1970:

Glashow, Iliopoulos and Maiani (GIM) predict the existence of a fourth quark, the charm quark. It has been observed that strangeness-changing neutral currents, $J^{\mu}_{had} = \bar{s}(x)\gamma_{\mu}(v - a\gamma_5)d(x)$, are extremely rare, e.g. $(\Delta S = 1)$

$$\frac{\Gamma(K^{\pm} \to \pi^{\pm}\nu\bar{\nu})}{\Gamma(K^{\pm} \to all)} = 10^{-10}$$

When introducing a fourth quark as follows

$$\begin{pmatrix} u \\ d' \end{pmatrix} ; \begin{pmatrix} c \\ s' \end{pmatrix}$$

with ($\theta_c$ : Cabibbo angle, $V$ is unitary)

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = V \begin{pmatrix} d \\ s \end{pmatrix} ; \; V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

an additional term arises which at tree-level exactly cancels strangeness-changing neutral currents. In order for the mixing matrix $V$ to cancel in the neutral current an equal number of quarks with charge $-2/3$ and $+1/3$ is needed.

It is recognized that with respect to the electroweak interaction leptons and quarks are intimately connected:

The Weinberg-Salam model is plagued by so-called anomalies (= divergent fermion triangle diagrams which can ruin renormalizability) which can be cured when including the quarks.

The Glashow-Weinberg-Salam (GWS) model also includes the electroweak interaction between quarks which is treated analogous to the one between leptons:
Charged Current (CC) (couples to the $W^{\pm}$ boson):

$$J^{\mu}_{CC} = \bar{\nu}_{e,L}\gamma^{\mu}e_L + \bar{u}_L\gamma^{\mu}V_{ud}d_L + \ldots$$

Neutral Current (NC) (couples to the $Z^0$ boson):

$$J^{\mu}_{NC} = \bar{e}\gamma^{\mu}(v_e - a_e\gamma_5)e + \bar{d}\gamma^{\mu}(v_d - a_d\gamma_5)d + \ldots$$

This gives rise to quark-induced anomalies, however with opposite sign, which cancel the lepton-induced anomalies.

The GWS model is part of the Standard Model describing the electroweak interaction between quarks and leptons.

1971:

’t Hooft proves that Yang-Mills gauge theories are renormalizable even if the symmetry is spontaneously broken.

In 1954 Yang and Mills (Shaw, Klein (1939)) generalized local gauge invariance as a dynamical principle to the non-Abelian gauge group SU(2) in an attempt to formulate a theory of hadron dynamics. As a result massless self-interacting vector particles emerged belonging to the SU(2) triplet. In non-Abelian gauge theories not only the particle fields carry the charge of the symmetry group but also the gauge fields. Thus there exists a self-coupling of the gauge fields.

In 1967 Fadeev and Popov succeeded in quantizing Yang-Mills fields. Weinberg and Salam used Yang-Mills fields to describe charged fundamental vector particles, the $W$ bosons. However, the $W$ and $Z$ bosons are massive and naively adding mass terms to the Yang-Mills Lagrangian spoils renormalizability and unitarity of the theory. A more sophisticated mechanism is needed to introduce mass terms for the gauge bosons, e.g. the Higgs-Kibble mechanism.

1973:

The birth of Quantum Chromo Dynamics (QCD):

Pati, Salam and Fritzsch, Gell-Mann, Leutwyler and Weinberg use the Yang-Mills theory to describe the dynamics of strong interaction.

They suggest that quarks interact with each other via the exchange of massless vector particles, the gluons.

QCD is the quantum field theory of strong interaction among quarks based upon a local non-Abelian color gauge symmetry.

Since leptons are colorless states and the strong interaction does not distinguish between different quark flavors (“flavor blind”), it is natural to assume that color plays the role of charge in the strong interaction. Then a dynamical theory of strong interaction among quarks has to be a color gauge theory with color-SU(3) as the gauge group. The SU(3) color octet gauge bosons that emerge in this theory are called gluons. The gluons couple to the color degrees of freedom of the quarks.

1973:

Gross, Wilczek and Politzer show that non-Abelian gauge theories are *asymptotic free*.

As a consequence of the running of the coupling constant of QCD (at 1-loop and $N_f \leq 16$):

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f)\log(Q^2/\Lambda^2)}$$

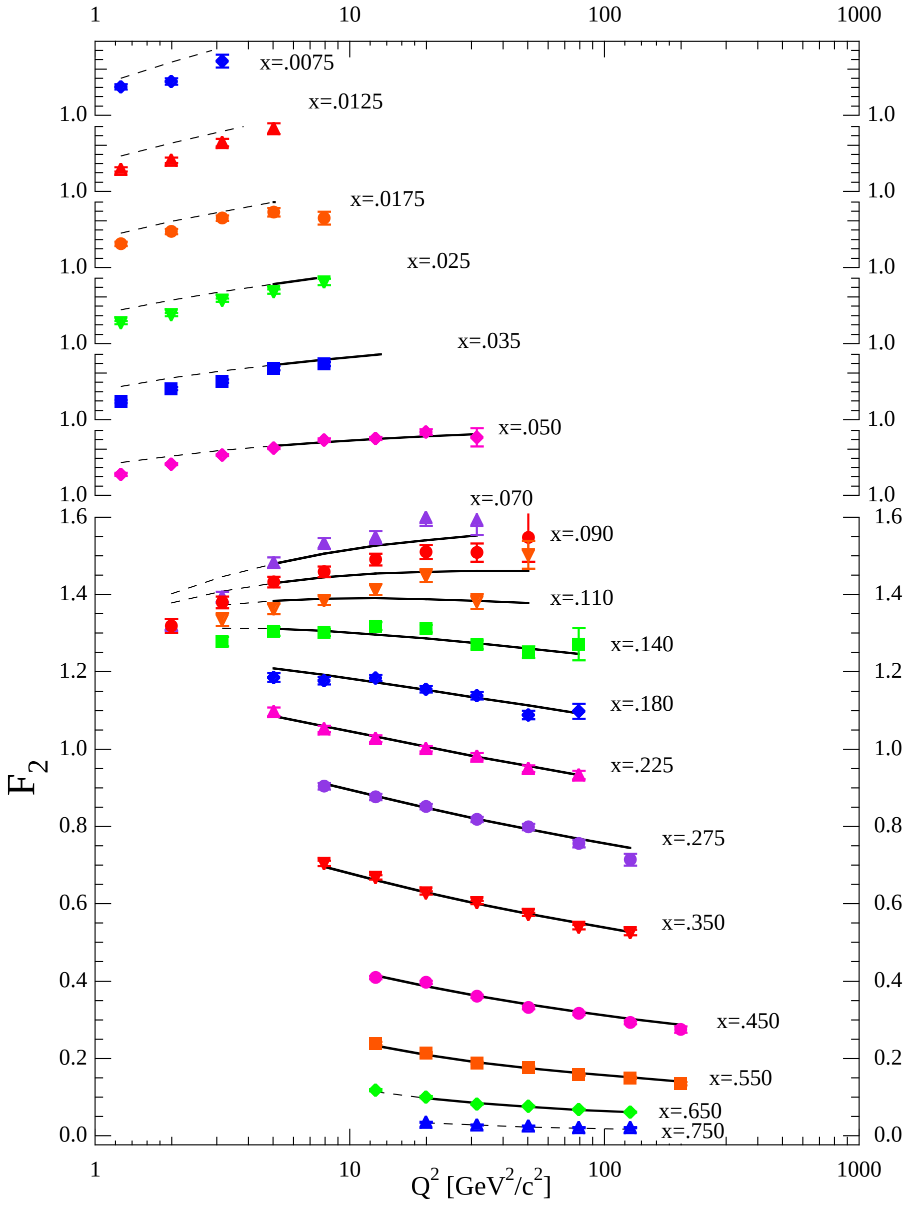
there is a regime, $Q^2 \gg \Lambda^2$, where quarks can be considered quasi-free, $\alpha_s \ll 1$ and perturbation theory is applicable.

Now it's plausible why the parton model works so well at high $Q^2$ when assuming quasi-free quarks.

The violation of Bjorken-scaling in deep inelastic scattering processes can be understood within QCD. The QCD calculation of the $Q^2$ dependence of the structure functions using perturbation theory agrees impressively well with data.

The growth of the coupling constant for small $Q^2$, i.e. at large distances, might give a hint towards a better understanding of quark (color) confinement:

In contrast to QED, the quanta of the fields in QCD, the quarks and gluons, have not been observed as free particles.



## Test of perturbative QCD

The structure function $F_2(x, Q^2)$ as measured in $\nu N$ charged current interaction by the CCFR collaboration at Fermilab.

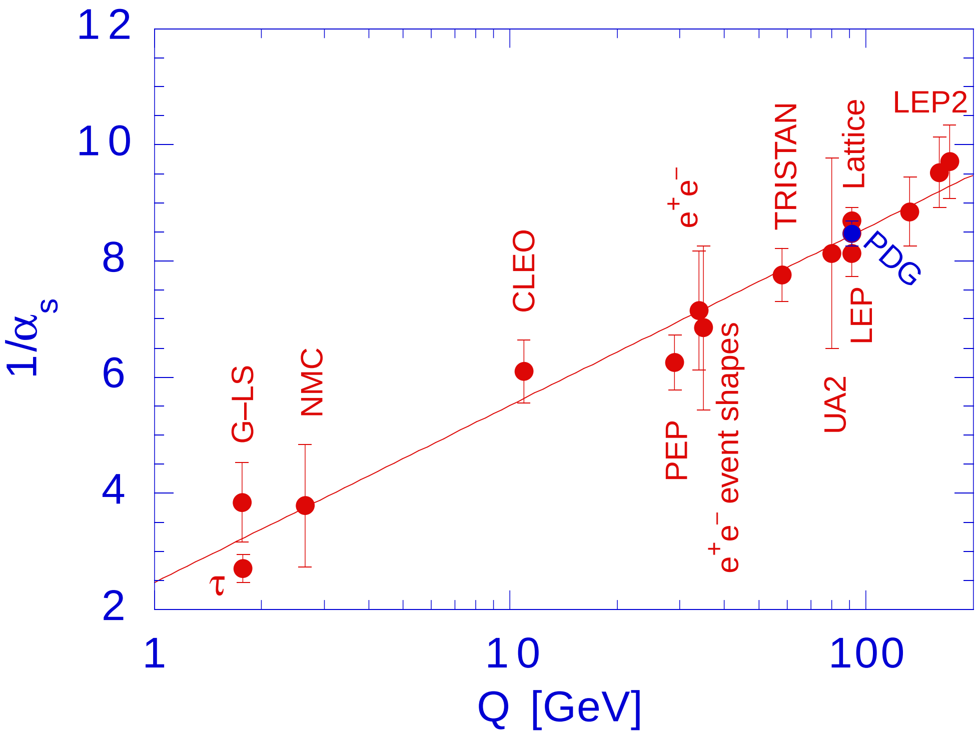
The solid lines represent the QCD predictions describing the observed violation of Bjorken scaling.

from Chris Quigg,

http://arxiv.org/abs/hep-ph/0001145

# The running of the strong coupling “constant” $\alpha_s$

The line shows the expected evolution as predicted by QCD.



from Chris Quigg, http://arxiv.org/abs/hep-ph/0001145

1973:

The ISR experiment at CERN finds first evidence for neutral current interactions. In the Gargamelle bubble chamber neutrinos are seen to interact with other particles and remain as neutrinos, e.g. $\nu_\mu + N \to \nu_\mu + p + \pi^- + \pi^0$.

1974:

"The 1974 November revolution":

F. Gilman: *All the pieces were there but somehow only a few people . . . were ready to say loudly that we should swallow the whole picture: quarks, QCD, the electroweak theory and most of all that there had to be another quark, the charm quark.*

Ting et al. (Brookhaven) and Richter et al. (SLAC) discover independently the $J/\Psi$ which appeared as a peak (resonance) in $e^+e^-$ production at an energy of 3.1 GeV, the first meson of a new class of massive, long-lived mesons. It was quickly established that the $J/\Psi$ is a new $q\bar{q}$ bound state, consisting of a charm and anti-charm quark.

At a conference in 1974 Iliopoulos presents for the first time in a single report the view of particle physics now called the Standard Model.

After 1974 it was largely accepted that with the Standard Model of particle physics we finally have a theory of strong and electroweak interactions among leptons and quarks.