# 9. Experimentelle Tests der Quantenelektrodynamik bei hohen Energien

9.1 Der Prozess $e^+e^- \rightarrow \mu^+\mu^-$

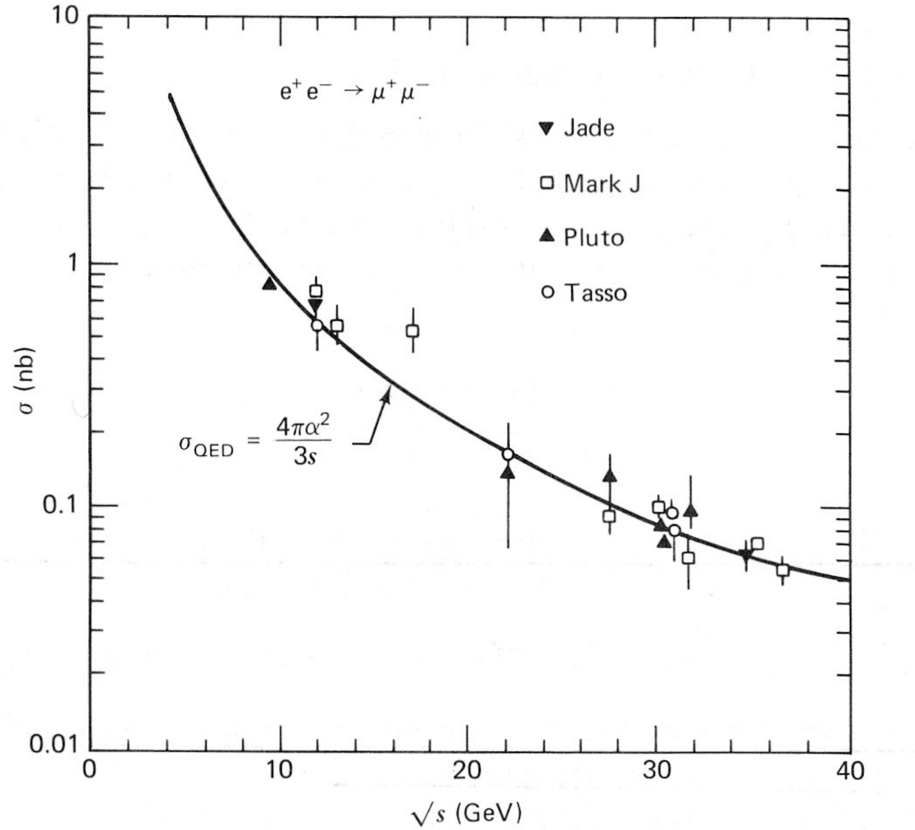
9.2 QED Streuprozesse

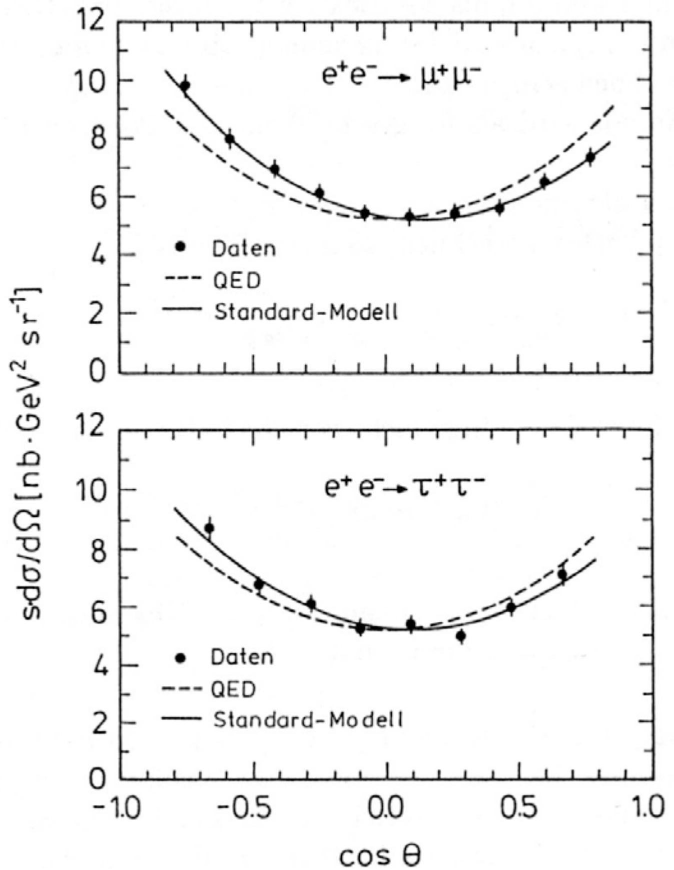
9.3 $e^+e^-$-Annihilation in Hadronen

9.4 Elastische Lepton-Nukleon-Streuung

9.5 Inelastische Lepton-Nukleon-Streuung

9.6 Das Quark-Parton Modell, Strukturfunktionen




Der totale Wirkungsquerschnitt für die Reaktion $e^+e^- \rightarrow \mu^+\mu^-$ als Funktion der Schwerpunktsenergie (aus Ref. [Halzen-Martin]

Die differentiellen Wirkungsquerschnitte für die Reaktionen $e^+e^- \rightarrow \mu^+\mu^-$ und $e^+e^- \rightarrow \tau^+\tau^-$ (aus Ref. [Schmüser]

# $e^+e^-$ Wirkungsquerschnitt

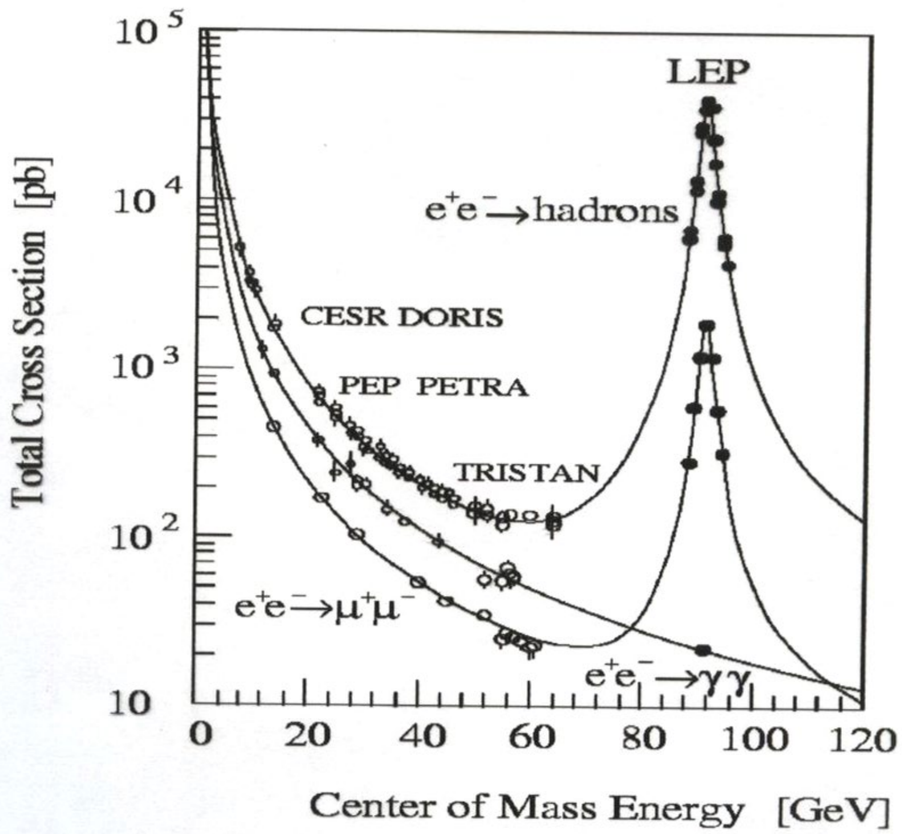
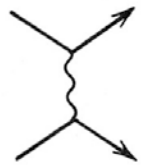
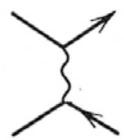
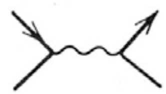
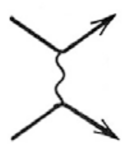
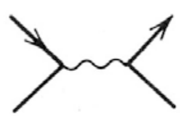
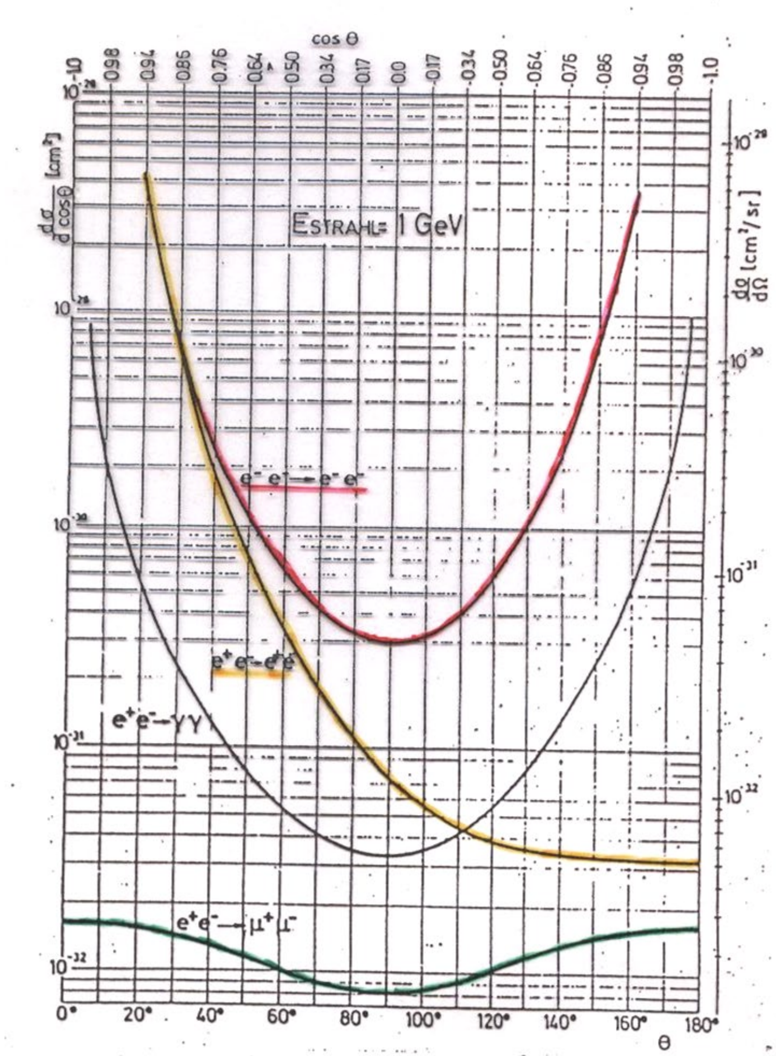


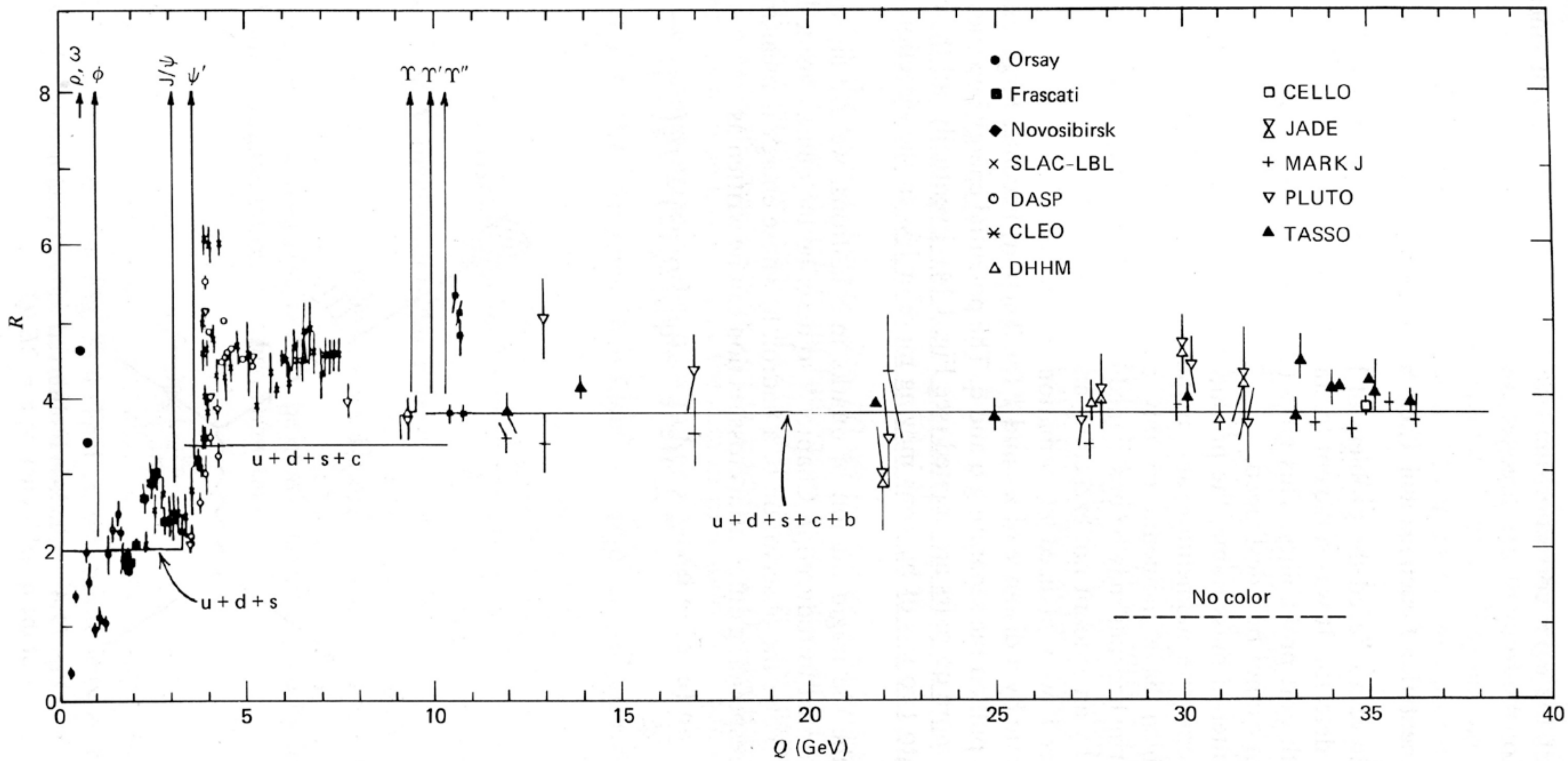
**TABLE 6.1**

Leading Order Contributions to Representative QED Processes

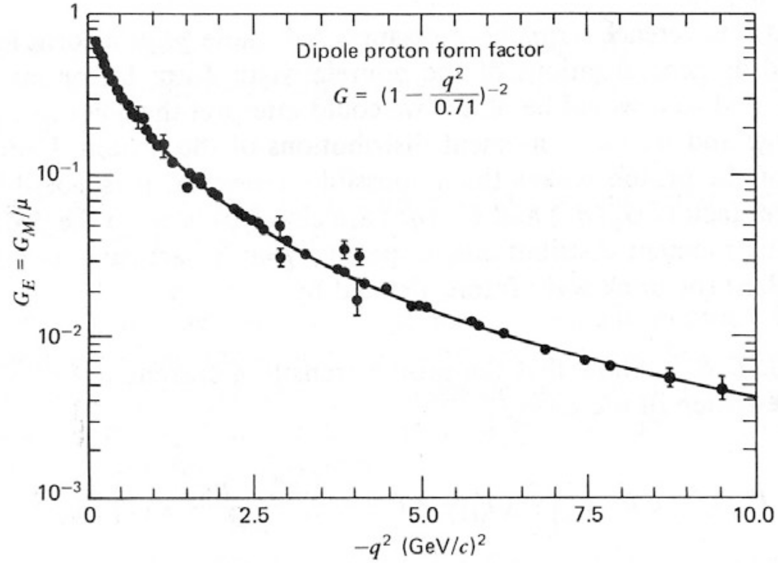
| | **Feynman Diagrams** | | $\overline{|\mathcal{M}|^2}/2e^4$ | | |
|---|---|---|---|---|---|
| | Forward peak | Backward peak | Forward | Interference | Backward |
| Møller scattering $e^- e^- \to e^- e^-$ |  |  | $\frac{s^2+u^2}{t^2}$ + | $\frac{2s^2}{tu}$ + | $\frac{s^2+t^2}{u^2}$ |
| ↓ (Crossing $s \leftrightarrow u$) ↓ | | | | ($u \leftrightarrow t$ symmetric) | |
| | Forward | "Time-like" | Forward | Interference | Time-like |
| Bhabha scattering $e^- e^+ \to e^- e^+$ |  |  | $\frac{s^2+u^2}{t^2}$ + | $\frac{2u^2}{ts}$ + | $\frac{u^2+t^2}{s^2}$ |
| $e^- \mu^- \to e^- \mu^-$ |  | | $\frac{s^2+u^2}{t^2}$ | | |
| (Crossing ↓ $s \leftrightarrow t$) $e^- e^+ \to \mu^- \mu^+$ | |  | | | $\frac{u^2+t^2}{s^2}$ |



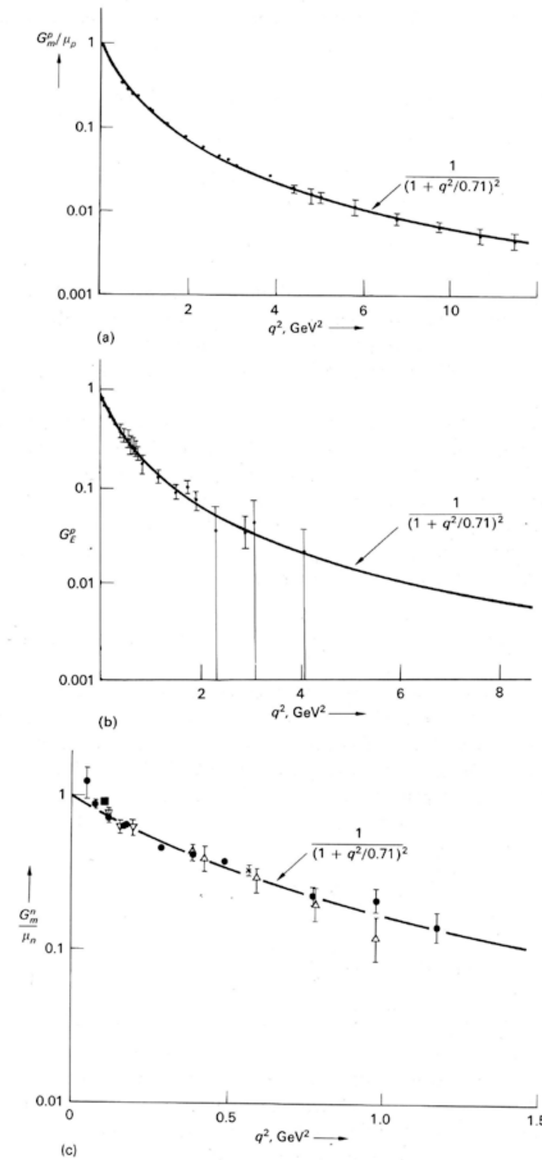

Differentielle Wirkungsquerschnitte für wichtige QED-Prozesse



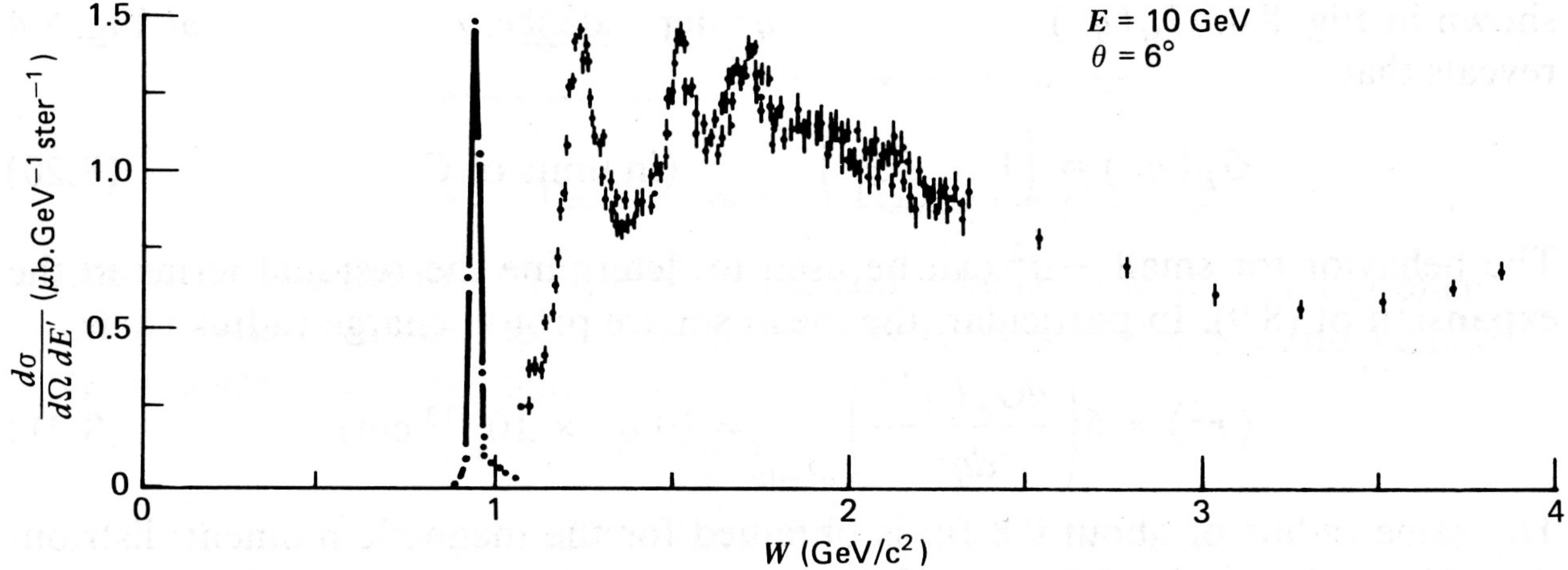

Ratio $R$ of (11.6) as a function of the total $e^-e^+$ center-of-mass energy. (The sharp peaks correspond to the production of narrow $1^{-}$ resonances just below or near the flavor thresholds.)



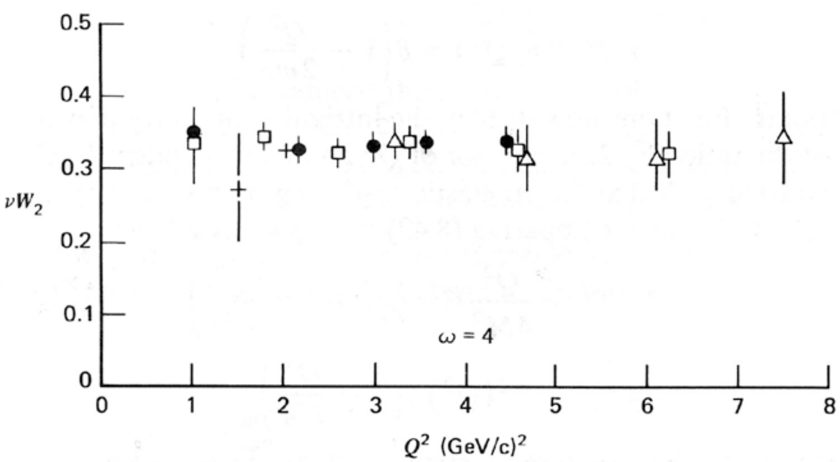

The proton form factors as a function of $q^2$.



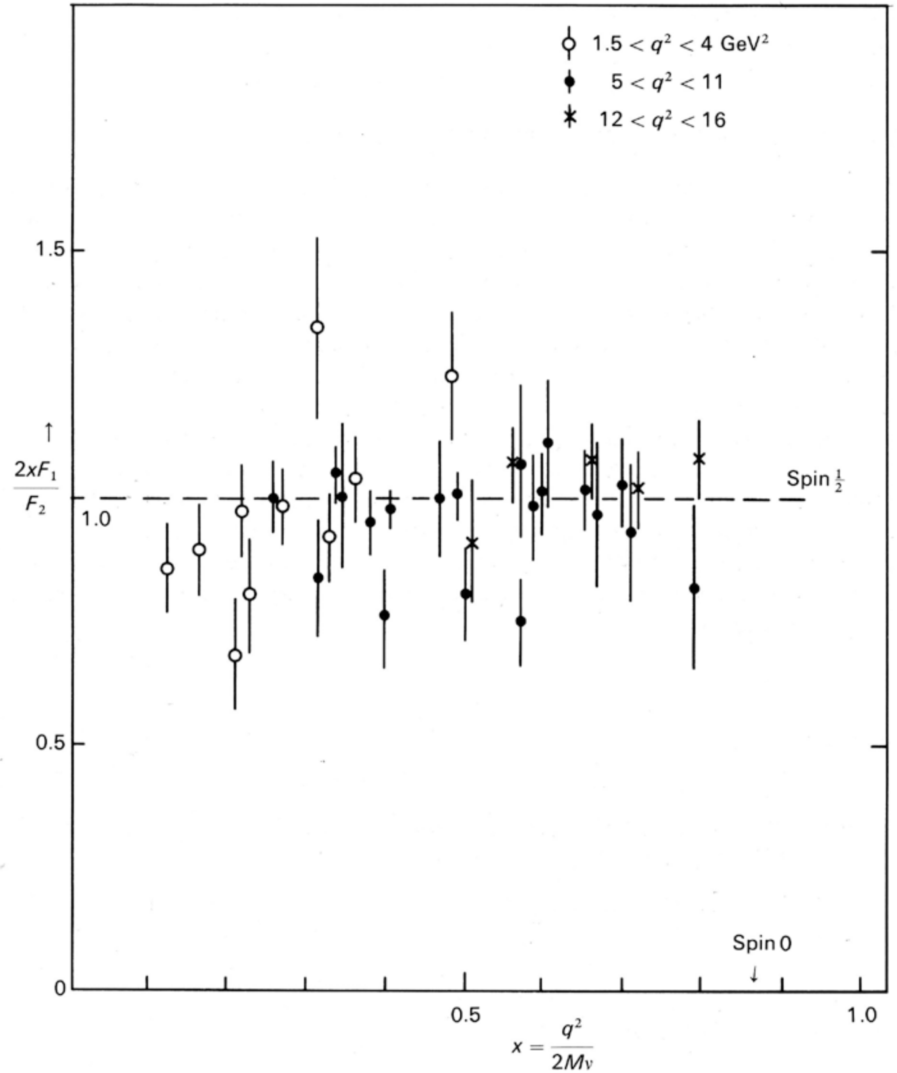

Comparison of the magnetic and electric form factors of neutron and proton. They are consistent with the scaling law (7.34). (a) Proton magnetic form factor; (b) proton electric form factor; (c) neutron magnetic form factor. (After Weber 1967.)




The ep → eX cross section as a function of the missing mass $W$. Data are from the Stanford Linear Accelerator. The elastic peak at $W = M$ has been reduced by a factor of 8.5.




The structure function $\nu W_2$ determined by electron–proton scattering as a function of $Q^2$ for $\omega = 4$. Data are from the Stanford Linear Accelerator.




The ratio $2xF_1/F_2$ measured in SLAC electron-nucleon scattering experiments. For spin-$\frac{1}{2}$ partons, with $g = 2$, a ratio of unity is expected in the limit of large $q^2$ – the Callan-Gross relation. (Data compiled from published SLAC data.)

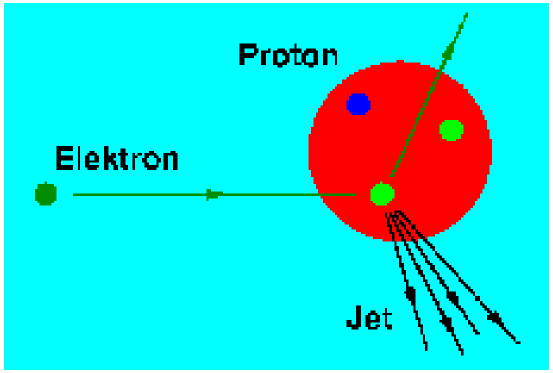
Test der Callan-Gross-Relation

# From where do we know the x-values?

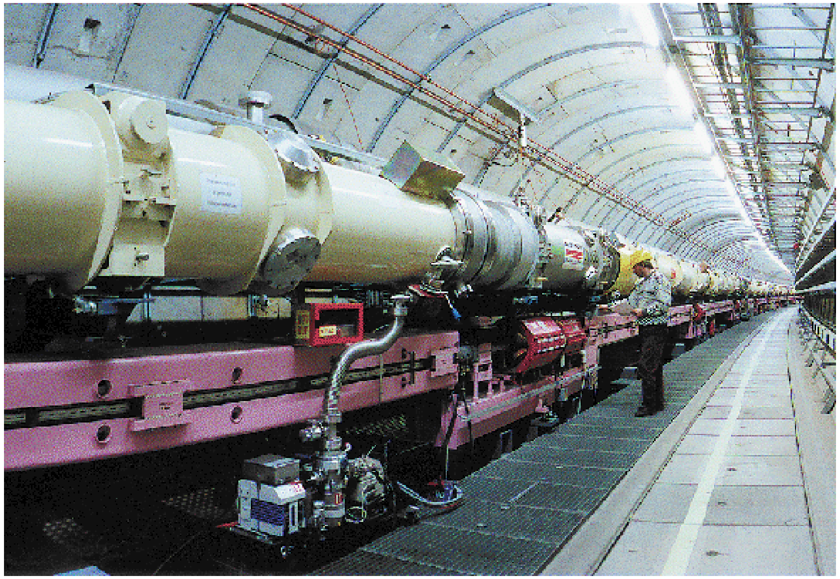
The structure of the proton is investigated in *Deep Inelastic Scattering* experiments:

Highest energy machine: the HERA ep collider at DESY/Hamburg
Operated from 1990 - 2007

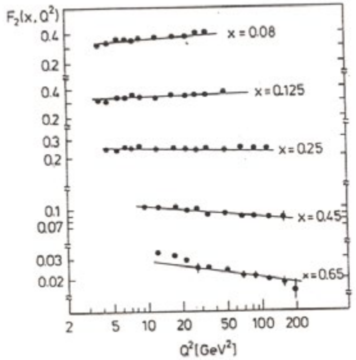
Scattering of 30 GeV electrons on 900 GeV protons:
→ Test of proton structure down to $10^{-18}$ m




HERA ep accelerator, 6.3 km circumference



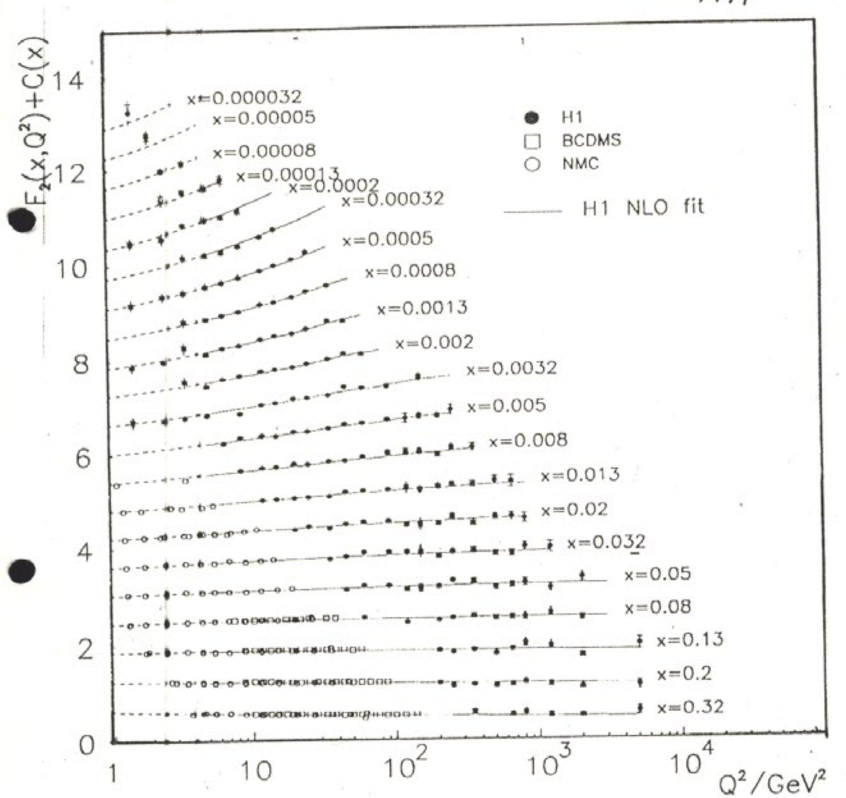
Strukturfunktion $F_2(x)$




– gemessen in Myon-Streuung an Eisen-Kernen

für verschiedene x-Werte

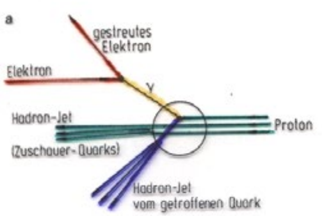
1994

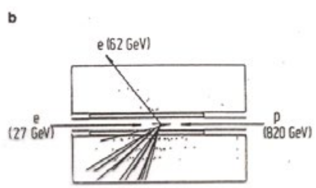



heute: HERA – Speicherring @ DESY / Hamburg

$(e^- p \rightarrow e^- + X \ldots)$

$\binom{27}{\text{GeV}} \times \binom{820}{\text{GeV}}$

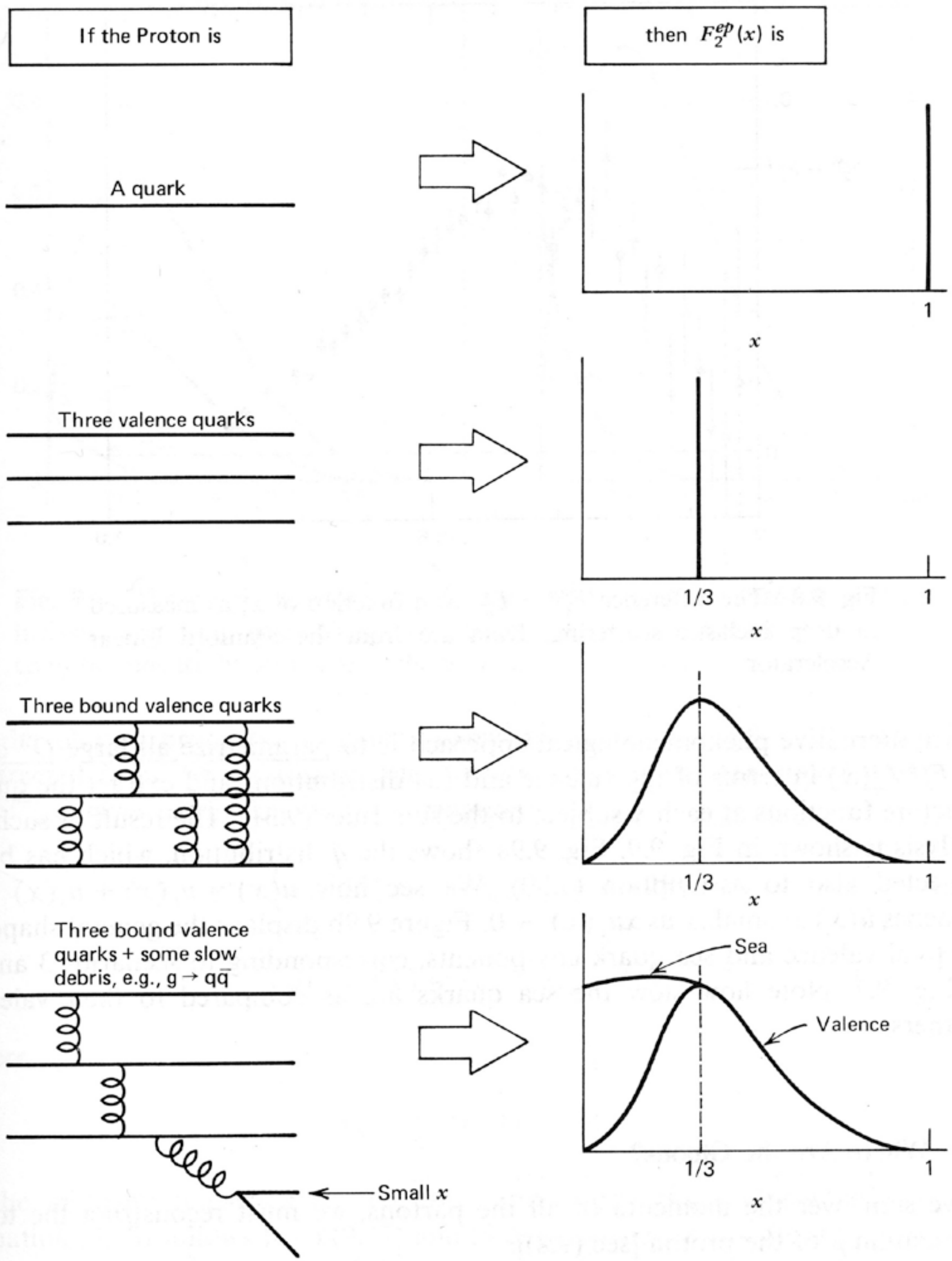


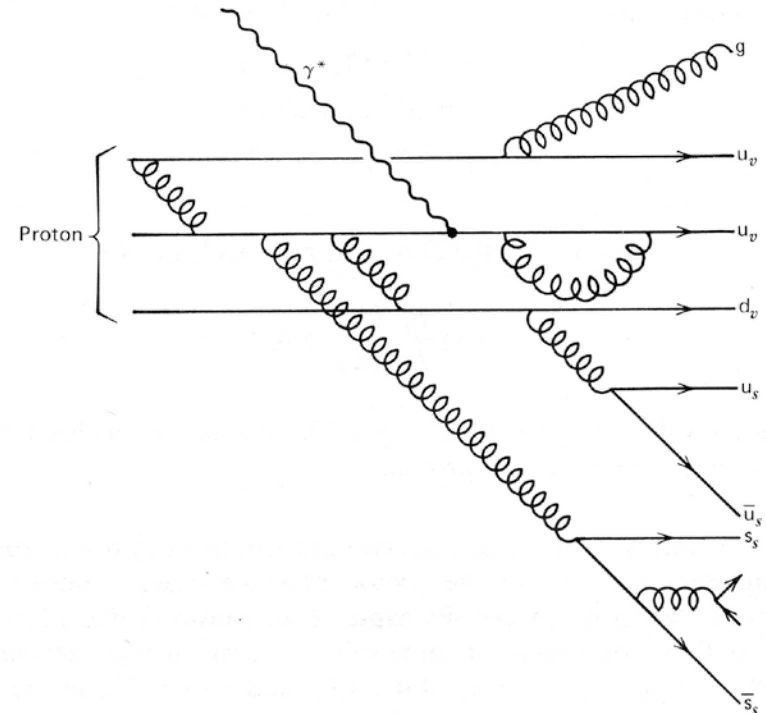

Beispiel: ZEUS Experiment

$Q^2 = 5300 \text{ GeV}^2$

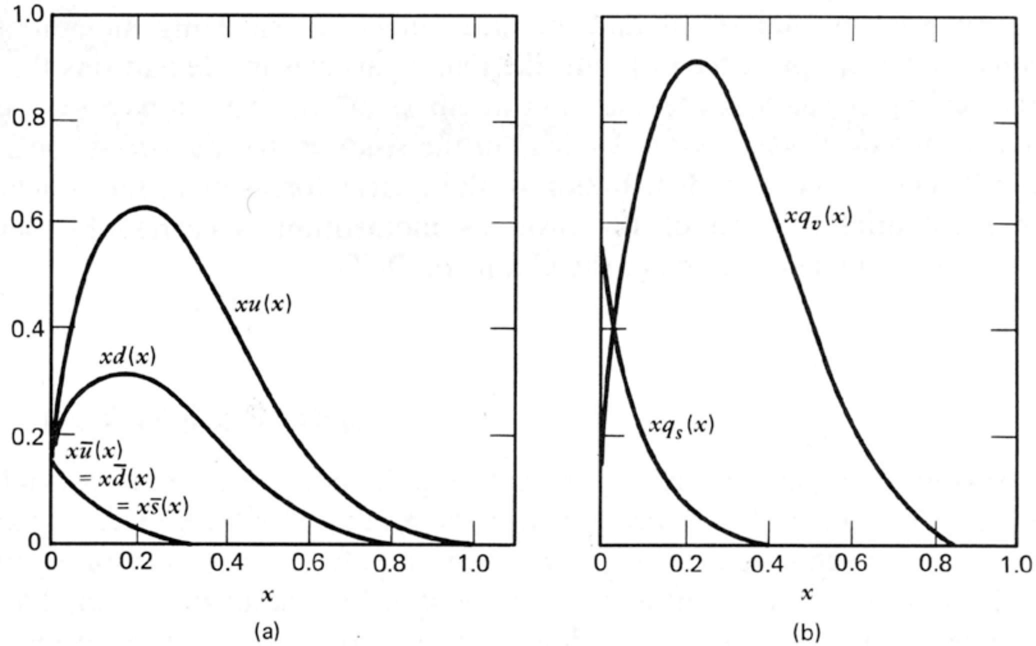
$x = 0.11$



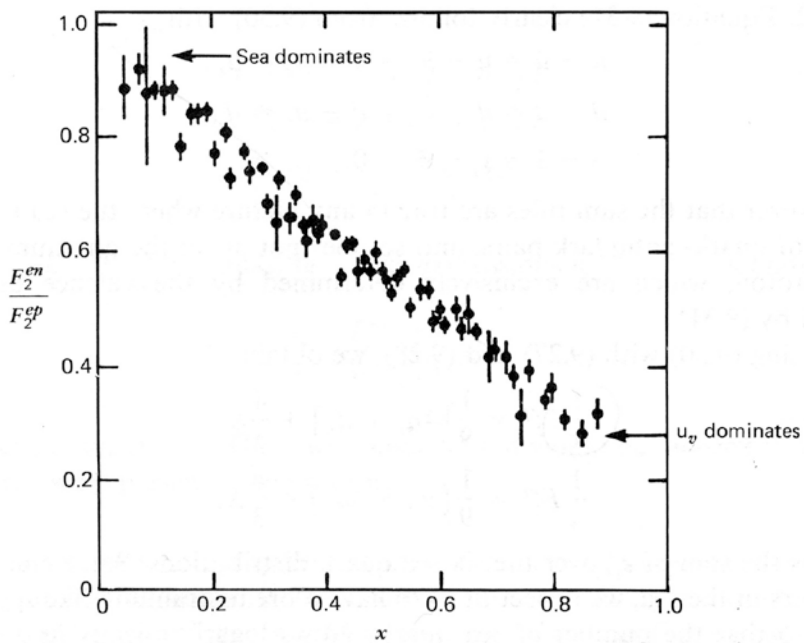

The structure function pictured corresponding to different compositions assumed for the proton.



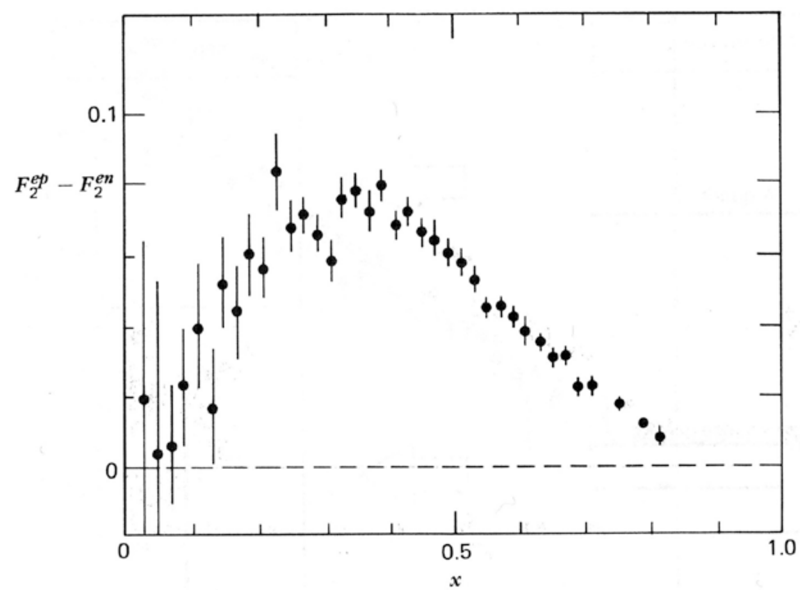

A proton made up of valence quarks, gluons, and slow debris consisting of quark–antiquark pairs.



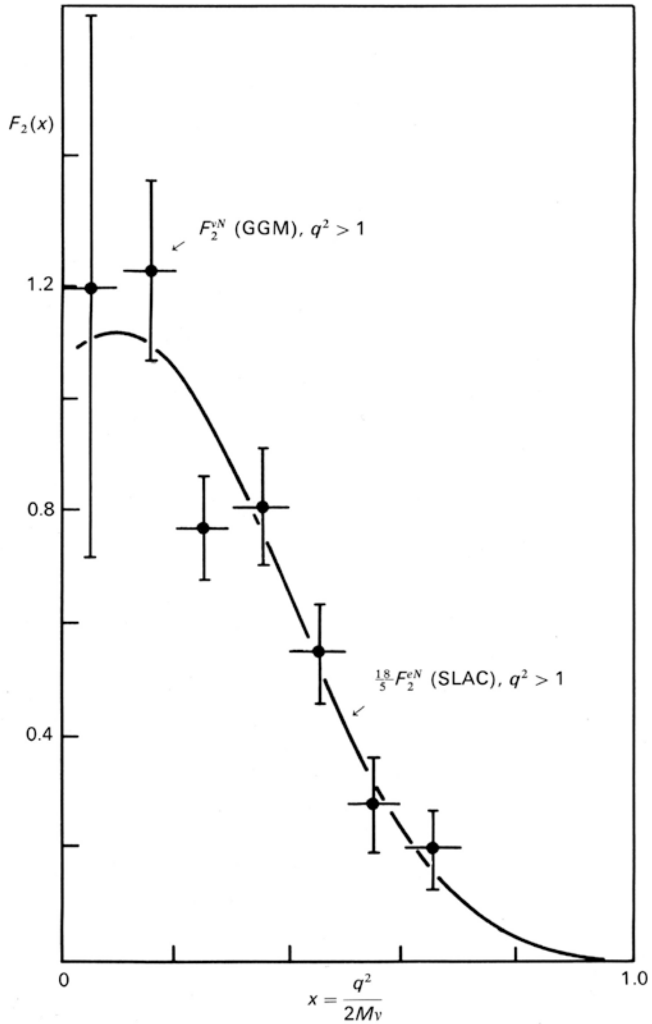

The quark structure functions extracted from an analysis of deep inelastic scattering data. Figure (b) shows the total valence and sea quark contributions to the structure of the proton.



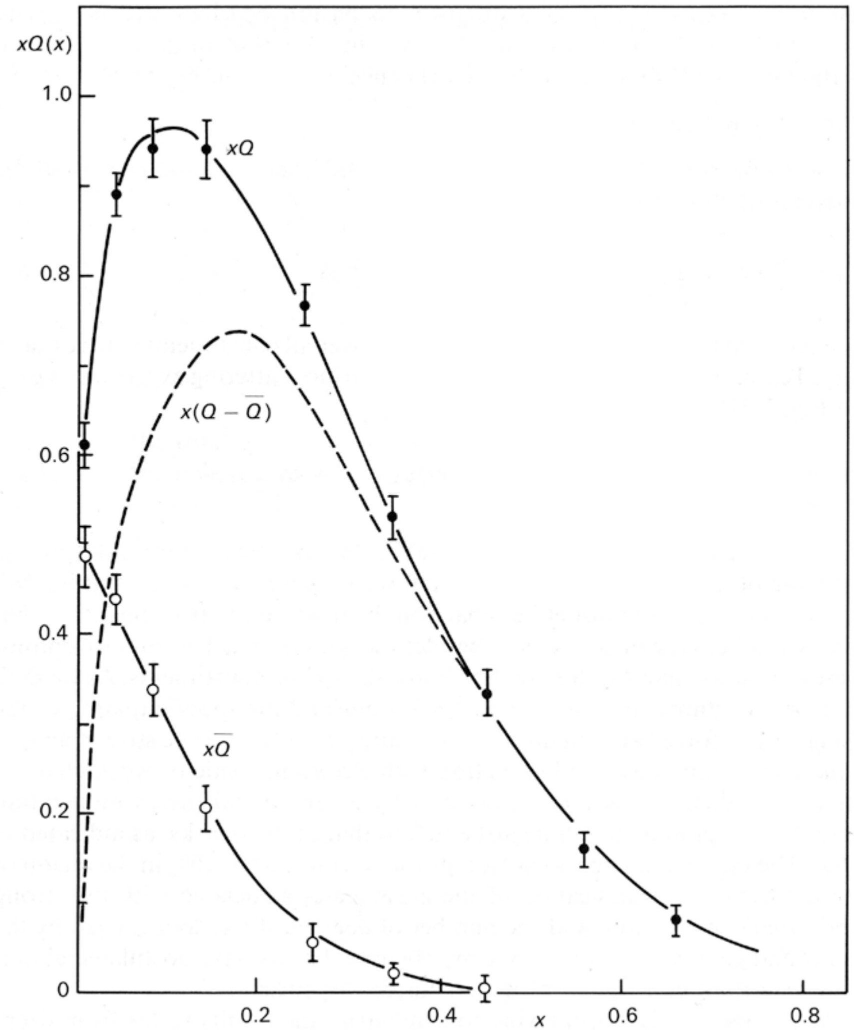

The ratio $F_2^{en}/F_2^{ep}$ as a function of $x$, measured in deep inelastic scattering. Data are from the Stanford Linear Accelerator.




The difference $F_2^{ep} - F_2^{en}$ as a function of $x$, as measured in deep inelastic scattering. Data are from the Stanford Linear Accelerator.

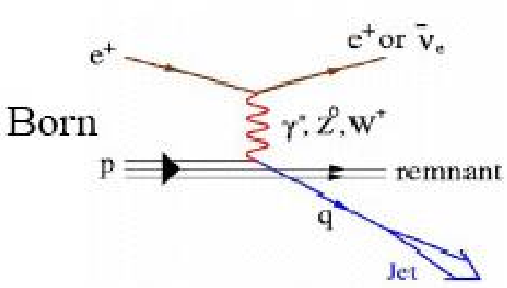


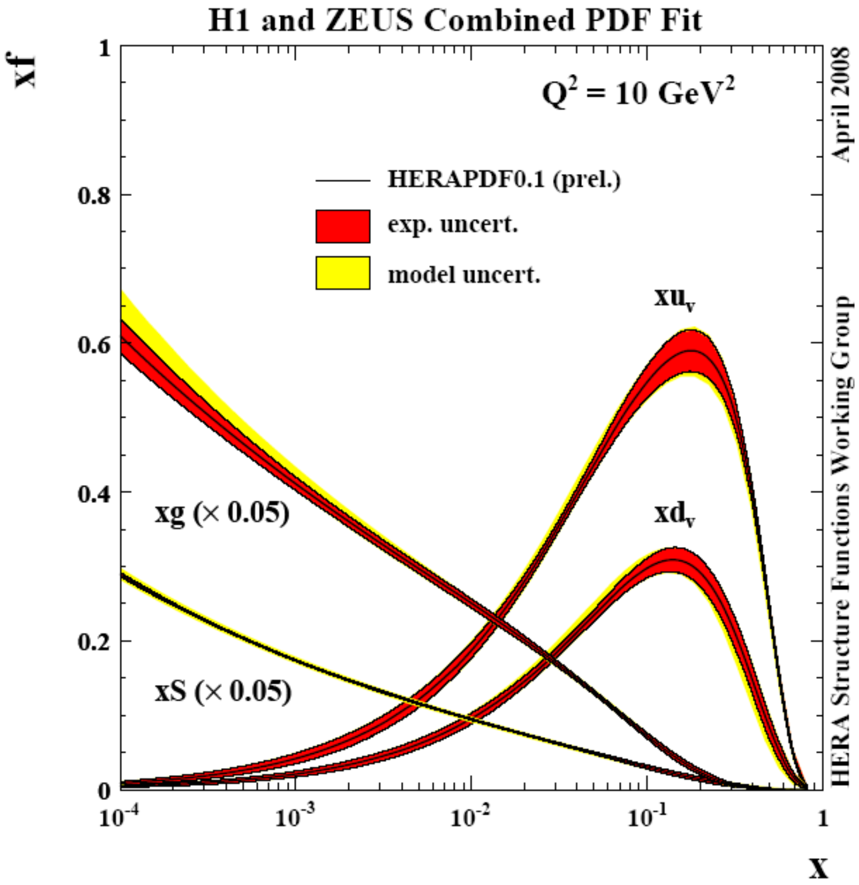

Comparison of $F_2^{\nu N}$ measured in neutrino-nucleon scattering in the Gargamelle heavy-liquid bubble chamber in a PS neutrino beam at CERN, with SLAC data on $F_2^{eN}$ from electron-nucleon scattering, in the same region of $q^2$. The data points are the neutrino results, and the curve is a fit through the electron data, multiplied by the factor $\frac{18}{5}$, which is the reciprocal of the mean squared charge of $u$- and $d$-quarks in the nucleon. This is a confirmation of the fractional charge assignments for the quarks. Note that the total area under the curve, measuring the total momentum fraction in the nucleon carried by quarks, is about 0.5. The remaining mass is ascribed to gluon constituents, which are the postulated carriers of the interquark color field




Momentum distributions of quarks ($Q$) and antiquarks ($\overline{Q}$) in the nucleon, at a value of $q^2$ of order 10 GeV$^2$, obtained from results on neutrino and antineutrino scattering in experiments at CERN and Fermilab. The neutrino and antineutrino differential cross-sections measure the structure functions $F_2$ and $F_3$ in Eq. (7.50), and the difference and sum of these, through Eq. (7.56), give the quark and antiquark populations weighted by the momentum fraction $x$. The antiquarks ($\overline{Q}$) are concentrated at small $x$, the region of the so-called quark-antiquark "sea". The "valence" quarks of the static quark model ($Q - \overline{Q}$) are concentrated towards $x = 0.2$.

# How do the x-values of the proton look like?




Parton density functions (pdf):

u- and d-quarks at large x-values

Gluons dominate at small x !!

Uncertainties in the pdfs,
in particular on the gluon distribution
at small x