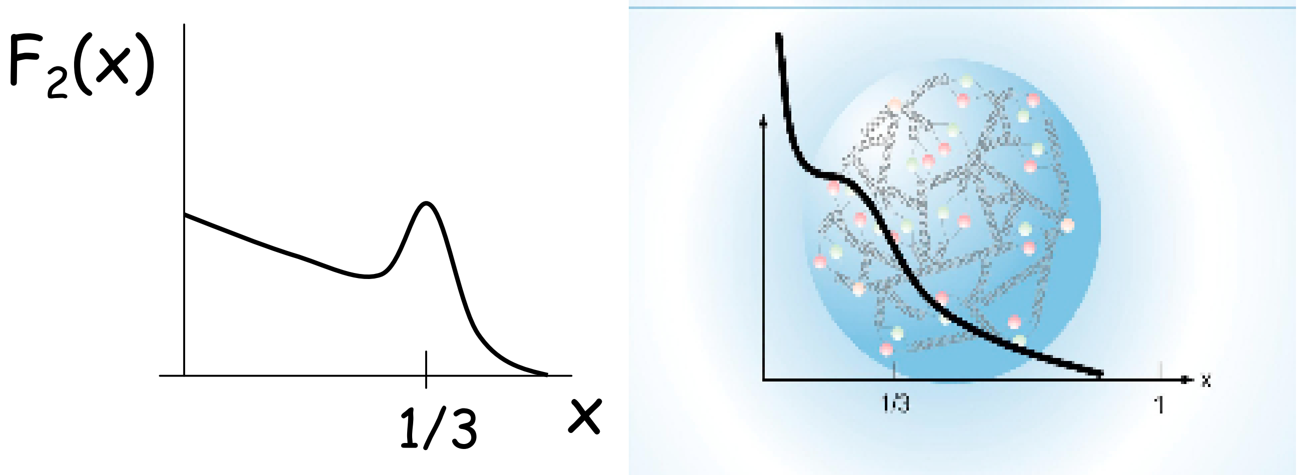
So what do we expect F_2 as a function of x at a fixed Q^2 to look like?



Three quarks with 1/3 of total proton momentum each.



Three quarks with some momentum smearing.



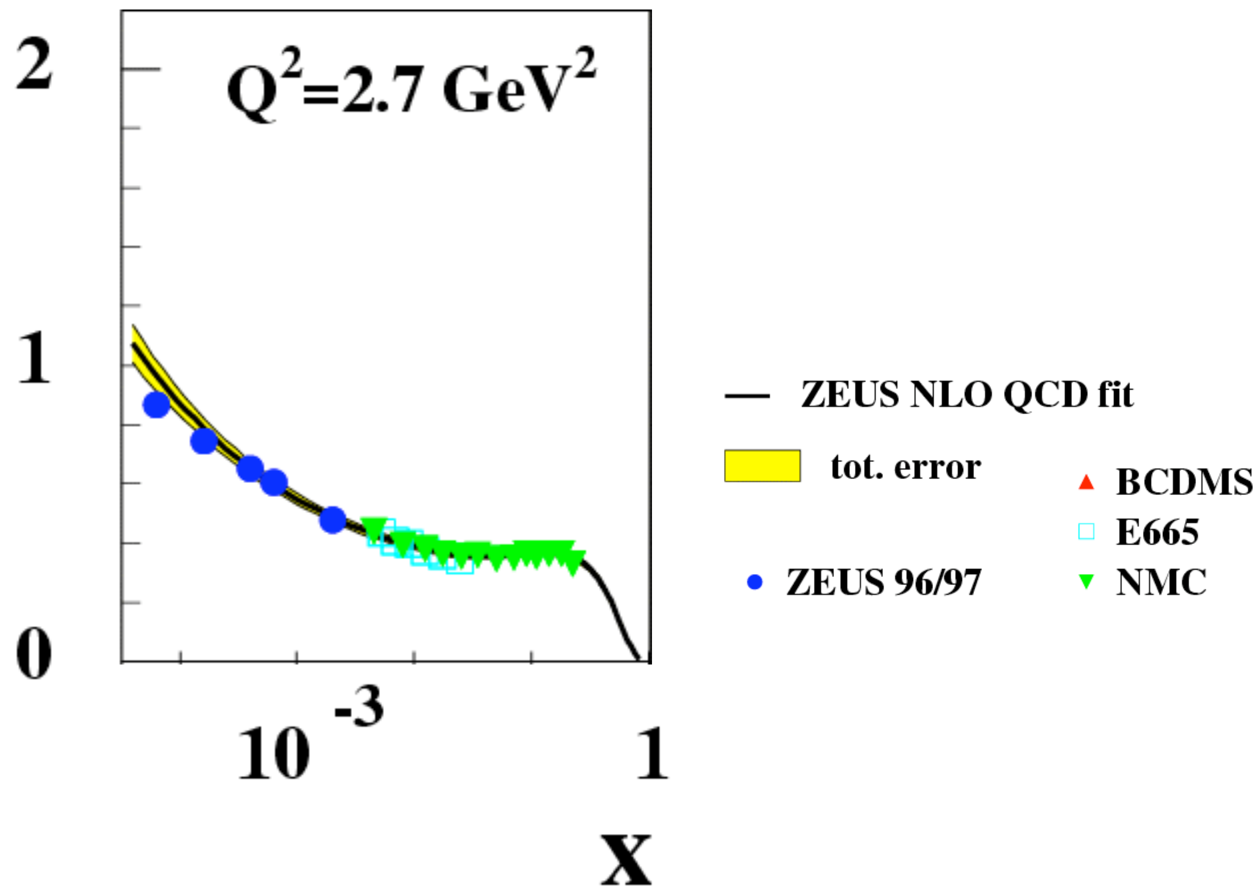
The three quarks radiate partons at low x.

....The answer depends on the Q^2!

Proton Structure Function F_2

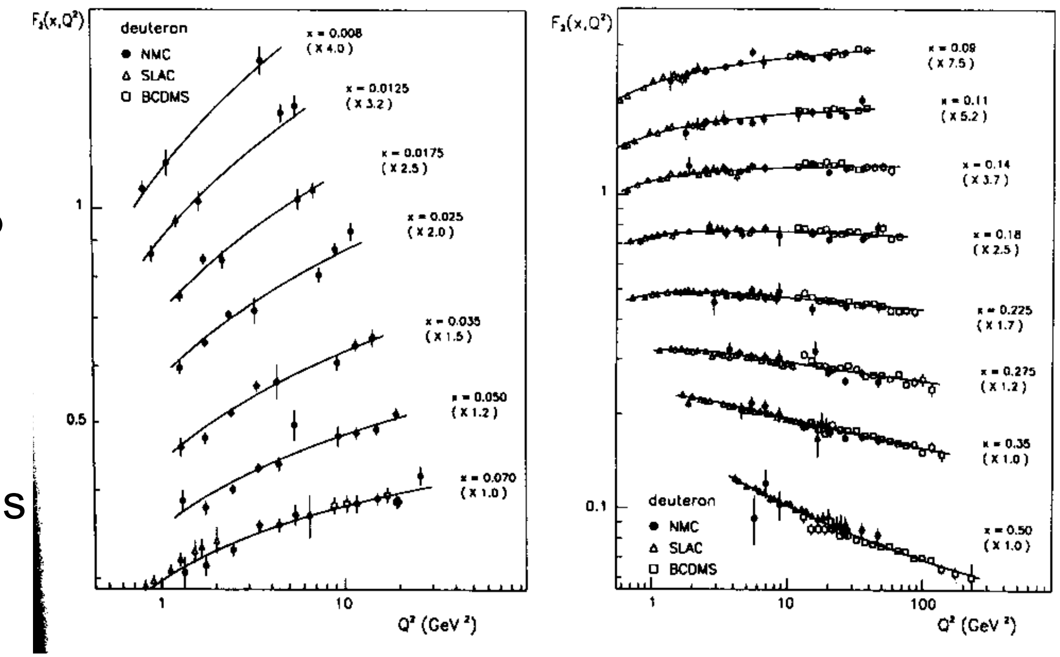
How this change with Q^2 happens quantitatively described by the:

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

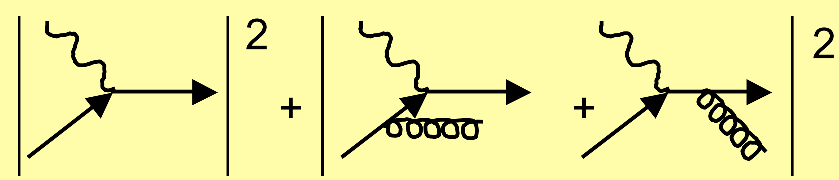


QCD predictions: scaling violations

- Originally: $F_2 = F_2(x)$
  - but also Q^2-dependence
- Why scaling violations?
  - if Q^2 increases:
    - ⇒ more resolution ($\sim 1/Q^2$)
    - ⇒ more sea quarks +gluons
- QCD improved QPM:



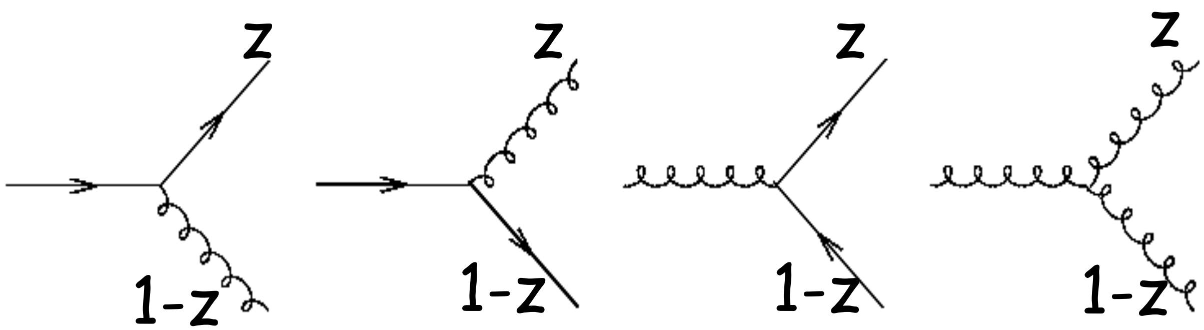
$$\frac{F_2(x,Q^2)}{x} =$$



- Officially known as: Altarelli-Parisi Equations (“DGLAP”)

DGLAP equations are easy to "understand" intuitively..

First we have four "splitting functions"



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

These additional contributions to $F_2(x,Q^2)$ can be calculated.

Now DGLAP equations (schematically)

convolution

$$\frac{dq_f(x,Q^2)}{d\ln Q^2} = \alpha_s\, [q_f \otimes P_{qq} + g \otimes P_{gq}]$$

strong coupling constant

q_f is the quark density summed over all active flavors

Change of quark distribution q with Q^2
is given by the probability that q and g radiate q.

Same for gluons:

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \alpha_s\, [\Sigma q_f \otimes P_{qg} + g \otimes P_{gg}]$$

Violation of Bjorken scaling predicted by QCD -
logarithmic dependence, not dramatic

DGLAP fit (or QCD fit) extracts the parton distributions from measurements.

(CTEQ, for instance :))

Basically, this is accomplished in two steps:

Step 1: parametrise the parton momentum density $f(x)$ at some Q^2. e.g. $f(x)=p_1 x^{p2}(1-x)^{p3}(1+p_4\sqrt{x}+p_5 x)$

$u_v(x)$	u-valence	"The original three quarks"
$d_v(x)$	d-valence	
$g(x)$	gluon	
$S(x)$	"sea" (i.e. non valence) quarks	

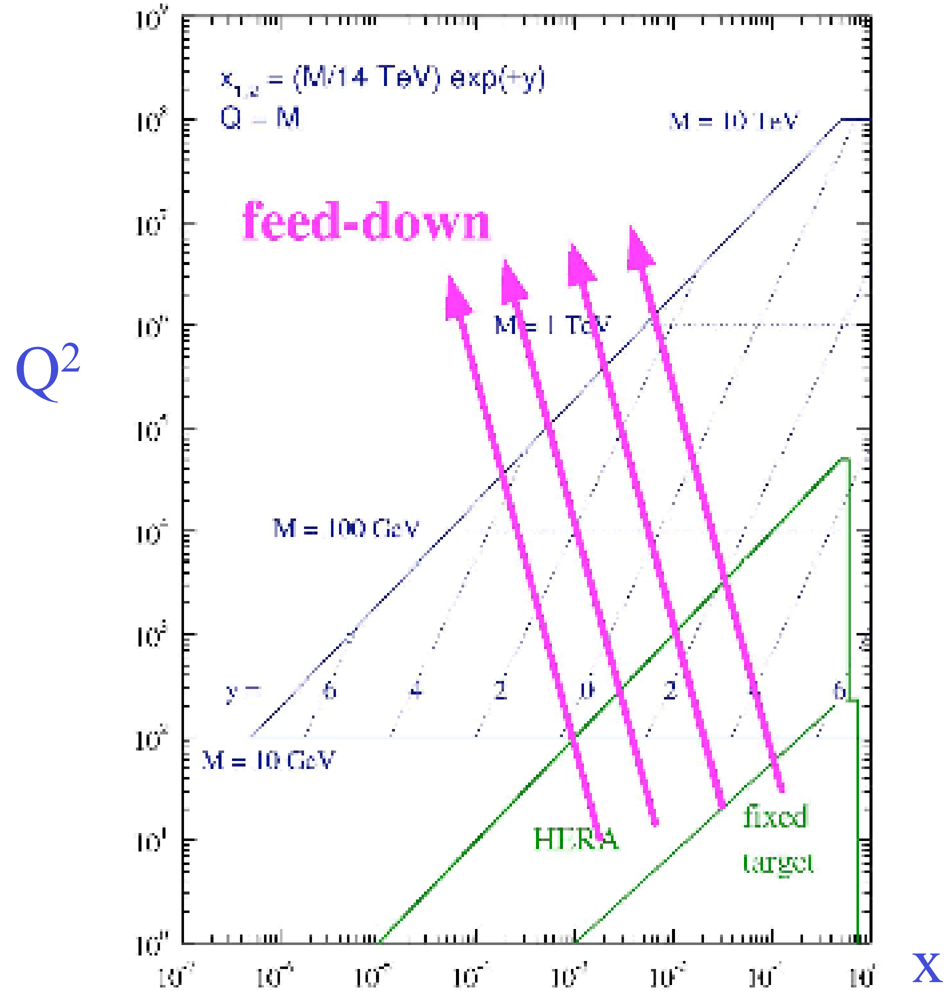
Step 2: find the parameters by fitting to DIS (and other) data using DGLAP equations to evolve $f(x)$ in Q^2.

$$\frac{\partial f_q(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} f_q(y,Q^2) P_{qq}\left(\frac{x}{y}\right) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} g(y,Q^2) P_{qg}\left(\frac{x}{y}\right)$$

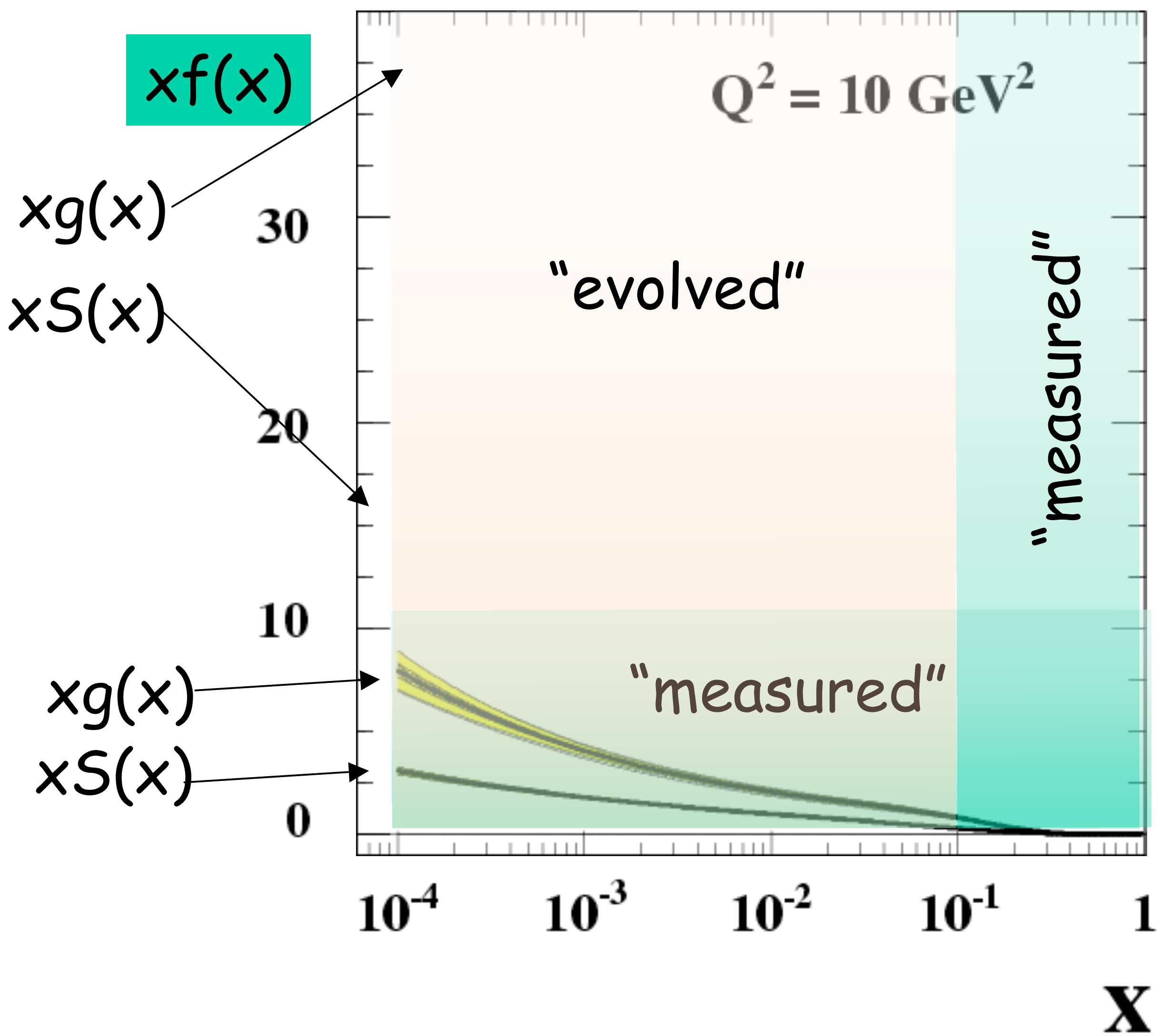
$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} f_q(y,Q^2) P_{gq}\left(\frac{x}{y}\right) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y} g(y,Q^2) P_{gg}\left(\frac{x}{y}\right)$$

QCD fits of $F_2(x,Q^2)$ data

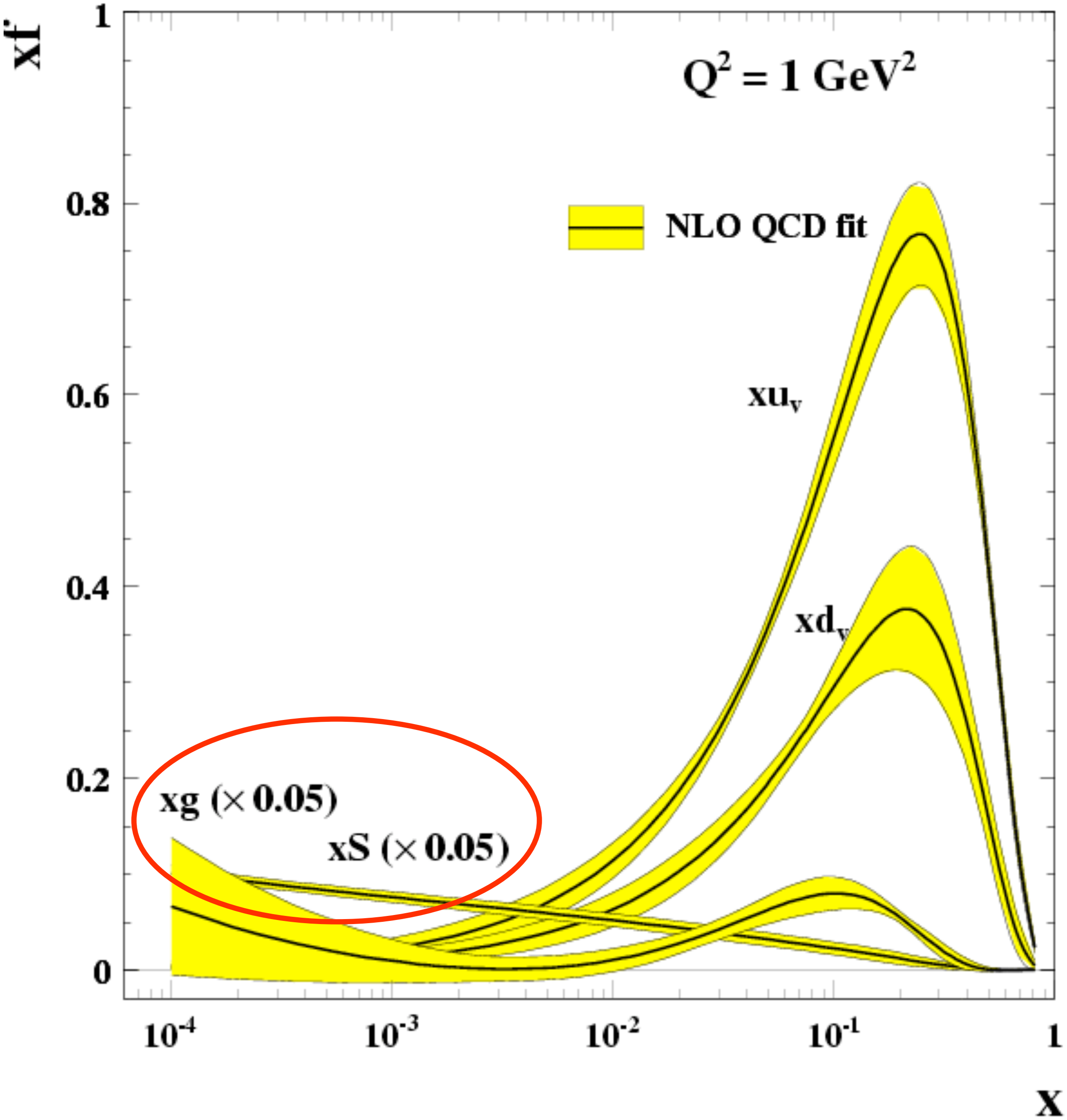
The DGLAP evolution equations are extremely useful as they allow structure functions measured by one experiment to be compared to other measurements - and to be extrapolated to predict what will happen in regions where no measurements exist, e.g. LHC.



Evolving PDFs up to $M_{W,Z}$ scale



Finally…



Valence quarks maximum around $x=0.2$; $q(x) \rightarrow 0$ for $x \rightarrow 1$ and $x \rightarrow 0$

Sea quarks and gluons – contribute at low values of x

QCD predictions: the running of α_s

- pQCD valid if $\alpha_s << 1$:

  $\Rightarrow\ Q^2 > 1.0\ (\text{GeV/c})^2$

- pQCD calculation:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\cdot \ln(Q^2/\Lambda^2)}$$

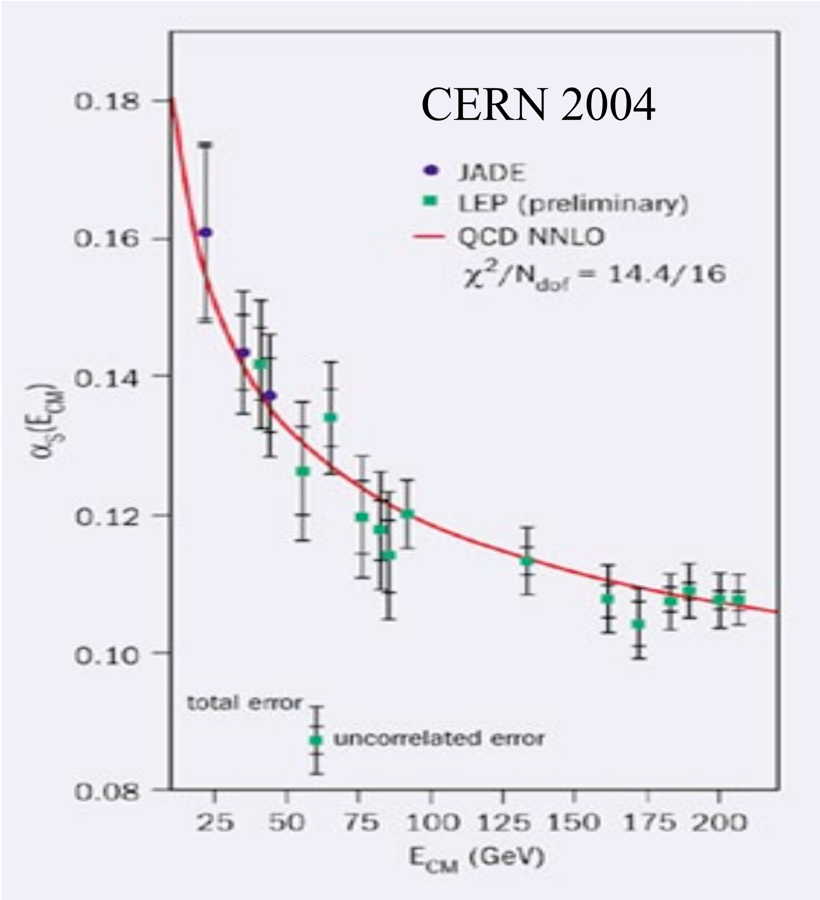
  – with Λ_{exp} = 250 MeV/c:

$$Q^2 \to \infty \quad \Rightarrow \quad \alpha_s \to 0$$

$\Rightarrow$ asymptotic freedom

$$Q^2 \to 0 \quad \Rightarrow \quad \alpha_s \to \infty$$

$\Rightarrow$ confinement



Running coupling constant is quantitative test of QCD.

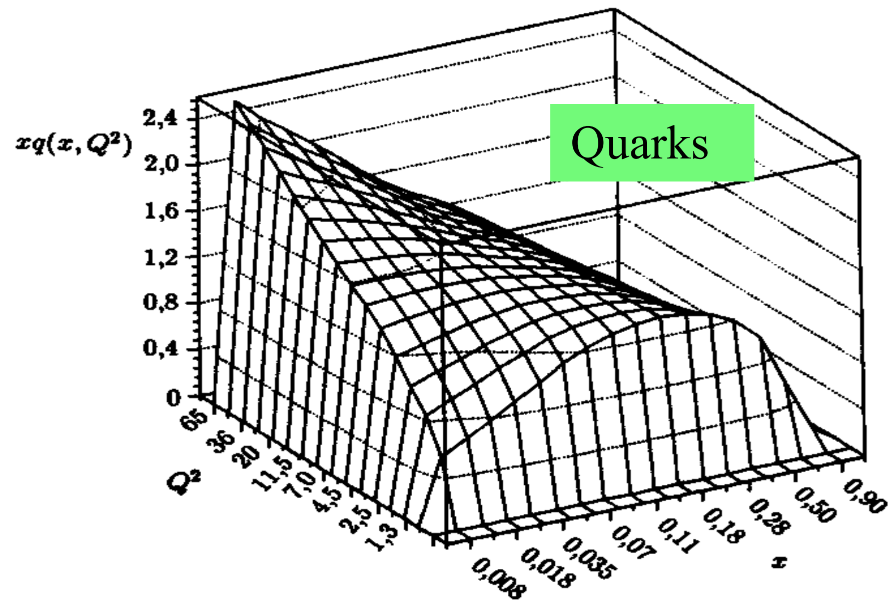
QCD fits of $F_2(x,Q^2)$ data

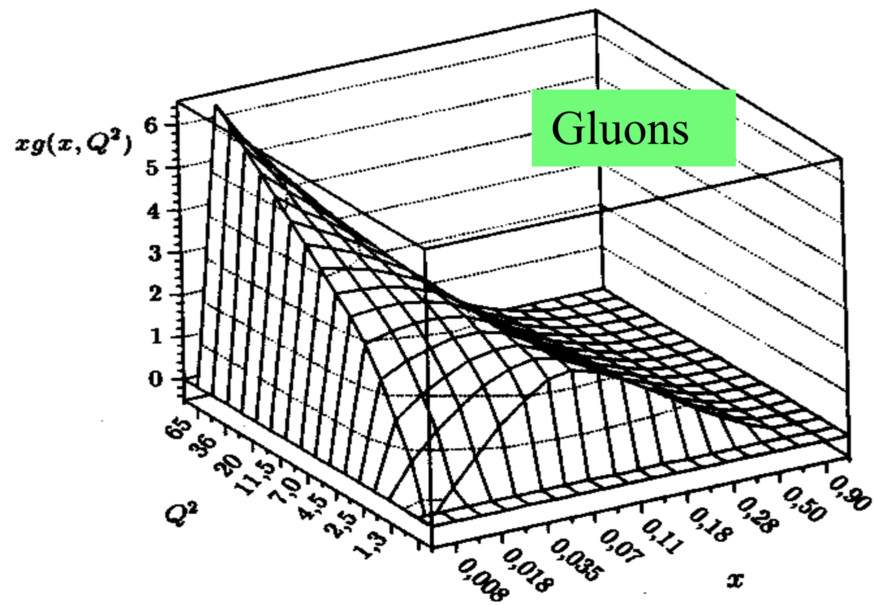
- Free parameters:
  - coupling constant:

$$\alpha_s = \frac{12\pi}{(33 - n_f)\ln(Q^2/\Lambda^2)} \approx 0.16$$

  - quark distribution $q(x,Q^2)$
  - gluon distribution $g(x,Q^2)$
- Successful fit:

Corner stone of QCD





What's still to do?

LOTS still to do!

EIC

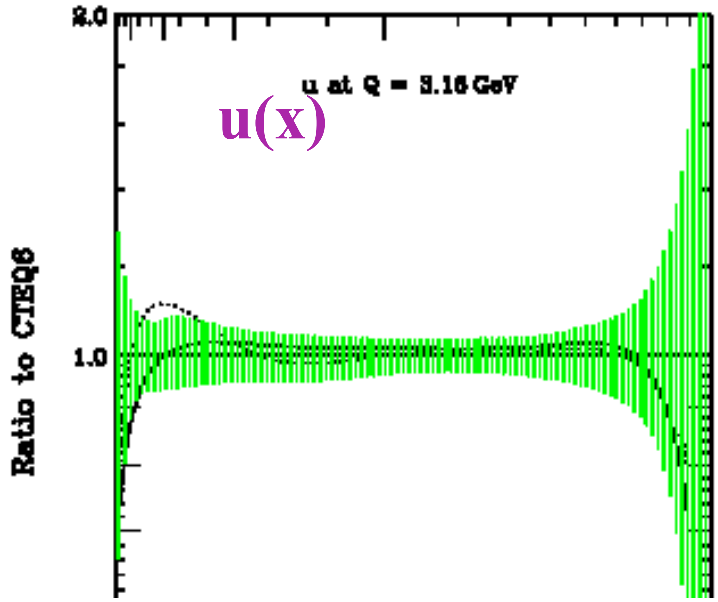
- Large pdf uncertainties still at large x, low x
- pdfs in nuclei
- F_L structure function - unique sensitivity to the glue

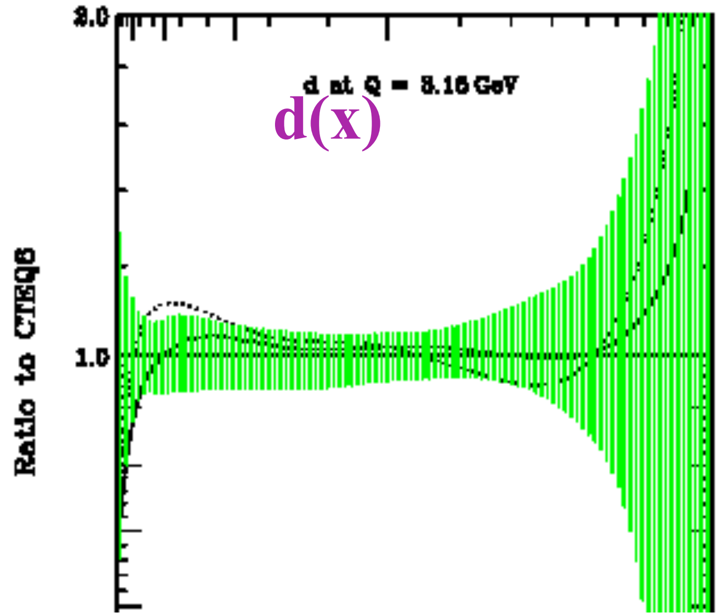
$$\int_0^1 dx F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{4\pi}\left(\frac{4}{9}\int_0^1 dx F_2(x,Q^2) + \frac{2\sum {e_q}^2}{12}\int_0^1 dx\, x G(x,Q^2)\right)$$

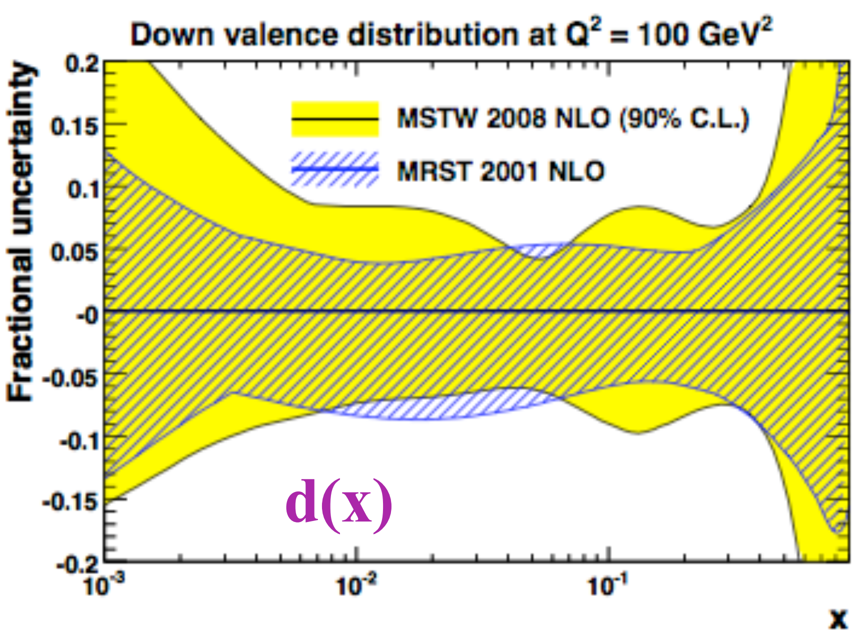
($F_2 = 2xF_1$ only true at leading order)

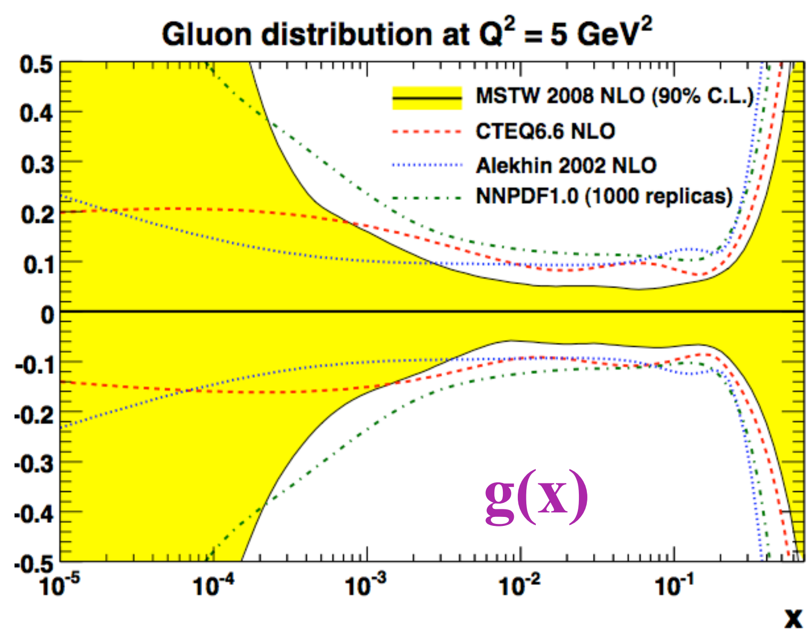
- Spin-dependent structure functions and transversity
- Generalized parton distributions
- Quark-hadron duality, transition to pQCD
- Neutrino measurements - nuclear effects different? F_3 structure function (Dave Schmitz talks next week)
- Parity violation, charged current,….
- NLO, NNLO, and beyond
- Semi-inclusive (flavor tagging)
- BFKL evolution, Renormalization

Large x (x > 0.1) -> Large PDF Uncertainties



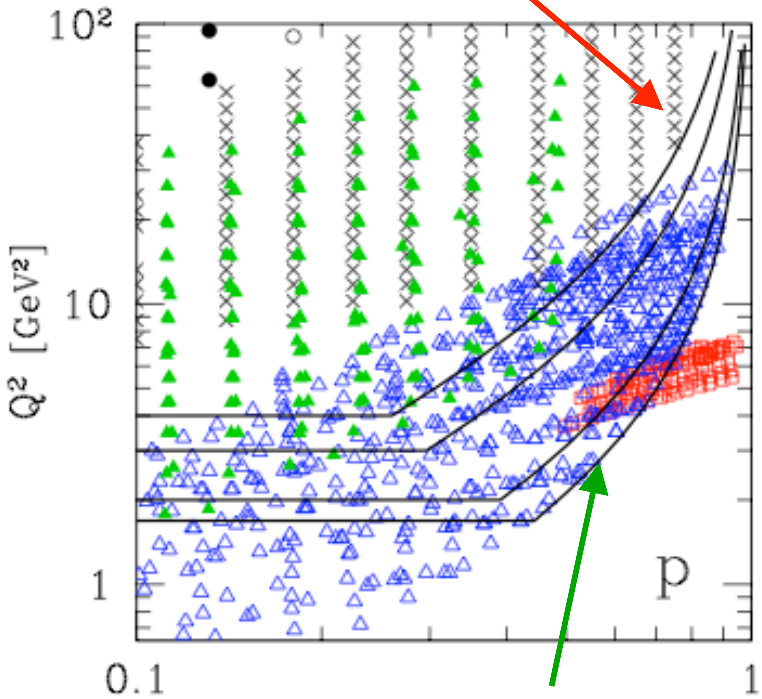




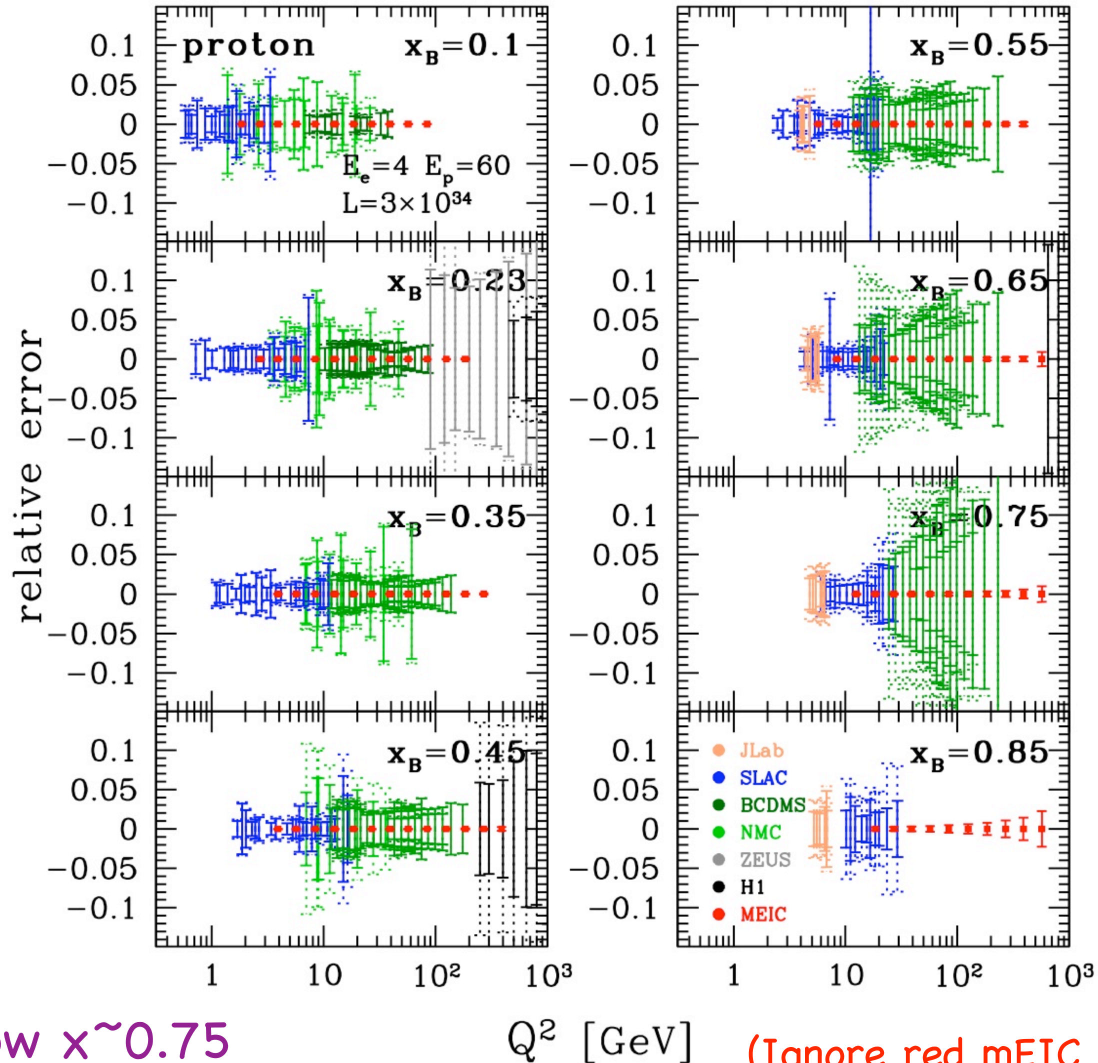


Typical W, Q cuts are VERY restrictive….

Current $Q^2 > 4$ GeV^2, $W^2 >$ 12.25 GeV^2, cuts



Recent CTEQ-Jlab effort to reduce cuts



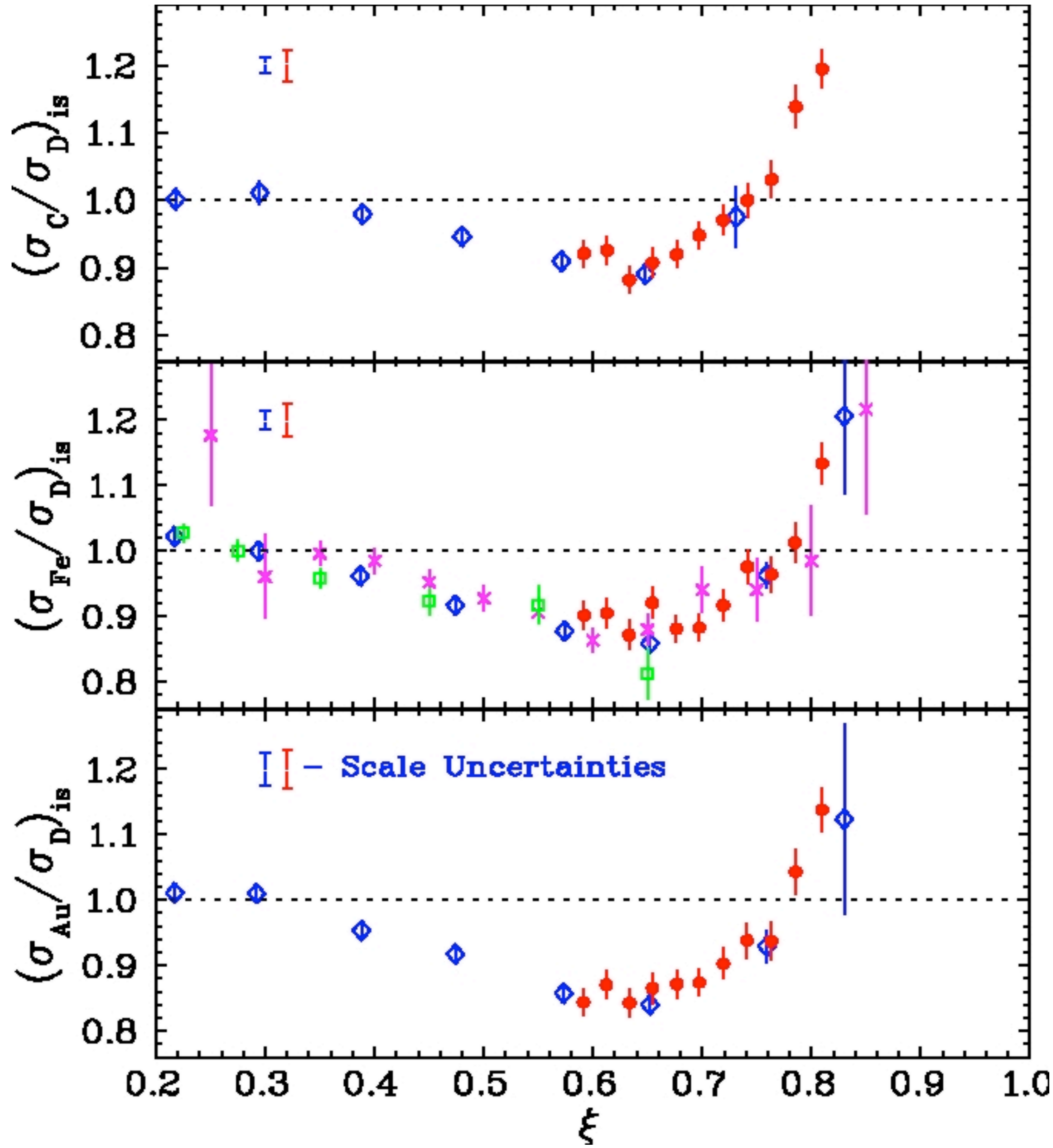
Essentially leave no data below x~0.75

What large x data there is has large uncertainty

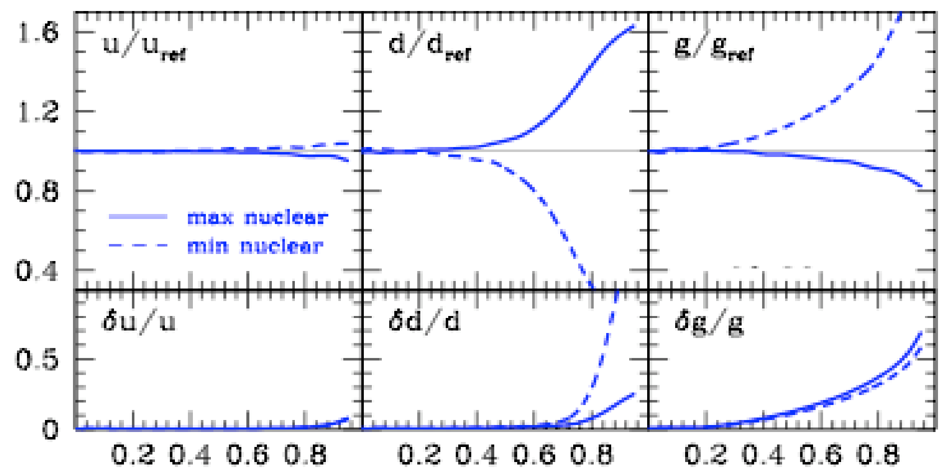
(Ignore red mEIC proposed data points.)

Nuclear medium modifications, pdfs

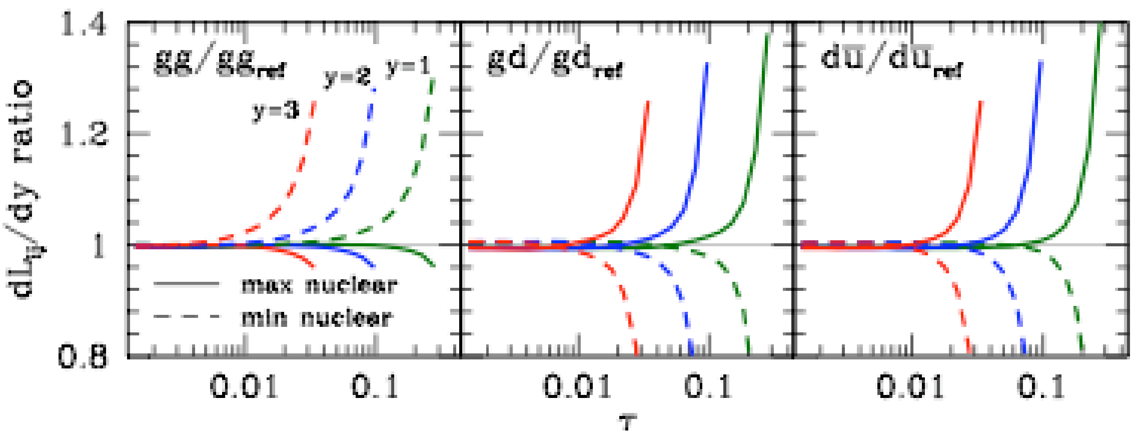
The moon at nuclear densities
(A_{moon} ≈ 5×10^{49})



The deuteron is a nucleus, and corrections at large x matter….



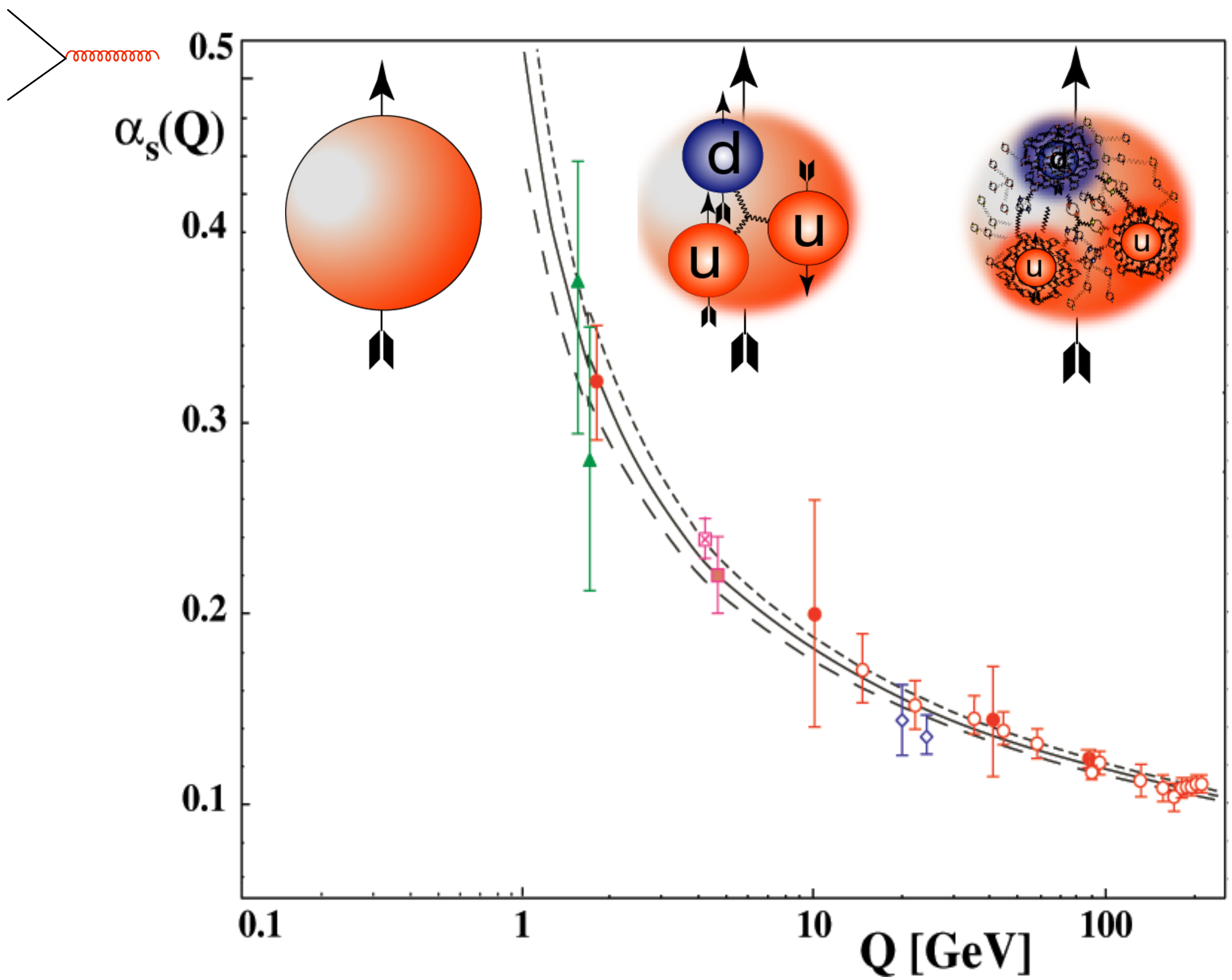
The extremes of variation of the u,d, gluon PDFs, relative to reference PDFs using different deuterium nuclear corrections



Differential parton luminosities for fixed rapidity y = 1, 2, 3, as a function of $\tau = Q^2/S$, variations due to the choice of deuterium nucleon corrections.

The gg, gd, dū luminosities control the "standard candle" cross section for Higgs, jet W^- production, respectively.

QCD and the Parton-Hadron Transition



Hadrons

Nucleons

Quarks and Gluons

Quark-Hadron Duality

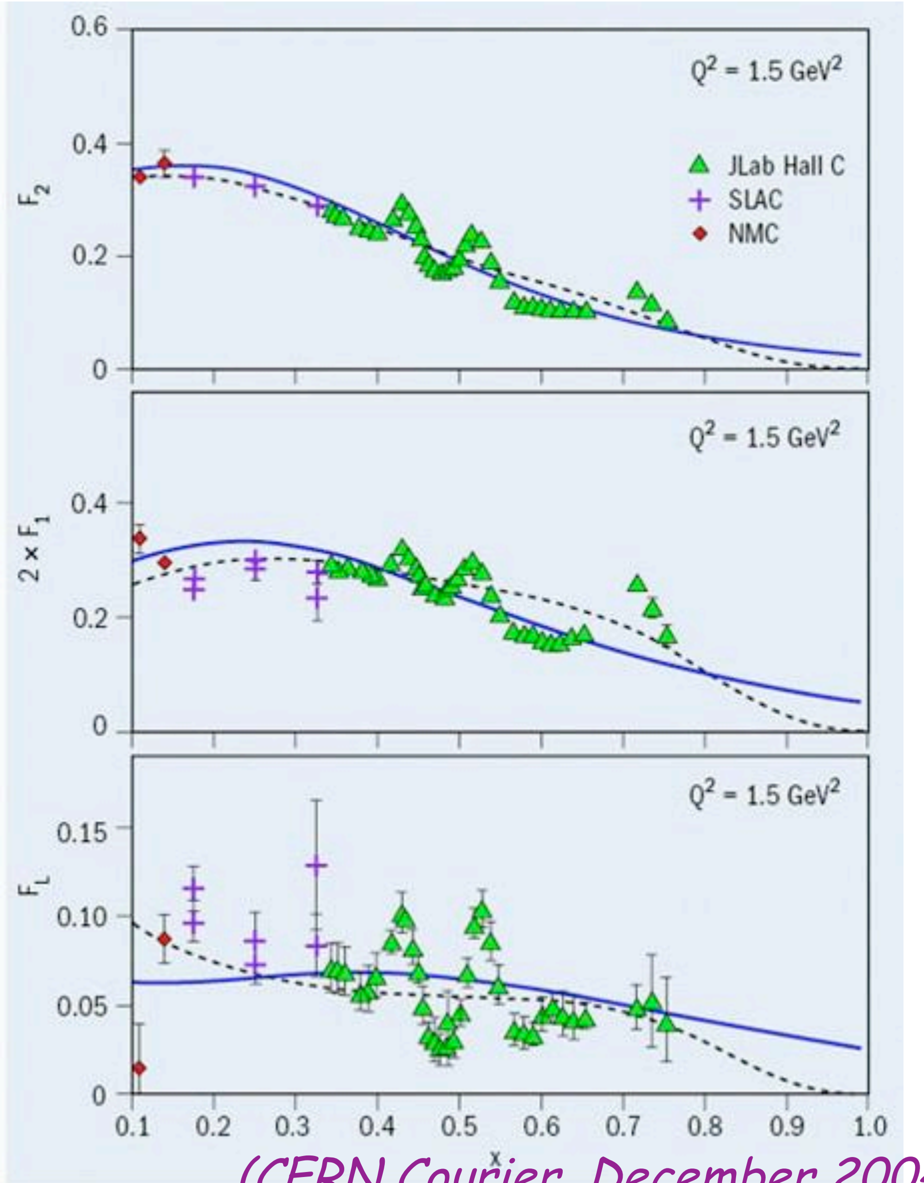
- At high energies: interactions between quarks and gluons become weak
  ("asymptotic freedom")
  - ➢ efficient description of phenomena afforded in terms of quarks
- At low energies: effects of confinement make strongly-coupled QCD highly non-perturbative
  - ➢ collective degrees of freedom (mesons and baryons) more efficient
- Duality between quark and hadron descriptions
  - reflects relationship between *confinement* and *asymptotic freedom*
  - intimately related to nature and transition from *non-perturbative* to *perturbative* QCD

Duality defines the transition from soft to hard QCD.

Duality observed (but not understood) in inelastic (DIS) structure functions

First observed in F_2 ~1970 by Bloom and Gilman at SLAC

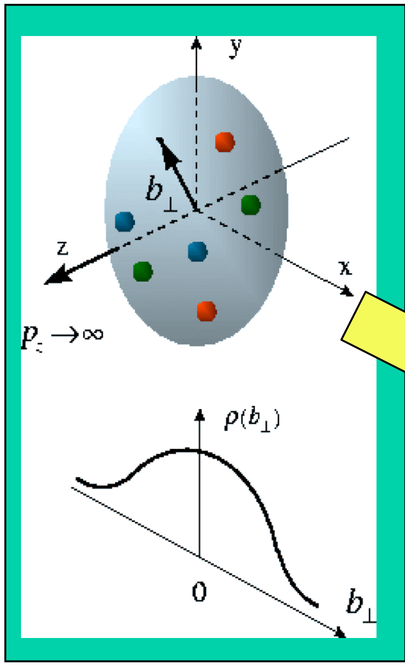
- Bjorken Limit: $Q^2, \nu \rightarrow \infty$
- Empirically, DIS region is where logarithmic scaling is observed: $Q^2 > 5$ GeV^2, $W^2 > 4$ GeV^2
- Duality: Averaged over W, logarithmic scaling observed to work also for $Q^2 > 0.5$ GeV^2, $W^2 < 4$ GeV^2, resonance regime

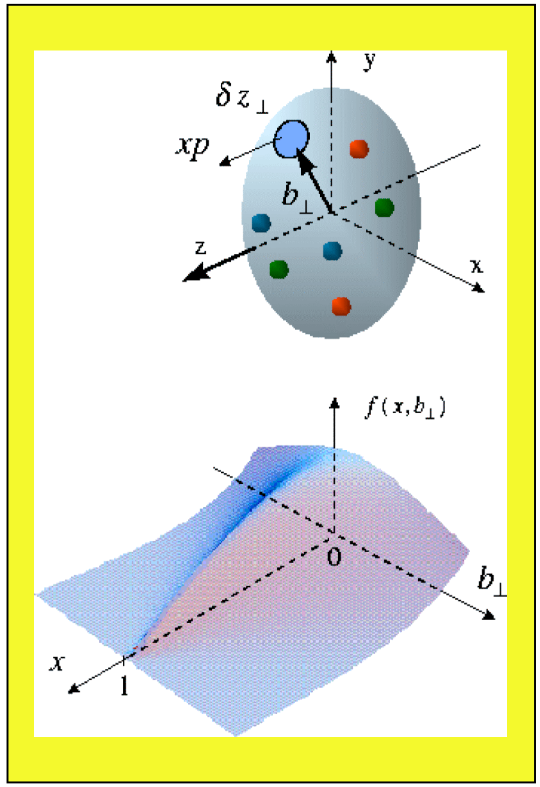


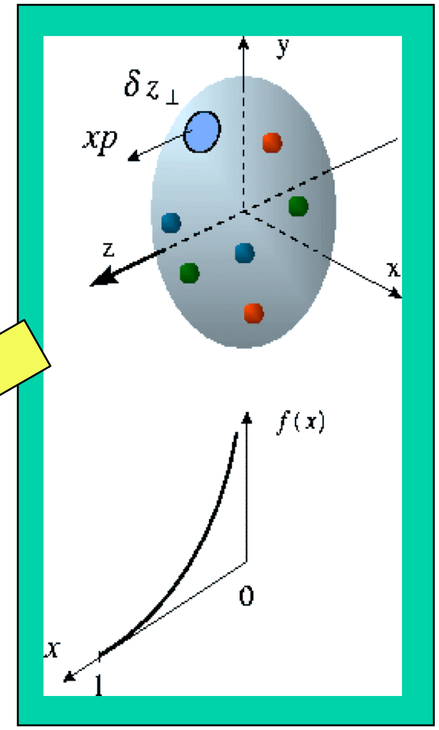
(CERN Courier, December 2004)

Beyond form factors and quark distributions – Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997)







Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Again, LOTS still to do!

EIC

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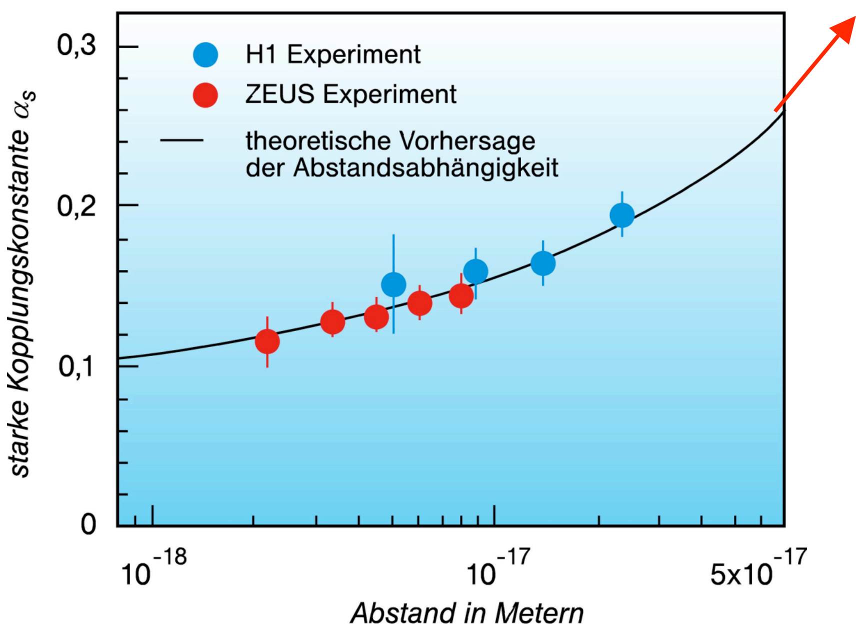
More challenges….

- Extrapolate α_s to the size of the proton, 10^{-15} m:



$$l \rightarrow r_{proton} \quad \Rightarrow \quad \alpha_s > 1$$

- If α_s >1 perturbative expansions fail…

→ *Non-perturbative QCD:*

- Proton structure & spin
- Confinement
- Nucleon-Nucleon forces
- Higher twist effects
- Target mass corrections