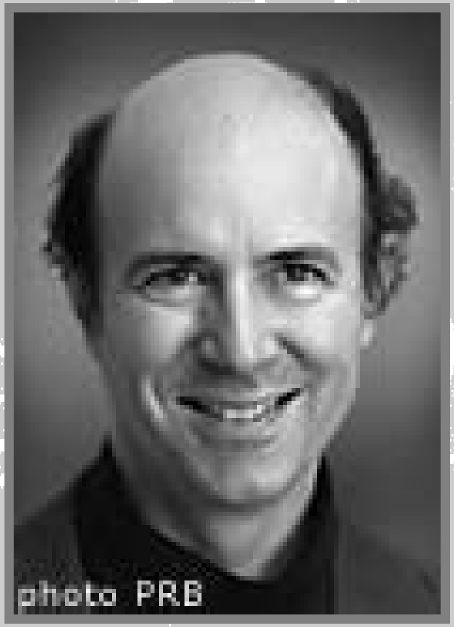
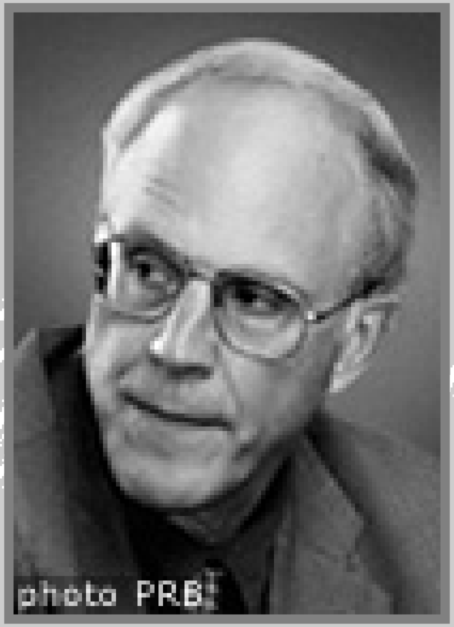
Nobelpreis 2004

David Politzer



Frank Wilczek

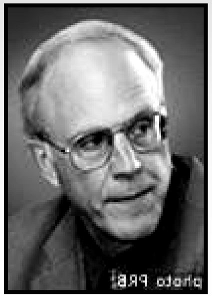


David Gross

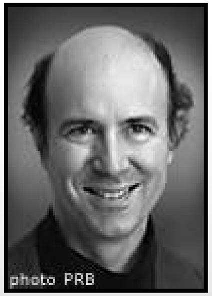
Th. Naumann DESY

Physik-Nobelpreis 2004

für die Entdeckung der asymptotischen Freiheit in der Theorie der starken Wechselwirkung an:



David J. Gross
Kavli Inst. for Theoretical Physics,
Univ. of California, Santa Barbara,



H. David Politzer
California Inst. of Technology (Caltech),
Pasadena, und

Frank Wilczek
Massachusetts Inst. of Technology (MIT),
Cambridge, alle USA.

Physik-Nobelpreis 2004

- Das Problem: QED
  - Die Ladung wird unendlich
- Die Lösung: QCD
  - Die Kopplung läuft: asymptot. Freiheit
  - Die Kernkraft wird stark: Confinement
- Der Test + DESY :
  - Laufende Kopplung
  - Protonen und Gluonen
  - QCD-Vakuum: Glueballs + Quagma
- Präzision
  - Störungstheorie + Gitter-QCD
- Der Weg zur Ur-Kraft
  - Super-Symmetrie + Große Vereinigung

Nobelpreise

Elektromagnetismus

- 1948 Tomonaga, Schwinger, Feynman: Quantum Electro Dynamics 1965

Schwache Kraft

- 1934 Fermi: Theory of Beta Decay 1938
- 1954 Yang, Lee: Gauge Theory of Weak Interactions 1957
- 1971 Glashow, Salam, Weinberg: Theory of Electroweak Interactions 1979
- 1971 t'Hooft, Veltman: Renormalization of Electroweak Interaction 1999

Starke Kraft

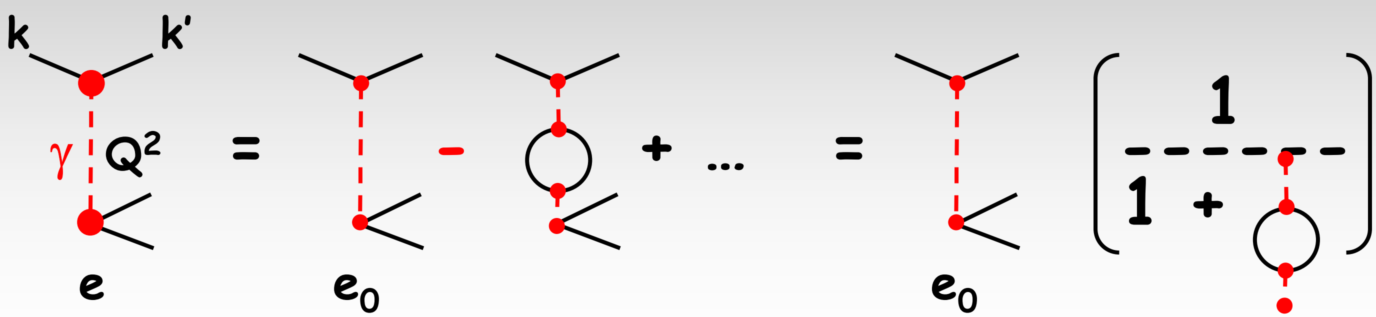
- 1935 Yukawa: Theory of Nuclear Forces 1949
- 1964 Gell-Mann: Symmetries of elementary particles: SU(3) 1969
- 1969 Friedman, Kendall, Taylor: Quark discovery in ep scattering 1990
- 1971 Wilson: Theory of phase transformations: Renorm. group 1982

QED:

laufende Konstanten

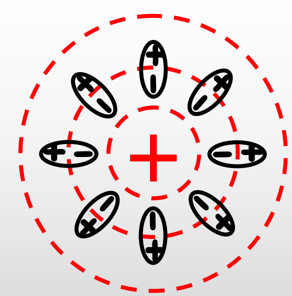
QED

Vakuum-Polarisation in e-e Streuung:



physikal. Ladung	nackte Ladung	Vakuum-Polarisation

dielektr. Screening:



klass. Elektron-Radius
$r = \alpha/m_e \sim 3$ fm
Compton-Wellenlänge
$\lambda_C = 1/m_e$

- Kopplung ~ Ladung²: $F = \alpha/r^2$ $\alpha = e^2/4\pi$
- infrarot stabil: $\alpha = 1/137$
  ultraviolett divergent - nackte Ladung unendlich !?
- Cutoff bei willkürl. Skala: Renormierung !

  Energie-Skala: $Q^2 = -(k-k')^2$
- betrachte nur Evolution von Energieskala Q zu Skala μ
  UV Divergenzen kürzen sich:

Die Evolution ist alles - das Ziel ist divergent.

ALRIGHT RUTH, I ABOUT GOT THIS ONE RENORMALIZED

Nobel Prize for first Quark Evidence.

Physics Today, Jan. 1991.

Das Problem

- **Landau 1955:**
  „weak coupling electrodynamics is …
  fundamentally logically incomplete."

  „within the limits of formal electrodynamics
  a point interaction is equivalent … to no interaction at all."

- **Dyson 1960:**
  "The correct theory will not be found within the next 100 years."

- **Feynman 1961:**
  "I still … do not subscribe to the philosophy of renormalization."

- **Weinberg 1972**, Gravitation + Cosmology:
  „we encounter theoretical difficulties beyond the range
  of modern statistical mechanics."

Renormierung

- Petermann, Stückelberg 1951. Gell-Mann, Low 1954.
- Bogoljubov, Shirkov 1956. Callan, Symanzik 1970.
- Wilson 1971. Teilchen- u. Festkörperphysik. OPE. Gitter.

- Renormiere Ladung + Cutoff so, daß Physik nicht von willkürl. Energie-Skala μ abhängt:
- **β-Funktion:** $2\beta = \partial\, \alpha(\mu) \,/\, \partial \ln(\mu)$
- Renormierungsgruppen-Glg:

  $\beta=0$ für $\mu\to0$ IR stabil $\alpha(0) = 1/137$

- **Problem:**

  Punkt-Ww. heißt UV stabil ! $\alpha(\infty) = ?$

  $\beta=0$ für $\mu\to\infty$

Gibt es asymptot. freie Feldtheorien ?
Gibt es Punkt-Ww. (an Elementarteilchen) ?

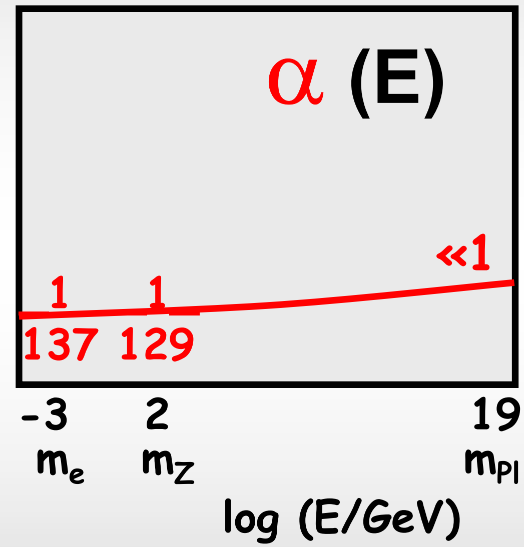
Die laufende Kopplung

$\alpha = e^2/4\pi$ Ladung ~ Kopplung = Feinstruktur-Konstante

Konstante **nicht konstant:**

$$2\beta = \partial\,\alpha(\mu) / \partial \ln \mu = \frac{2}{3\pi}\alpha^2 + \ldots$$

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log\frac{Q^2}{\mu^2}}$$



α (E) running (or crawling):

$$\partial\,\alpha(Q^2) / \partial Q^2 > 0$$

α (m_e = 0.5 MeV) = 1/137

α (m_Z = 91 GeV) = 1/128.9   CERN LEP

α (m_{Pl} = 10^{19} GeV) « 1   mehr Fermion-Loops

α (∞)   undefiniert   keine elektr. Punkt-Ww.

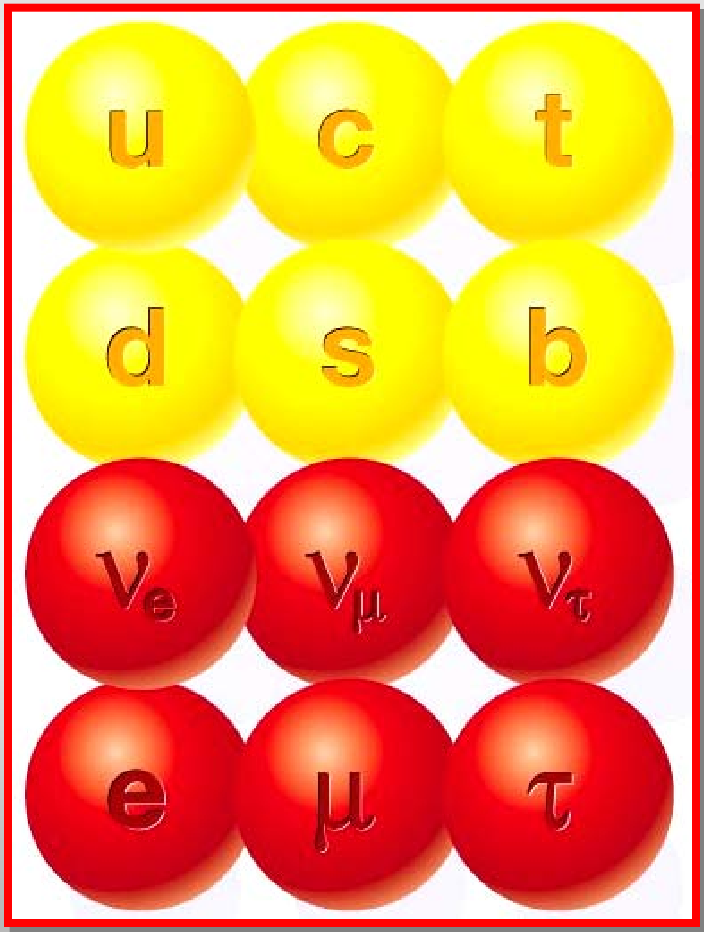
Das Standard Modell

Die Bausteine

3 Familien

QUARKS

LEPTONEN



Up

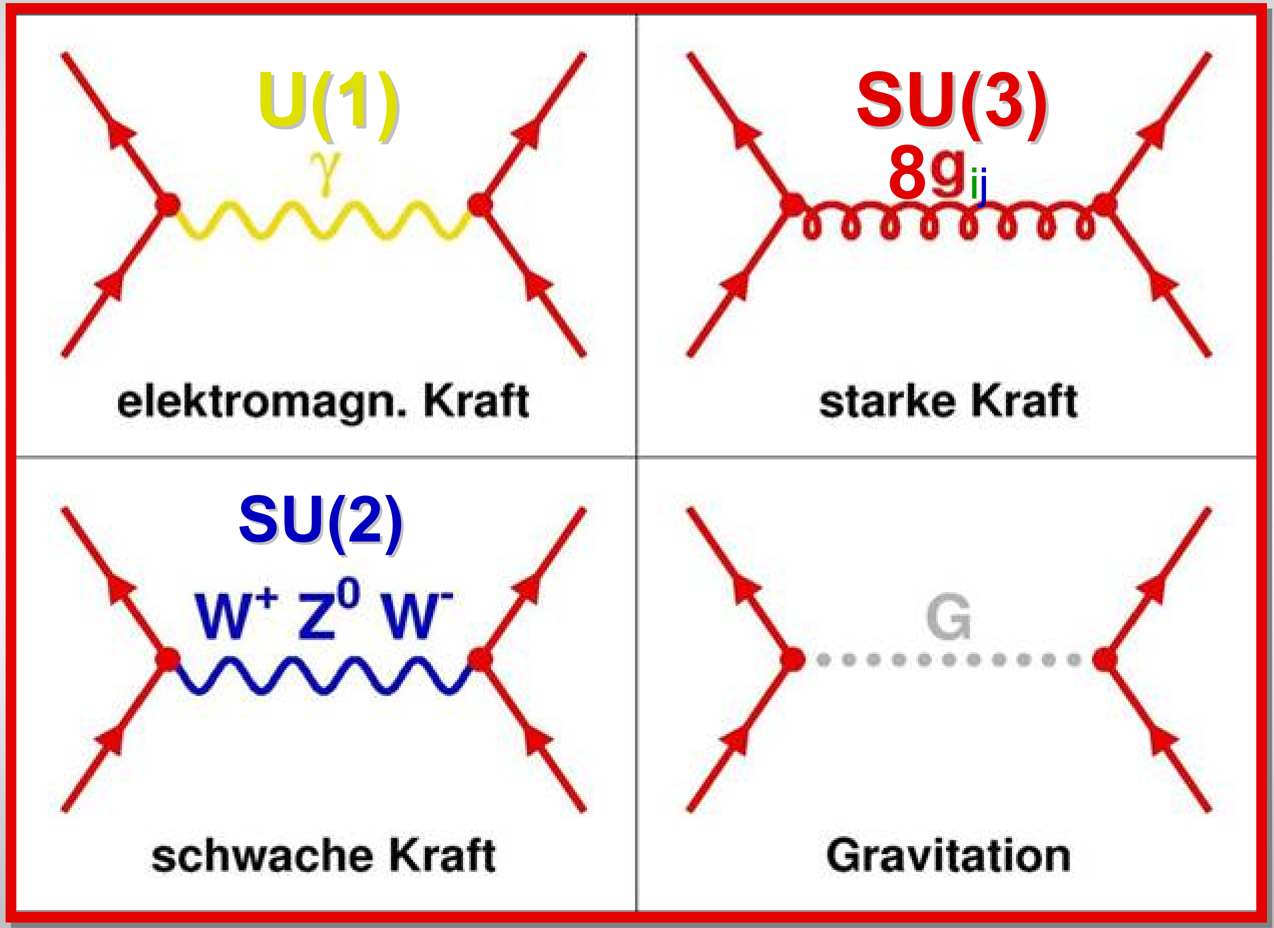
x2 = 6 Flavors

Down

Neutrinos

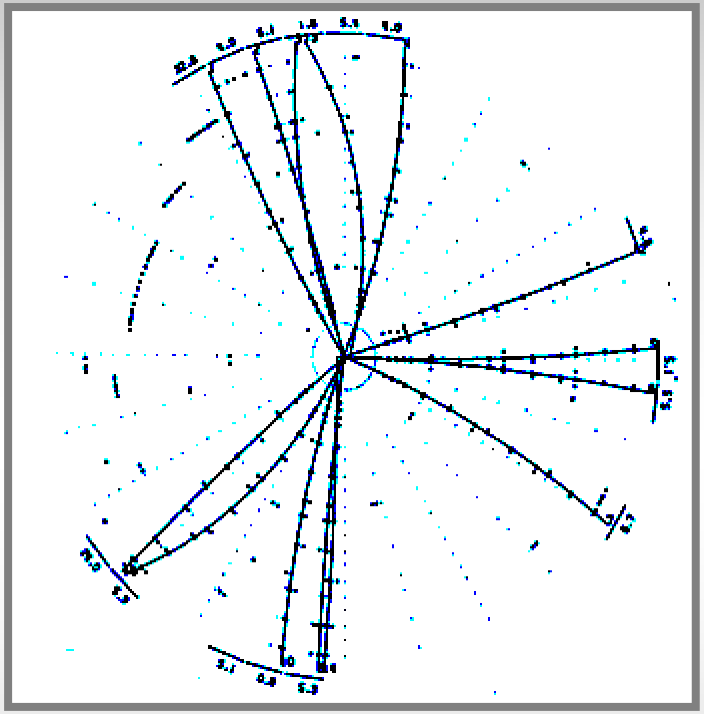
Elektronen

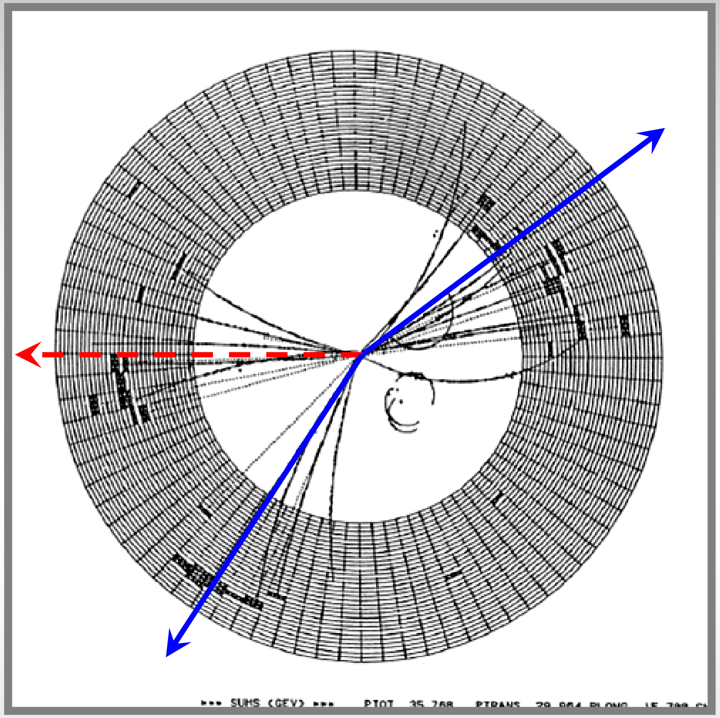
Die Kräfte



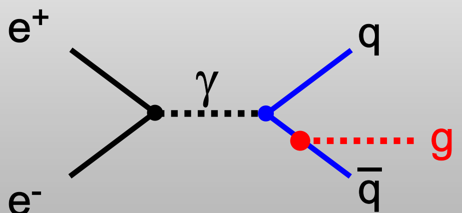
SU(N):
N^2-1 Austausch-Bosonen

Das Gluon





Entdeckt 1979 bei PETRA am DESY in



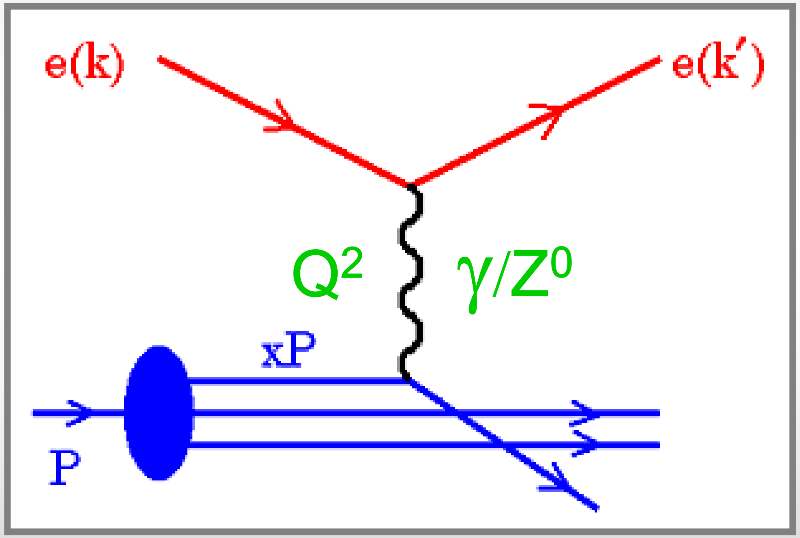
$e^+ e^- \rightarrow q\ \bar{q}\ g$

Kinematik

Energie^2 im Massenschwerpunkt-System:

$s = (k + P)^2 = 4\, E_e\, E_p$ HERA:

$s = 4 \cdot 27.6\ \text{GeV} \cdot 920\ \text{GeV} = (319\ \text{GeV})^2$



$Q^2 = -\,q^2 = -\,(k - k')^2$

Quadrat des Vererimpuls-Übertrags

Rutherford 1911:

Photon-Propagator

$d\sigma / dQ^2 = 4\pi\alpha^2 / Q^4$

$d\sigma / d\cos(\theta) = \pi\alpha^2 / 2E^2 \sin^4(\theta/2)$

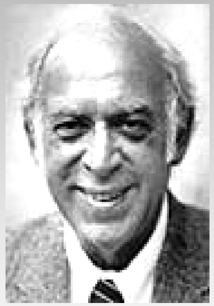
Mott 1929, Elektron-Spin:

$\sigma_{Mott} = \cos^2(\theta/2)\, \sigma_{Ruth.}$

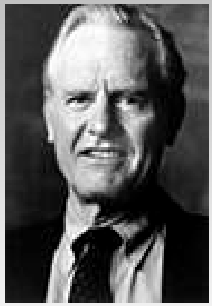
$x = Q^2 / (2P \cdot q)$ Bjorken

Impuls-Anteil des Partons im Proton (Quark, Gluon)

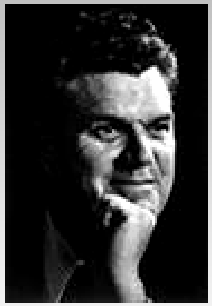
Quarks + Scaling



Friedman



Kendall



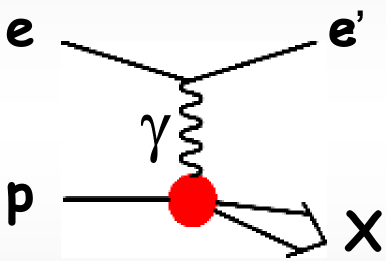
Taylor

Nobelpreis

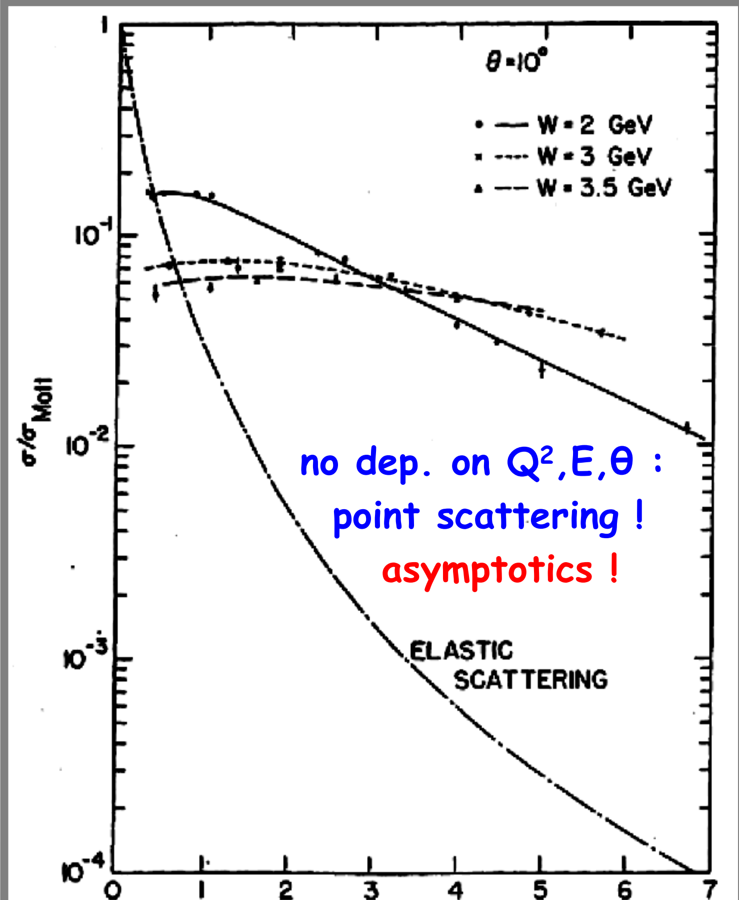
1990

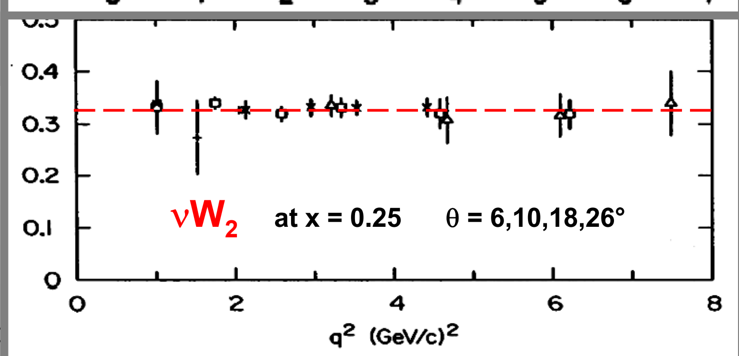
Stanford Linear Accelerator
USA, 1968-71:

Elektron-Proton
tief inelastische Streuung



E = 1.5 - 20 GeV
θ = 6° - 26°
Q^2 = 1 - 7 GeV^2





Callan-Gross Relation

Parton Spin		Photon Polarisation
0,1	$\sigma_T = 0$	longitudinal
1/2	$\sigma_L = 0$	transversal

$\sigma_L/\sigma_T = 0$

elektr. = magnet. Formfaktor (Spin flip)

$F_2(x) = 2x\, F_1(x)$ Callan-Gross

Bausteine des Protons:
punktförmig + Spin=1/2

Feynman: Parton-Modell

erst QCD Gluon-Strahlung
gibt transversale Freiheitsgrade:

$F_2(x) \neq 2x\, F_1(x)$ $\sigma_L > 0$

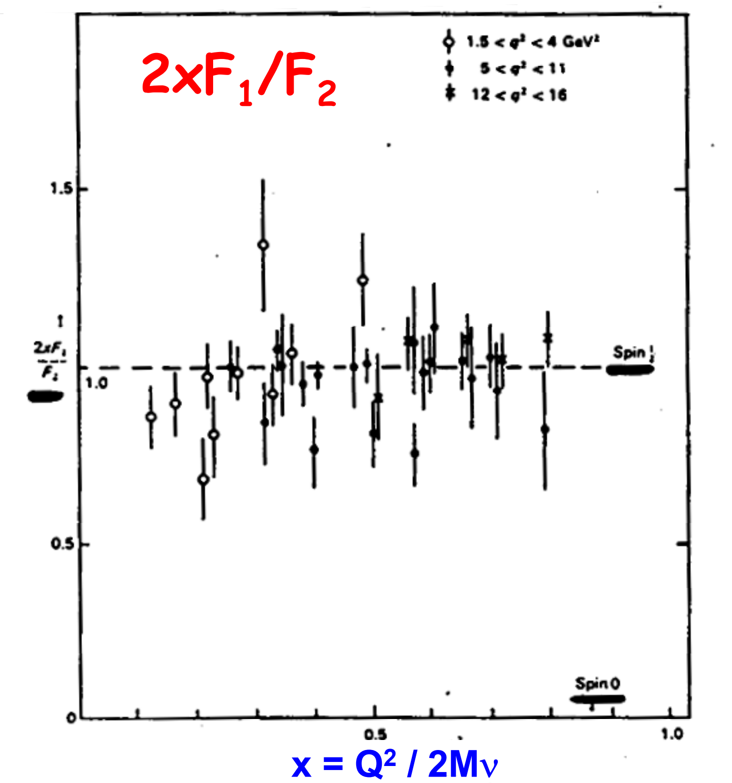
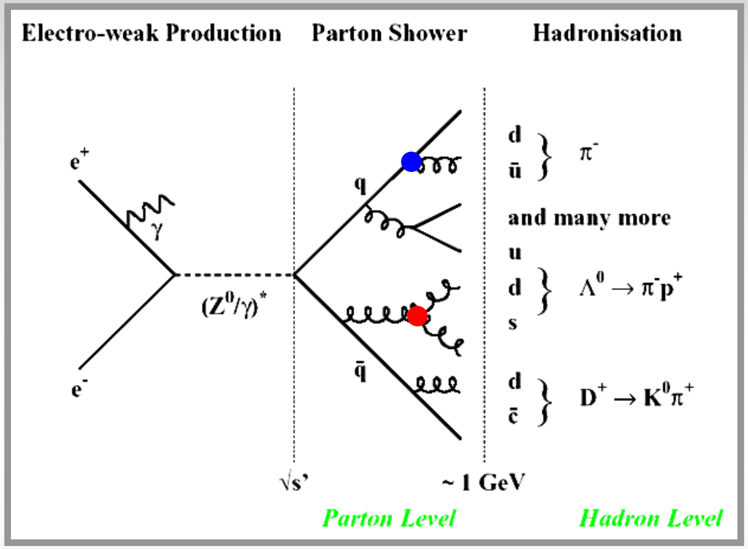
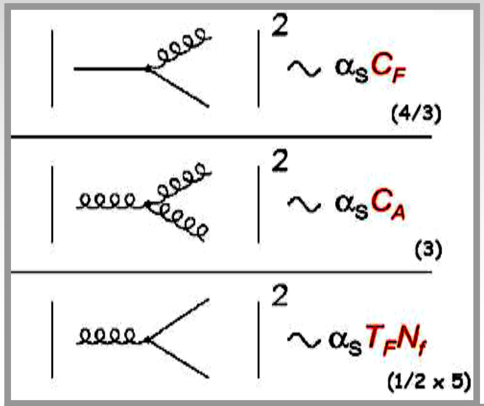


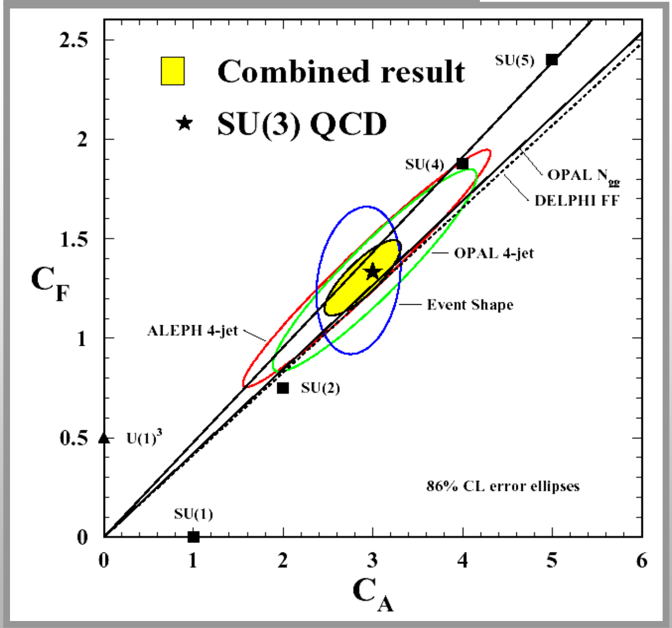
Abbildung 8.10 Das Verhältnis $2xF_1/F_2$, gemessen in Elektron-Nukleon-Streuexperimenten am SLAC. Für Spin-1/2 Partonen mit $g=2$ erwartet man, daß dieses Verhältnis im Grenzfall großer q^2 gegen Eins geht — die Callan-Gross-Relation. (Die Datenpunkte stammen aus verschiedenen publizierten SLAC-Resultaten.)

QCD = SU(3) ?

CERN LEP: $e^+e^- \rightarrow$ 4 jets event shape in NLO QCD







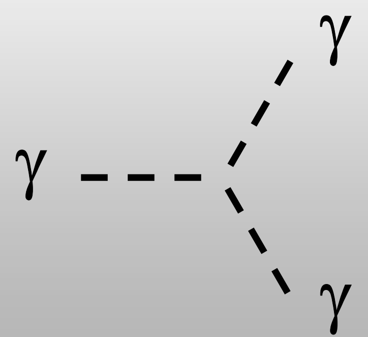
SU(N) Casimir-Operatoren
QCD Farb-Faktoren

	C_A	C_F
SU(3):	3	4/3
Expt.:	3.0±0.5	1.3±0.3

Quanten-Chromo-Dynamik

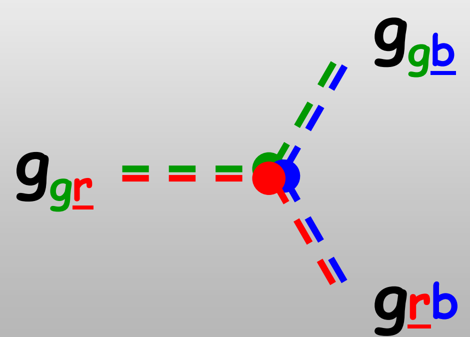
• QED

- U(1), abelsch
- 1 Ladungs-Typ
- 1 Photon:
- elektr. neutral
- keine Photon-Photon Selbst-Kopplung:
  - Licht klumpt nicht …



• QCD

- $SU(3)_{COLOR}$ nicht-abelsch
- 3 Ladungs-Typen: r,g,b
- $\{3\}\otimes\{\bar{3}\} = \{1\}\oplus\{8\}$: 8 Gluonen:
- tragen Farb-Ladungen
- Gluon-Gluon Selbst-Kopplung
  - Gluonium, Glueballs



Der QCD Lagrangian

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

<u>That's it!</u>

j … quark flavors   a,b,c … 3 colors   μ,ν … space-time

F.Wilczek, Physics Today, August 2000.

1973:
D.Gross, F.Wilczek, D.Politzer
Gibt es
Asymptotisch freie Eichtheorien ?

W.+P.: Doktoranden, 22+24 Jahre alt, erste Publikation !

D.J. Gross, F. Wilczek, ”Ultraviolet Behavior of Non-Abelian Gauge Theories”, Phys.Rev.Letters 30 1343 (1973).

H.D. Politzer, ”Reliable Perturbative Results for Strong Interactions”, Phys.Rev.Letters 30 1346 (1973).

D.J. Gross, F. Wilczek, “Asymptotically Free Gauge Theories. I”, Phys.Rev. D8 3633 (1973).

H.D. Politzer, “Asymptotic Freedom: An Approach to Strong Interactions”, Phys.Rep. 14 129 (1974).

β-Funktion nicht-abelscher Eichtheorien

entwickle nach Potenzen d. Kopplung + finde Nullstellen

$$\mu \frac{\partial \alpha_s}{\partial \mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{4\pi^2}\alpha_s^3 - \frac{\beta_2}{64\pi^3}\alpha_s^4 - \dots$$

$$\beta_0 = (11\, N_C - 2\, N_F) / 3$$

N_C … Zahl d. Farben N_F … Zahl d. Flavors

Casimir-Operatoren d. Eich-Gruppe SU(N)

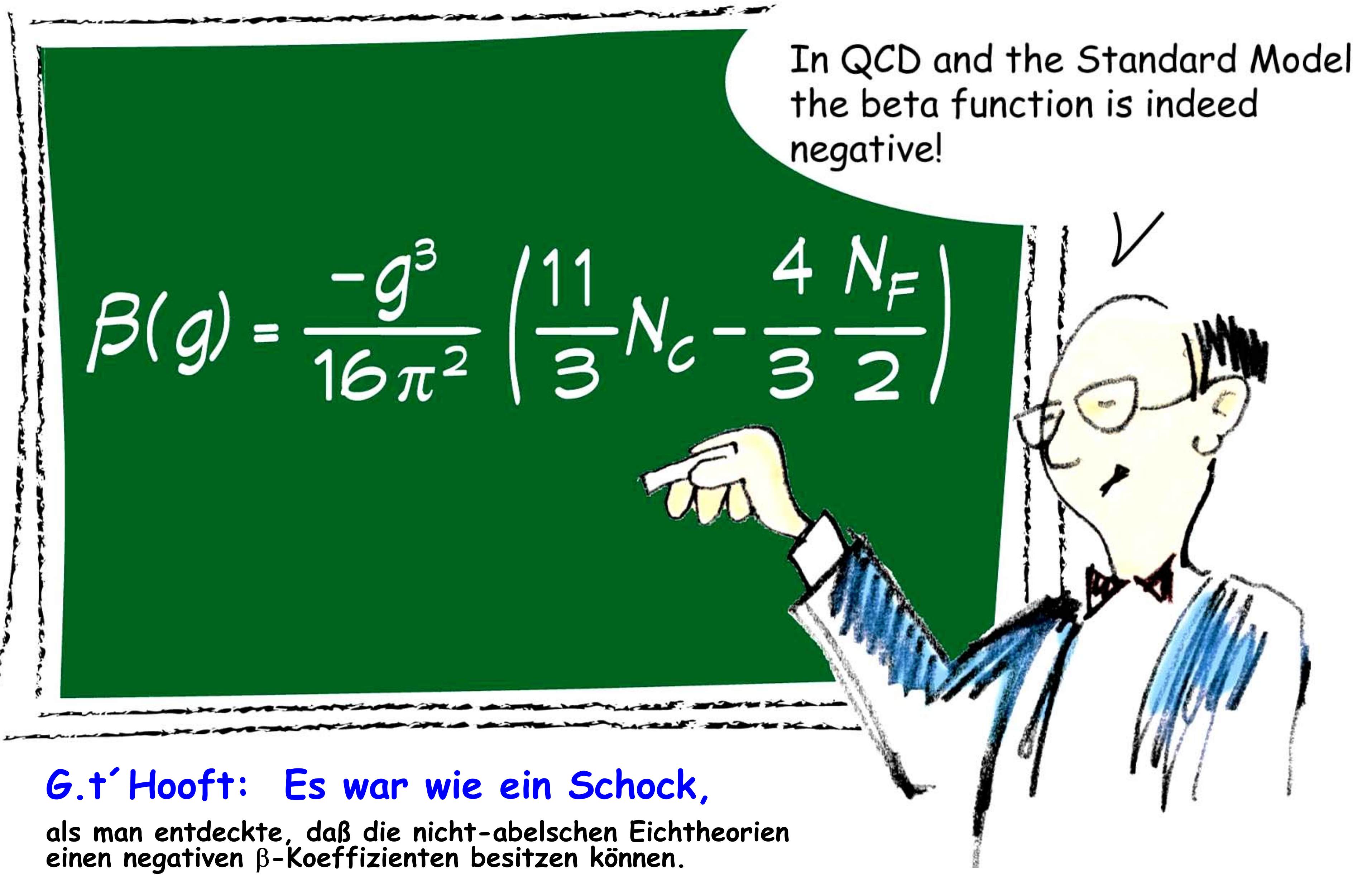
für $N_F \leq 16$ Fermion-Flavors gewinnen N_C Boson-Colors:

$$\partial\, \alpha\, (\mu) \,/\, \partial\, \ln \mu \; < \; 0$$

Nicht-abelsche Eichtheorien asymptotisch frei !

D.Gross, Zinnowitz 2004:
The discovery of asymptotic freedom was totally unexpected …

Field theory was not wrong.



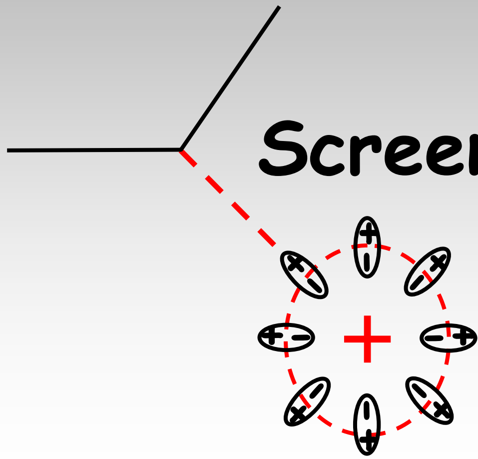
G.t´Hooft: Es war wie ein Schock,

als man entdeckte, daß die nicht-abelschen Eichtheorien einen negativen β-Koeffizienten besitzen können.

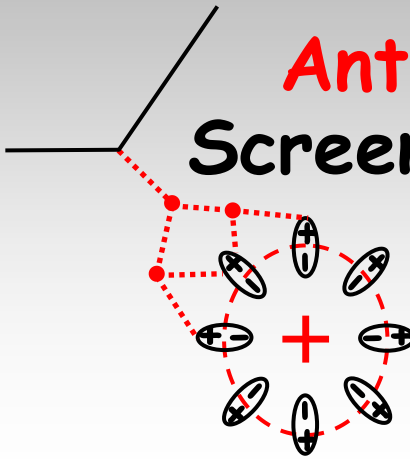
(Lexikon d. Physik, Spektrum Verlag 2000)

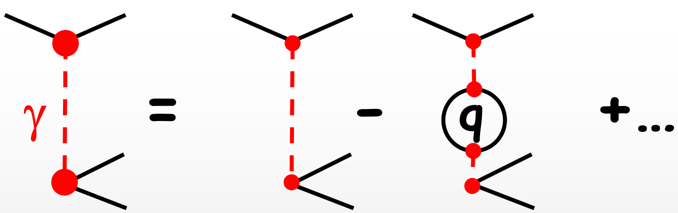
QED und QCD

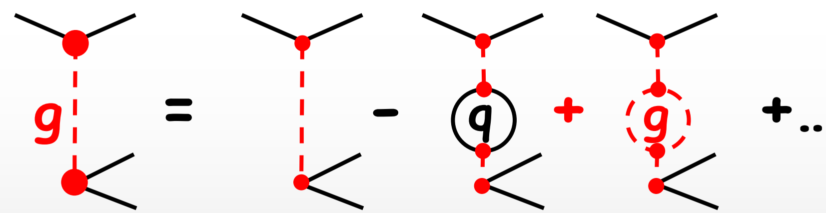
Screening:



Anti-Screening:







$-2N_F + 11N_C$

$b_0 = -4/3$

$\partial\, \alpha(Q^2) / \partial Q^2 > 0$

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 + b_0 \frac{\alpha(\mu^2)}{4\pi} \log \frac{Q^2}{\mu^2}}$$

$b_0 = (-2N_F + 11N_C)/3$

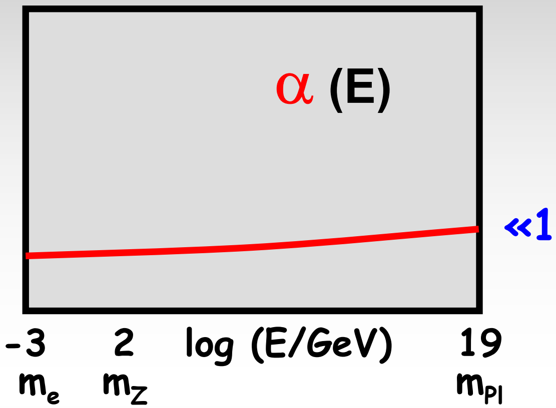
$\partial\, \alpha(Q^2) / \partial Q^2 < 0$

Gluon masselos !

$SU(2)_W$: $m_W > 10^5\ m_e$

QED und QCD

QED: $\partial \alpha(\mu^2) / \partial\mu^2 > 0$ Screening



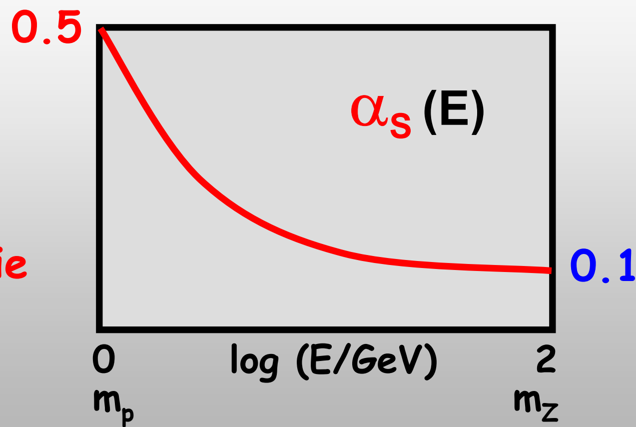
IR:

$\alpha = 1/137$

UV:

Landau-Singularität

QCD: $\partial \alpha(\mu^2) / \partial\mu^2 < 0$ Anti-Screening



IR:

$\alpha_S \rightarrow \infty$

Kollaps d. Störungstheorie

infrarote Sklaverei

Confinement

UV:

$\alpha_S \rightarrow 0$

asymptot. Freiheit

Confinement

statt $\alpha_s(\mu^2)$ definiere

$$\Lambda = \mu \exp[-2\pi/(b_0\alpha_s(\mu^2))]$$

$$\alpha_s(Q^2) = \frac{4\pi}{9 \ln(Q^2/\Lambda^2)} + \ldots \qquad (N_F=3)$$

$$\alpha_s(Q^2 \to \Lambda^2) \to \infty$$

Kollaps der Störungstheorie
Kernkraft schließt sich ein
infrarote Sklaverei:
keine freien Quarks !

$\hbar c \approx$ 200 MeV • fm
QCD-Skala • Protonradius

Proton = QCD Black Hole

Quarks

are

born free,

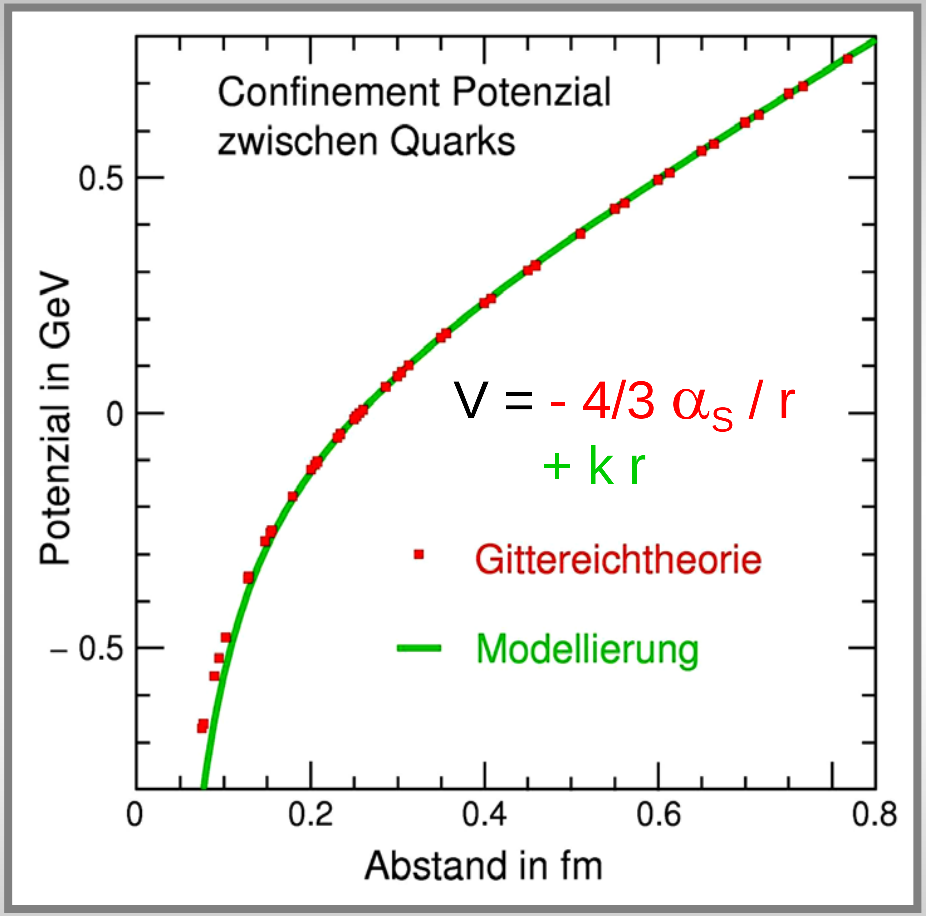
but everywhere

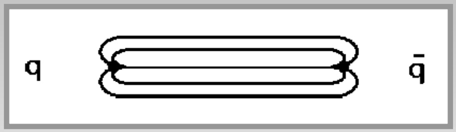
they are

in chains.

F.Wilczek
Nobel talk
2004

Quarkonium





Hadron-Radius:

Confinement

Color-String:
konstante Kraft=
Energie/Länge:

$k = 1$ GeV / fm

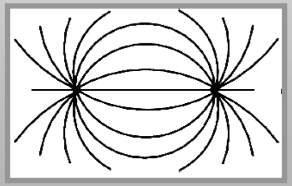
Spektroskopie
gebundener Zustände
schwerer Quarks:

$\Psi, \Psi', \Psi'', \ldots = (c\ \bar{c})$

$\Upsilon, \Upsilon', \Upsilon'', \ldots = (b\ \bar{b})$

wie Positronium

Appelquist, Politzer 1974.

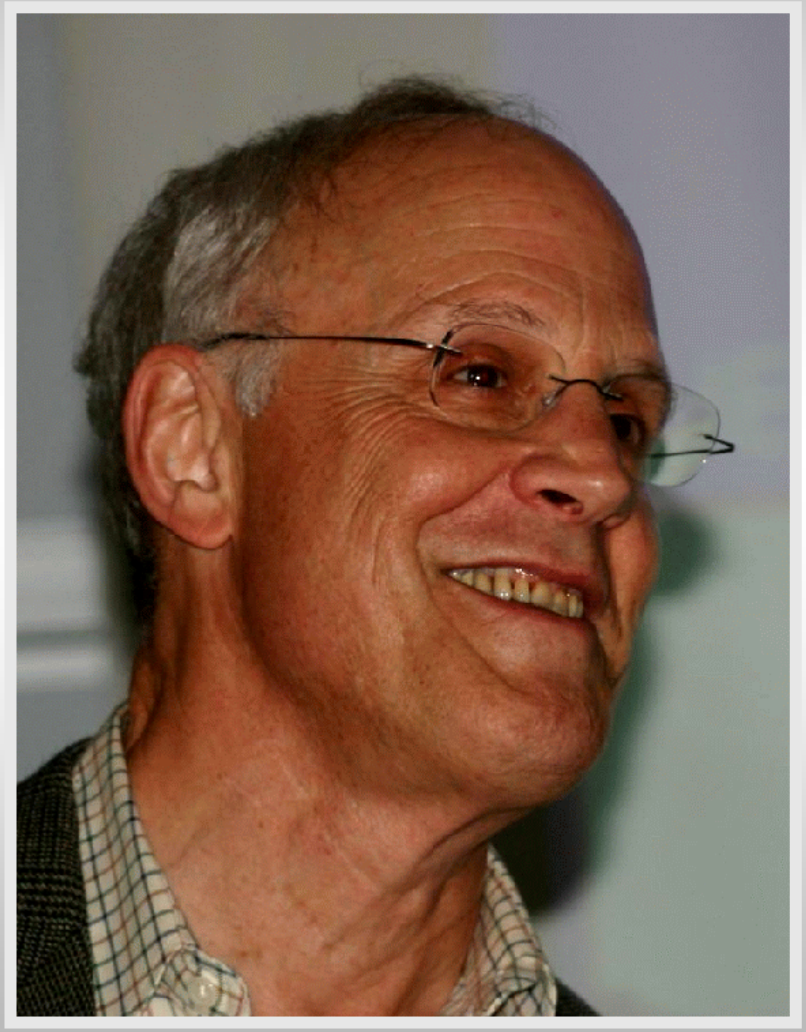


schwere Quarks = kurze Distanz:

$V = -4/3\ \alpha_S/r$ Coulomb-Kraft

asymptot. Freiheit

D.Gross 2004:



Experiments
are performing
tests of QCD with
amazing precision …

D.Gross, Loops & Legs,
DESY Theory Workshop,
Zinnowitz, Germany,
April 2004.

Experimente

von
infraroter Sklaverei

zur
asymptotischen Freiheit

Die laufende Kopplung

$$\alpha_s(Q^2) = \frac{4\pi}{9 \ln (Q^2/\Lambda^2)} + \ldots$$

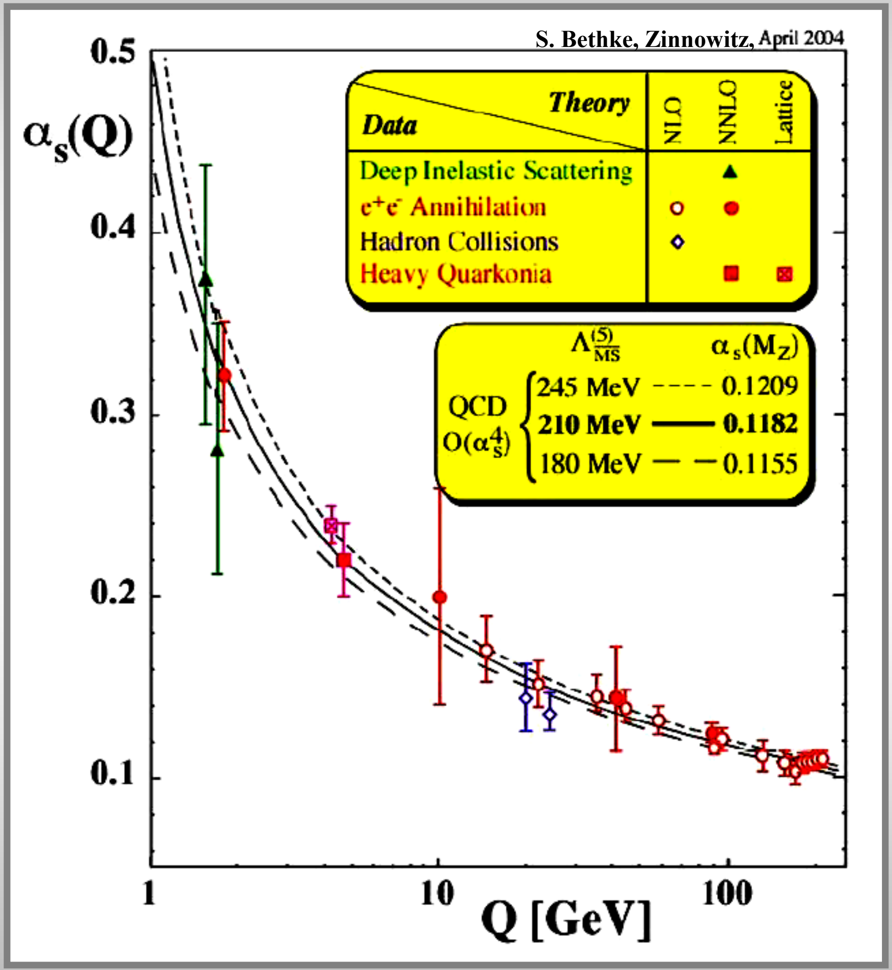
$\alpha_s(M_Z) = 0.1182 \pm 0.0027$

QCD Skala:

$\Lambda = 210 \pm 30$ MeV (MS, N_F=5)

$\hbar c \approx$ 200 MeV • fm

QCD-Skala • Protonradius



Frank Wilczek:

The most dramatic of these [tests], that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only

clearly verified at HERA twenty years later.

F.Wilczek
publication list
www. 2001.

HOME SITE HELP ABOUT

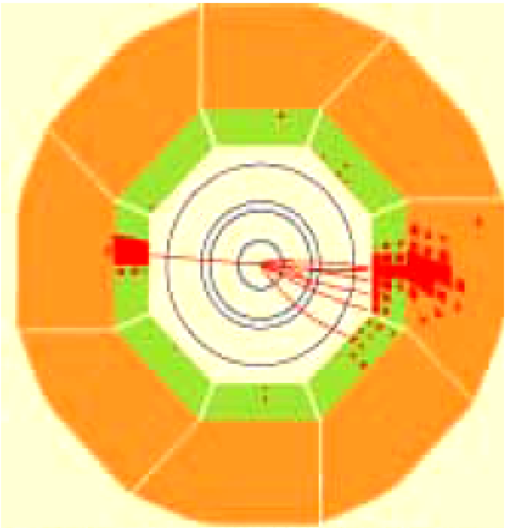
Nobelprize.org

NOBEL **PHYSICS** CHEMISTRY MEDICINE LITERATURE PEACE ECONOMICS

LAUREATES ARTICLES EDUCATIONAL

The Nobel Prize in Physics 2004

BACK



Picture: the DESY-laboratory, Hamburg

The theory shows its true colours

The aftermath of a high-energy collision between a proton and an electron, as seen by the H1 experiment at the DESY laboratory in Hamburg. The experiment is shown in cross-section, perpendicular to colliding beams of protons and electrons. The electron has struck one of the quarks in a proton. An impressive shower of particles - providing information about the struck quark - is spontaneously produced from the energy strored in the gluon force-field. The charged particles in the shower bend in the experiment's strong magnetic field.

And you're glue

Nature, Vol. 400, 1 July 1999.

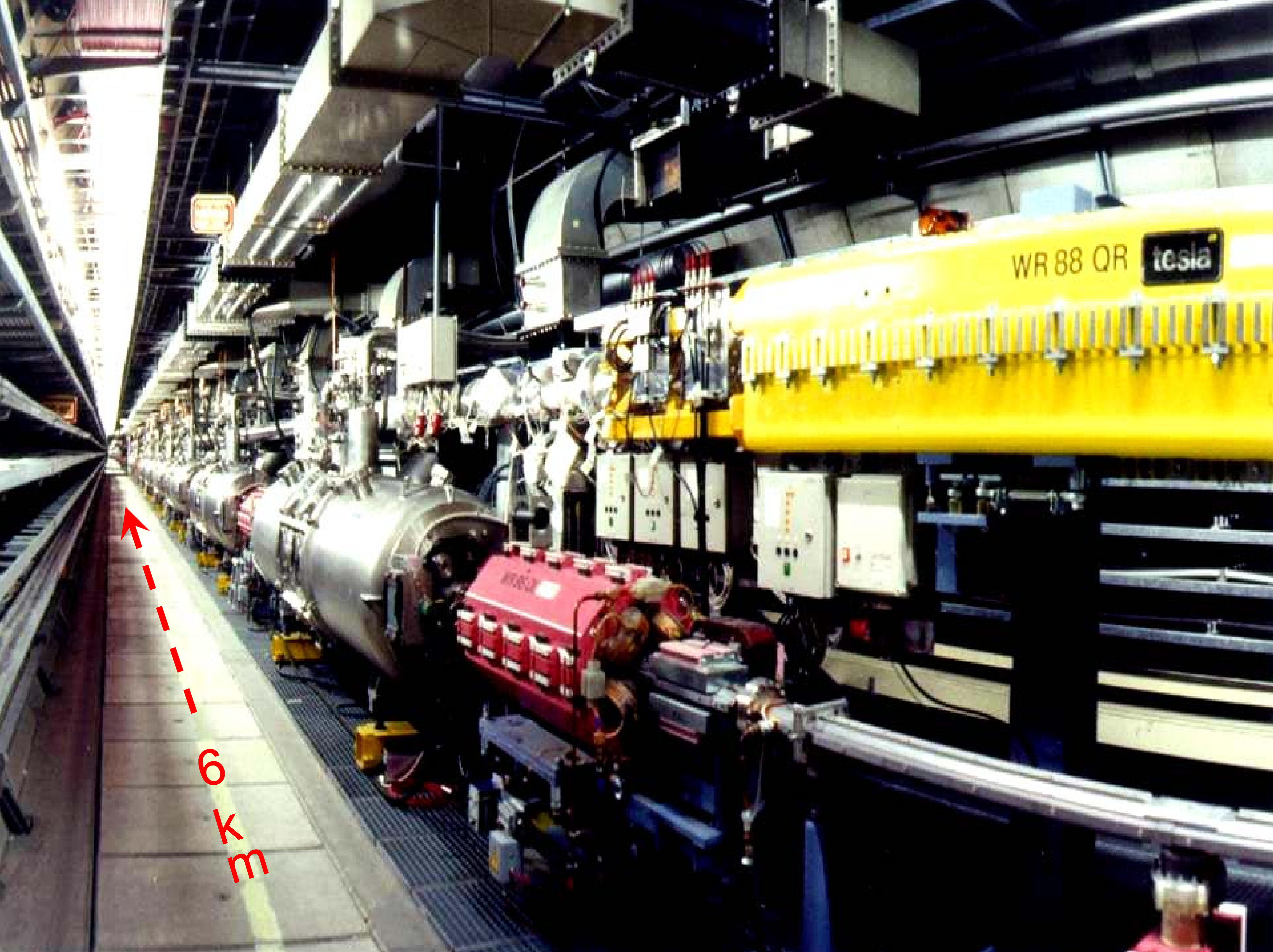
Frank Wilczek

It's a widely believed half-truth that protons and neutrons are made out of quarks. Actually, physicists are increasingly discovering that it's considerably less than half the truth. The modern theory of the strong force, which binds quarks inside protons and neutrons, and these particles in turn to make atomic nuclei, is quantum chromodynamics (QCD). The other ingredients of QCD, the colour gluons, were once conceived as mere paste that somehow links together more substantial stuff (their name reflects this). No longer. On closer inspection, the quarks appear as the showier, but gluons as the weightier and more dynamic, constituents of matter. Definitive images[1] from a microscope capable of looking inside protons, the HERA accelerator in Hamburg, Germany, reveal as well that there is more to gluons than meets the eye.

To understand these evolving views, you must consider how one goes about looking inside a proton, to 'see' what it is made of. An ordinary microscope, using ordinary light, is woefully inadequate, because the wavelength of light is about one billion times larger than the size of the proton. Even fancy electron or scanning tunnelling microscopes can barely resolve single atoms, and fall far short of seeing the nucleus inside. The right tool for the job is a high-energy accelerator. They produce virtual photons of very short wavelength (and lifetime), that can be used to take snapshots of the proton's interior (Box 1, overleaf).

There's a catch, however, to this seemingly straightforward procedure. You get to see only what the virtual photon allows you to see. And because the photons couple only to electrically charged particles, constituents of


H1
ZEUS
Protonen 920 GeV
Elektronen 27.6 GeV
PETRA

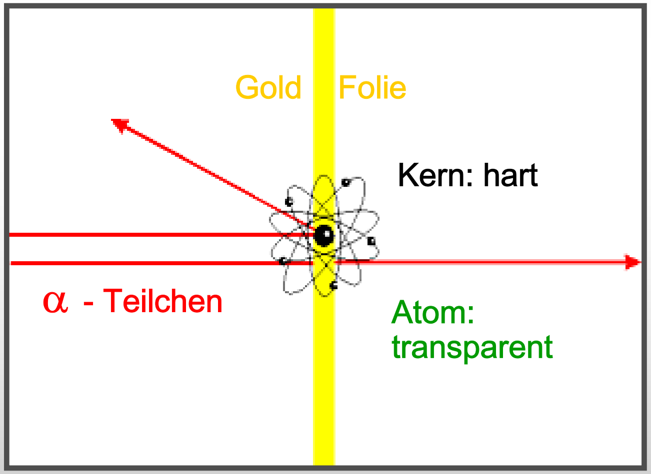

WR 88 QR
tesla
6 km


ZEUS

Struktur der Materie

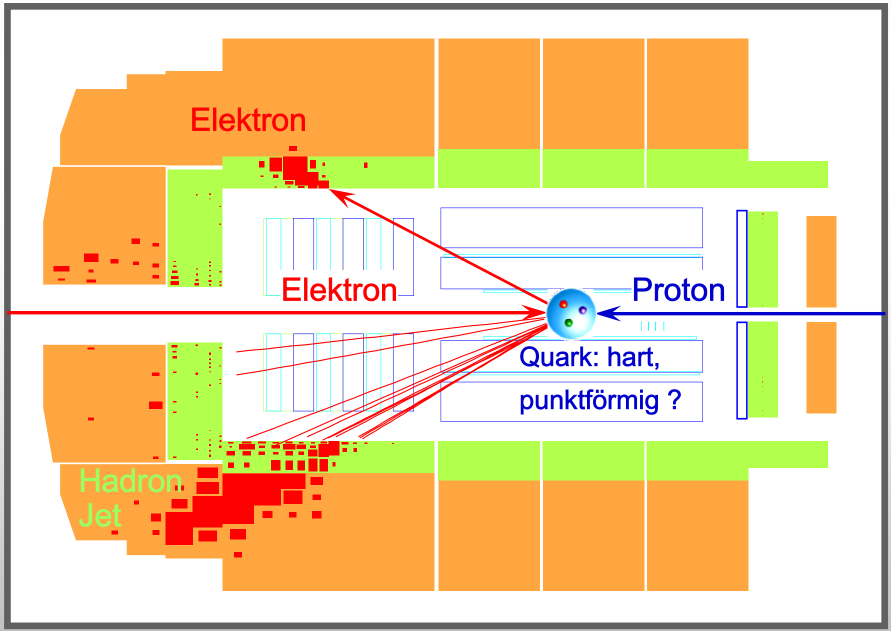
Rutherford 1910 :

Entdeckung des Atomkerns



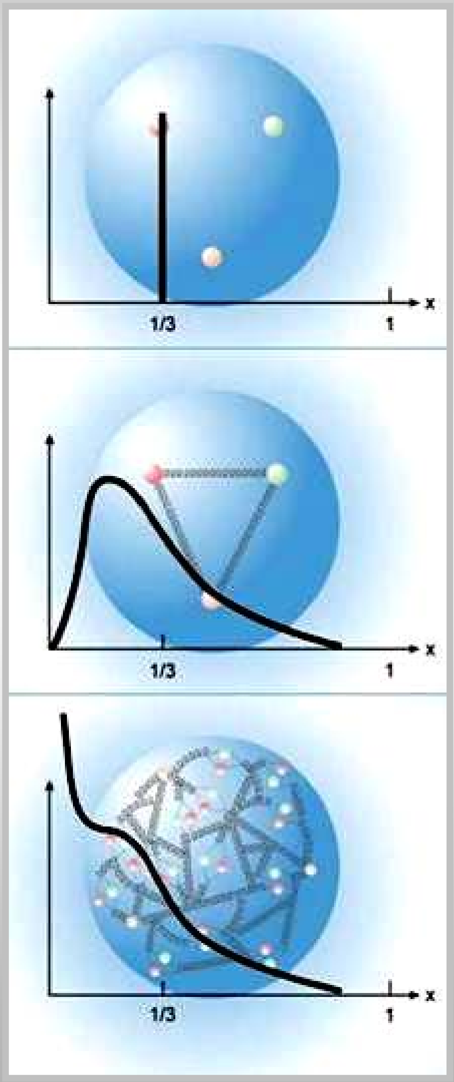
HERA 2000 :

Struktur des Protons



Proton-Struktur

QCD
Order



- **SLAC 1968:**

  drei Valenzquarks:

  x = 1/3

- drei gebundene Quarks:

  ~ p/2 in 3 Quarks +

  ~ p/2 in N Gluonen

  Impuls-Anteil des Quarks im Hadron:

  x ~ 1/6

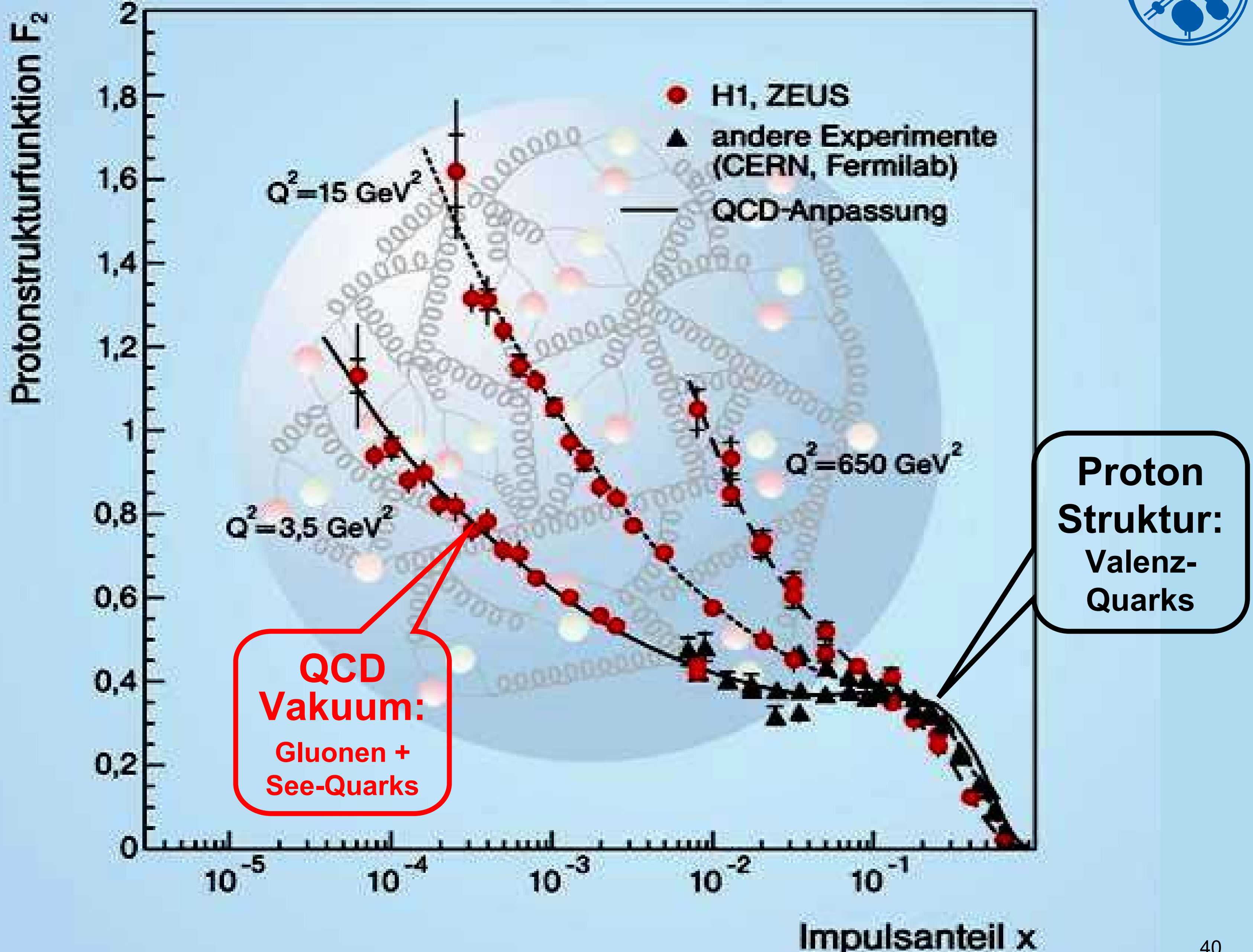
- **HERA 1994:**

  x > 0.1: Valenzquarks

  x « 0.1: Seequarks + Gluonen :

  reine QCD !

Proton-Struktur



Das Vakuum kocht ...

1974 - an der Wiege der QCD:

PHYSICAL REVIEW D VOLUME 10, NUMBER 5 1 SEPTEMBER 1974

Possible non-Regge behavior of electroproduction structure functions*

A. De Rújula, S. L. Glashow, and H. D. Politzer
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138

S. B. Treiman, F. Wilczek, and A. Zee†
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 15 April 1974)

N·H
ELSEVIER
26 September 1996
PHYSICS LETTERS B
Physics Letters B 385 (1996) 411–414

On the asymptotic behaviour of $F_2(x, Q^2)$

A. DeRoeck [a], M. Klein [b], Th. Naumann [b,1]
[a] *DESY, Notkestr. 85, D-22607 Hamburg Germany*
[b] *DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen Germany*

Received 6 May 1996; revised manuscript received 25 June 1996
Editor: K. Winter

Abstract

We discuss how the proton structure function $F_2(x, Q^2)$ is described in the HERA kinematic range by double asymptotic expressions for low x and large Q^2.

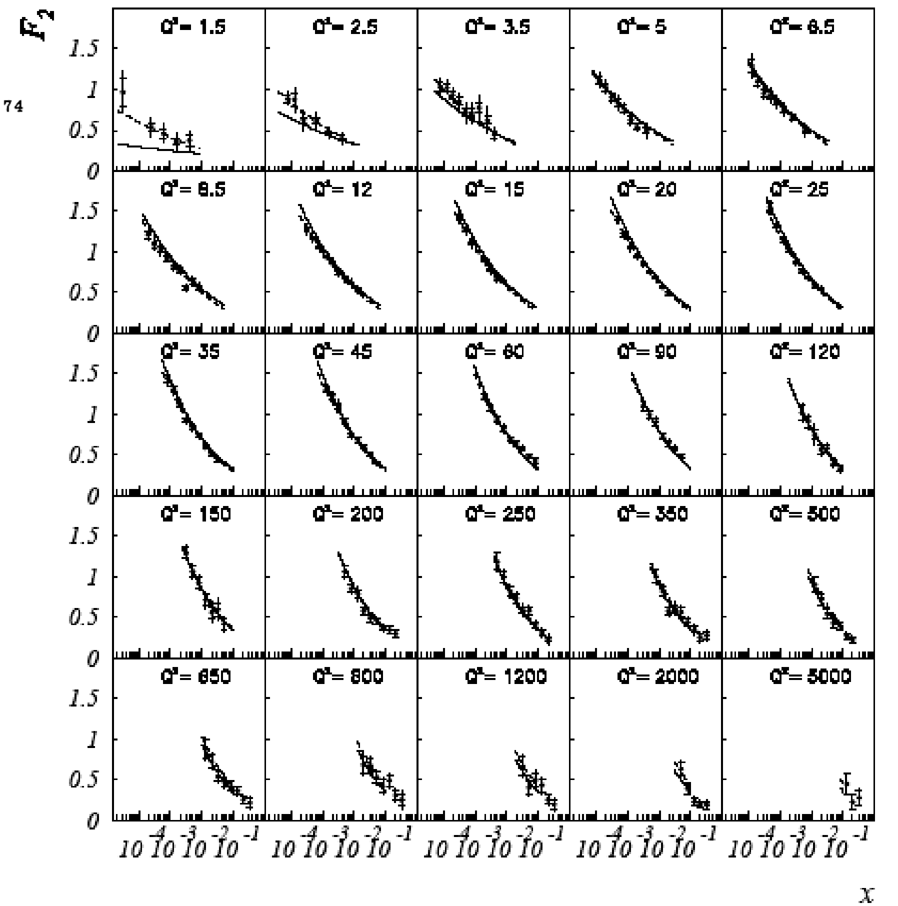


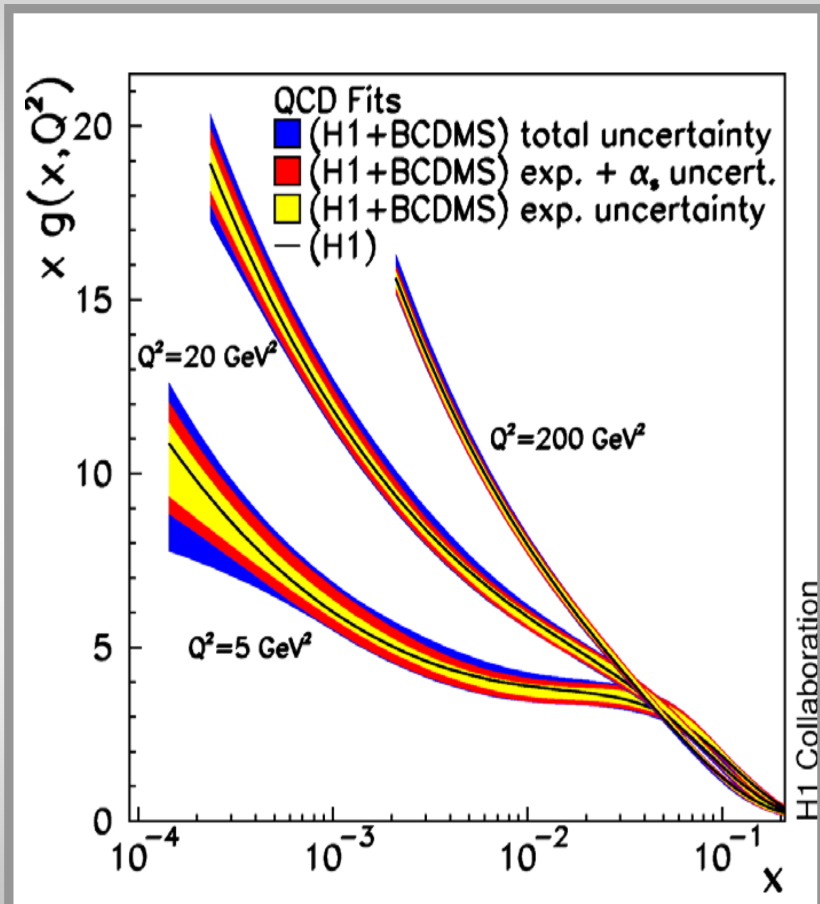
Figure 1: The proton structure function $F_2(x, Q^2)$ as measured by the H1 experiment at HERA together with a fit to the NLO double asymptotic expression (1) (full line) for $Q^2 > 5$ GeV^2 and with a fit to the modified DLL expression $F_2 = N_f e^{-\gamma\sqrt{T/\xi}}$ (dashed line) in the full Q^2 range.

Proton-Struktur:

Aufblasen des Protons aus dem QCD Vakuum

QCD-Asymptotik

Gluon-Dichte



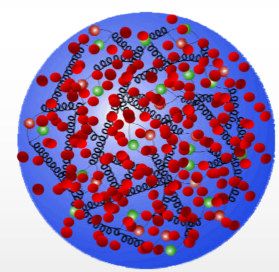
Gluon-Selbstkopplung

treibt Proton-Struktur und $\alpha_S(Q^2)$

$\partial\sigma(x,Q^2) \,/\, \partial \ln Q^2 \;\sim\; \alpha_S(Q^2)\; xg(x,Q^2)$

Test d. nicht-abelschen QCD :

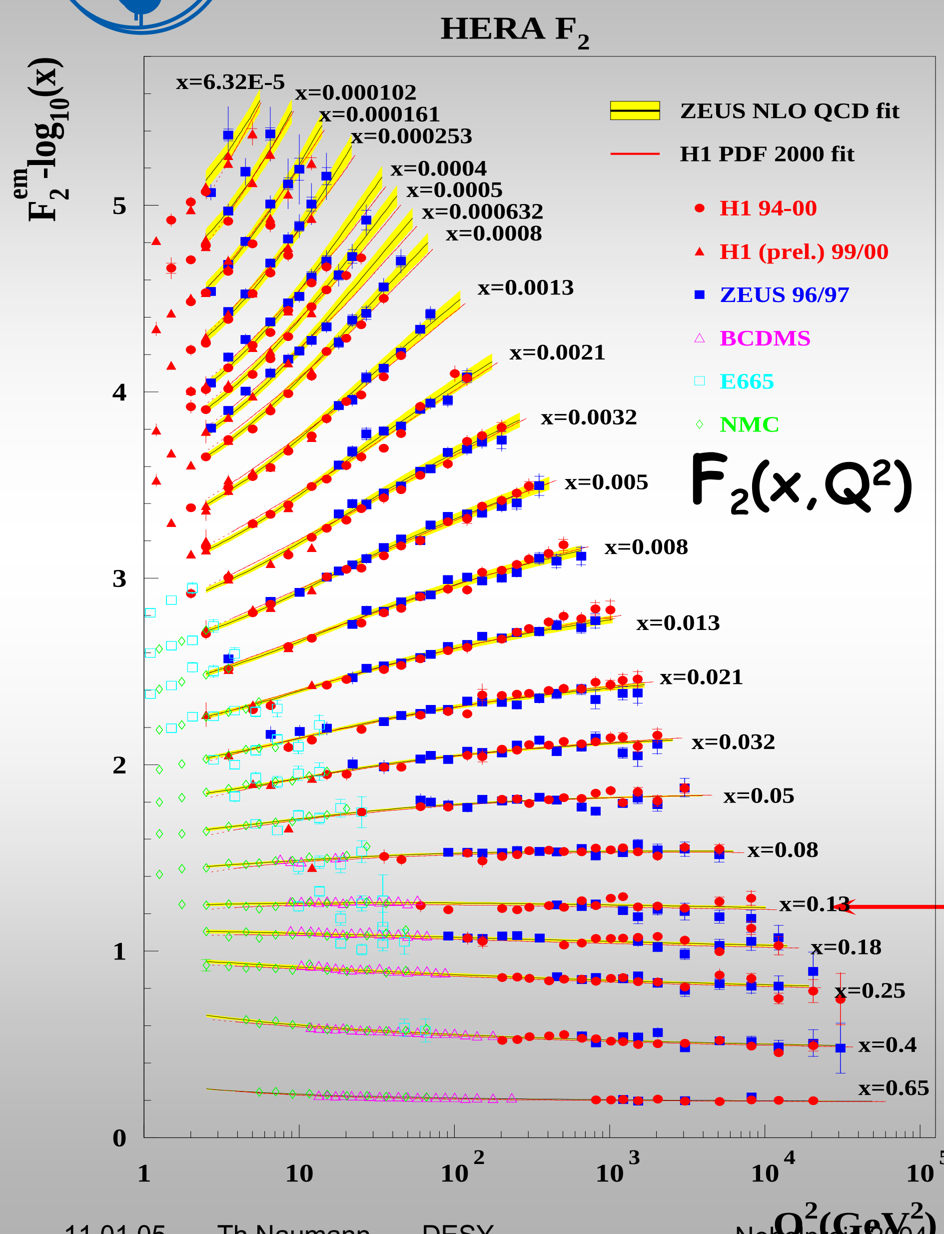
Aufkochen des QCD Vakuums:

$Q^2 \uparrow$  $x \downarrow$

$\alpha_S \rightarrow 1$: Kollaps d. Störungstheorie ?

- **Gluonen = Bosonen**
  Gluon-Saturation ? Shadowing ?
- **Gluonium, Glue-Balls ?**
- **Quark-Gluon-Plasma ?**

Proton Strukturfunktion



D. Gross:
tests of QCD with
amazing precision …

x klein:
Anregung d.
QCD Vakuums

QCD-Fits d. log.
Skalenverletzungen:
- $\alpha_s(Q^2)$
- $xg(x,Q^2)$
- $xq(x,Q^2)$

Scaling

x groß:
Gluon-Abstrahlung

Die starke Kopplung

DESY Experimente H1+ZEUS:

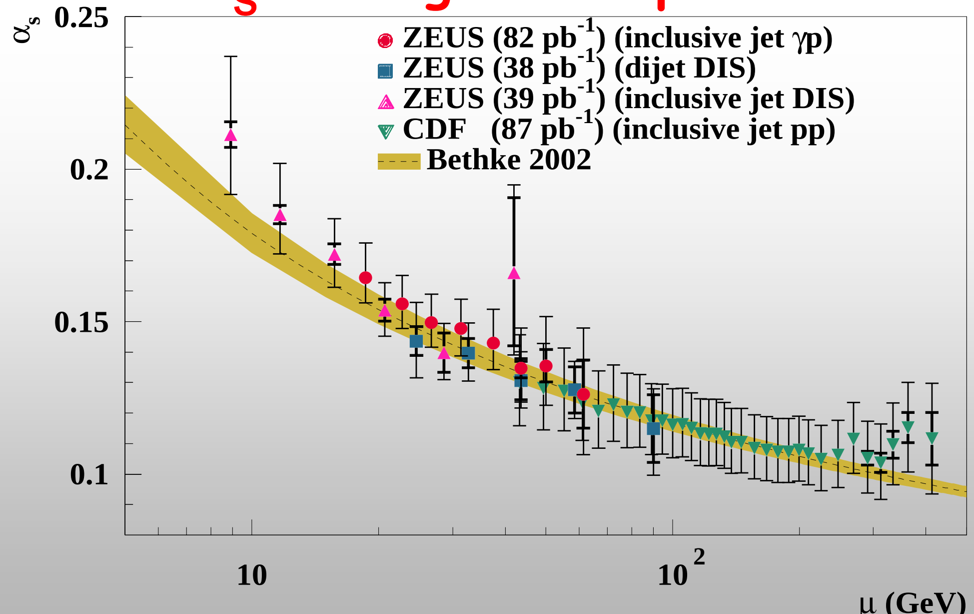
- QCD-Fit der Skalenverletzungen:

α_s = 0.115 ± 0.002 (exp.+fit) ± 0.005 (scale)

- Jet-Wirkungsquerschnitte:

α_s = 0.120 ± 0.002 (exp.) ± 0.004 (syst.)

α_s running in 1 Experiment:

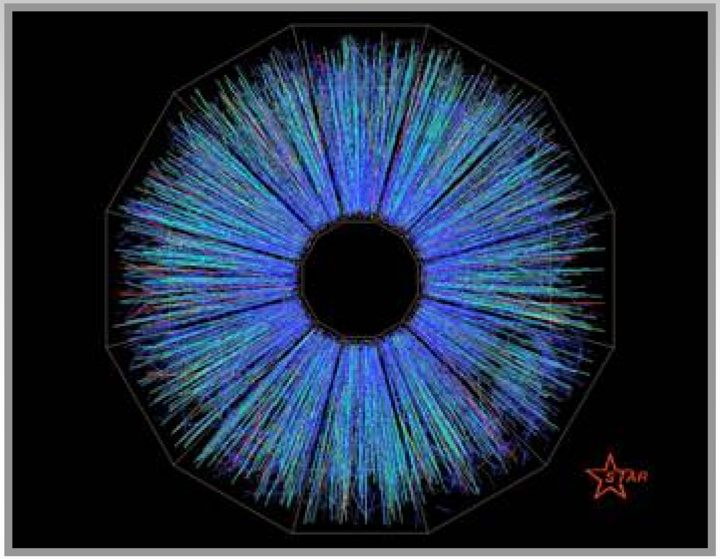


α_s (ln Q^2) crawling not running !

Quark-Gluon-Plasma

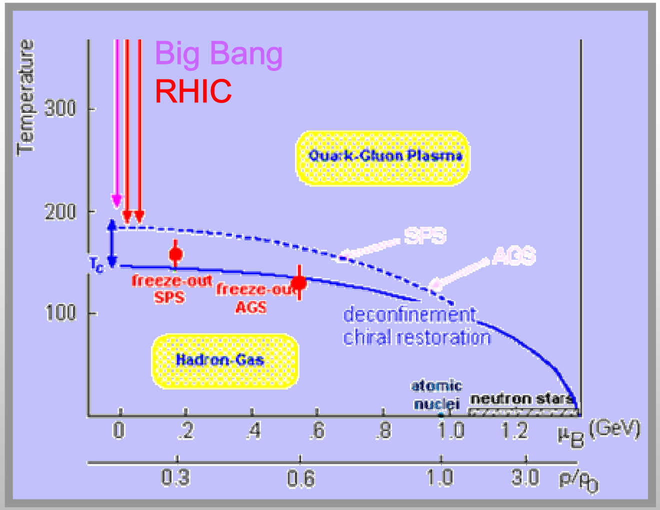
Gott schuf die Quarks frei

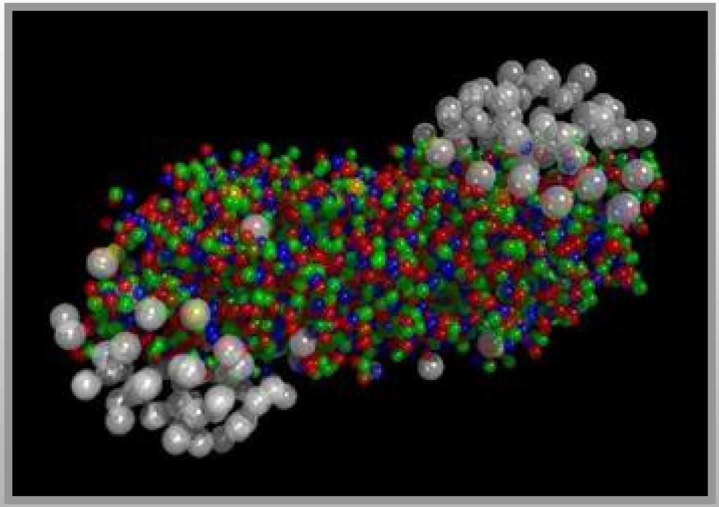
- <μs nach dem Urknall
- danach QCD Confinement:
  Phasenübergang Quagma - Hadron-Gas
  Nukleonen frieren aus



RHIC am BNL, Brookhaven, USA:

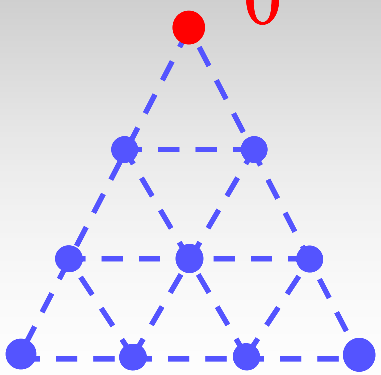
- Au-Au Kollisionen mit 100 GeV/Nukleon
  >1000 Quarks, Thermalisierung:





GSI Darmstadt >2009

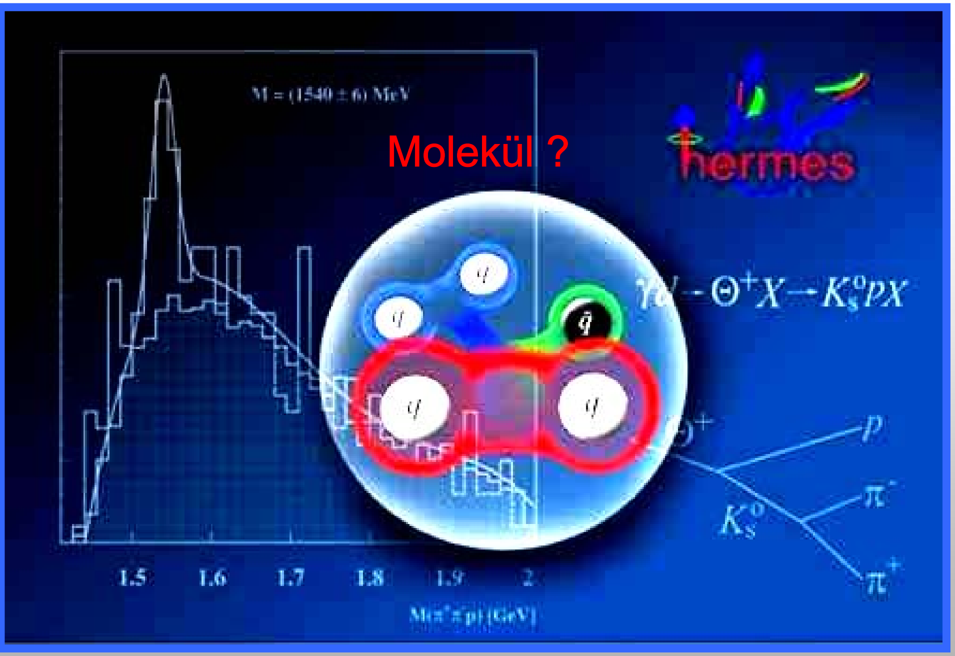
Penta-Quarks

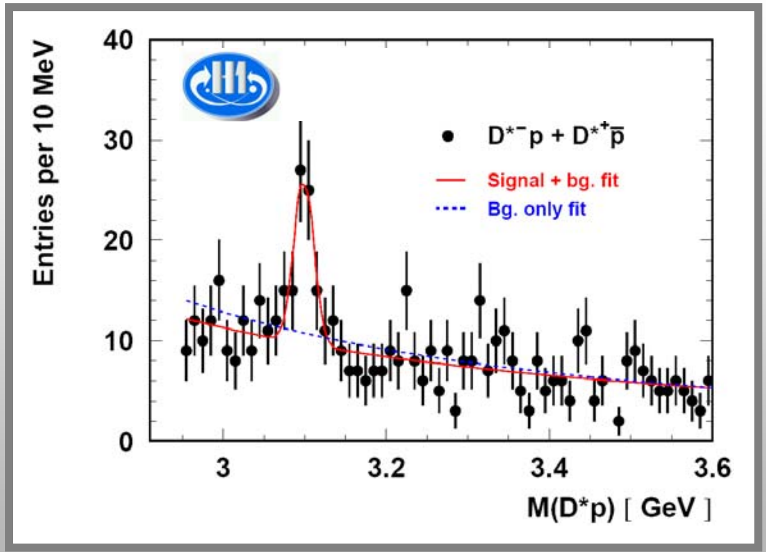


Quarkmodell:

Baryon: (qqq) Meson: $(q\bar{q})$

Expt.:	HERMES	H1
Zustand	$\theta^+ = pK^0$	$\theta_c = pD^*$:
exotisch:	$(uudd\bar{s})$	$(uudd\bar{c})$

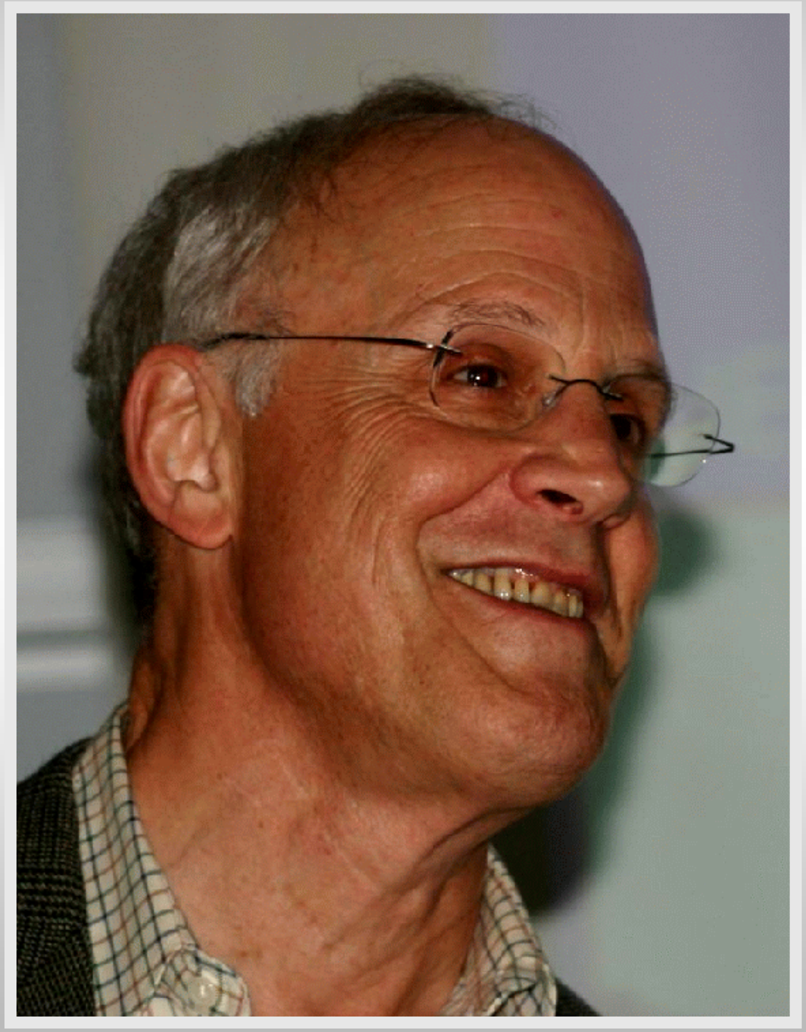




Präzision

für den Weg zur Vereinigung

D.Gross 2004:



Theoretical calculations of perturbative QCD are truly heroic.

D.Gross, Loops & Legs,
DESY Theory Workshop,
Zinnowitz, Germany,
April 2004.

QCD in 2 Loops

$$\mu \frac{\partial \alpha_s}{\partial \mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{4\pi^2}\alpha_s^3 - \frac{\beta_2}{64\pi^3}\alpha_s^4 - \cdots ,$$

$$\beta_0 = 11 - \frac{2}{3} n_f ,$$

$$\beta_1 = 51 - \frac{19}{3} n_f ,$$

$$\beta_2 = 2857 - \frac{5033}{9} n_f + \frac{325}{27} n_f^2 ;$$

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln(\mu^2/\Lambda^2)} \left[1 - \frac{2\beta_1}{\beta_0^2} \frac{\ln\left[\ln(\mu^2/\Lambda^2)\right]}{\ln(\mu^2/\Lambda^2)} + \frac{4\beta_1^2}{\beta_0^4 \ln^2(\mu^2/\Lambda^2)} \times \left(\left(\ln\left[\ln(\mu^2/\Lambda^2)\right] - \frac{1}{2} \right)^2 + \frac{\beta_2 \beta_0}{8\beta_1^2} - \frac{5}{4} \right) \right] .$$

β-Funktion in 3 Loops

$$q^2 \frac{\partial a_s}{\partial q^2} = -\beta_0 a_s^2 - \beta_1 a_s^3 - \beta_2 a_s^4 - \beta_3 a_s^5 + O(a_s^6)$$

$$\beta_0 = \frac{11}{3} C_A - \frac{4}{3} T_F n_f$$

$$\beta_1 = \frac{34}{3} C_A^2 - 4 C_F T_F n_f - \frac{20}{3} C_A T_F n_f$$

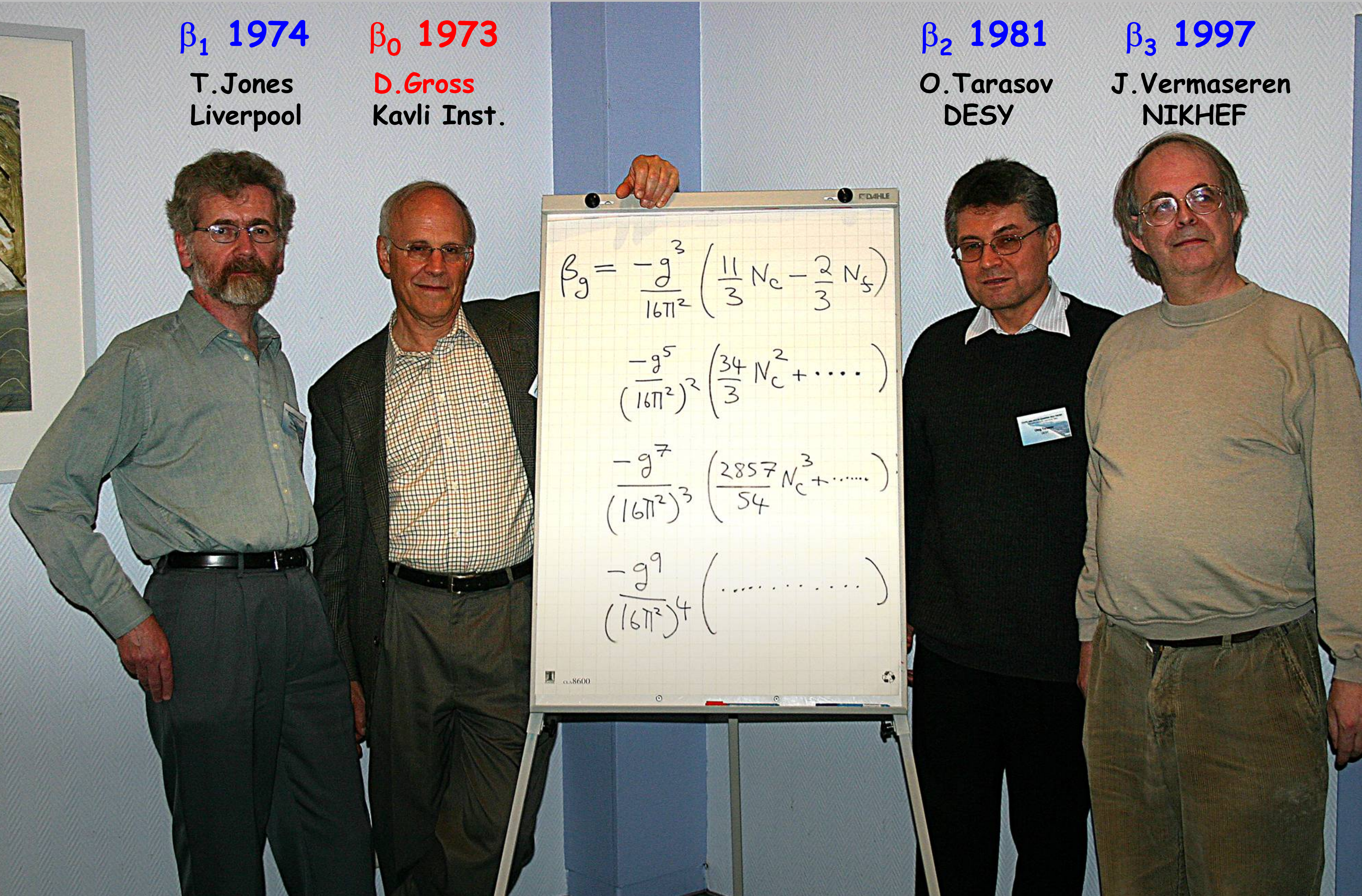
$$\beta_2 = \frac{2857}{54} C_A^3 + 2 C_F^2 T_F n_f - \frac{205}{9} C_F C_A T_F n_f - \frac{1415}{27} C_A^2 T_F n_f + \frac{44}{9} C_F T_F^2 n_f^2 + \frac{158}{27} C_A T_F^2 n_f^2$$

$$\begin{aligned}
\beta_3 = {} & C_A^4 \left(\frac{150653}{486} - \frac{44}{9} \zeta_3 \right) + C_A^3 T_F n_f \left(-\frac{39143}{81} + \frac{136}{3} \zeta_3 \right) \\
& + C_A^2 C_F T_F n_f \left(\frac{7073}{243} - \frac{656}{9} \zeta_3 \right) + C_A C_F^2 T_F n_f \left(-\frac{4204}{27} + \frac{352}{9} \zeta_3 \right) \\
& + 46 C_F^3 T_F n_f + C_A^2 T_F^2 n_f^2 \left(\frac{7930}{81} + \frac{224}{9} \zeta_3 \right) + C_F^2 T_F^2 n_f^2 \left(\frac{1352}{27} - \frac{704}{9} \zeta_3 \right) \\
& + C_A C_F T_F^2 n_f^2 \left(\frac{17152}{243} + \frac{448}{9} \zeta_3 \right) + \frac{424}{243} C_A T_F^3 n_f^3 + \frac{1232}{243} C_F T_F^3 n_f^3 \\
& + \frac{d_A^{abcd} d_A^{abcd}}{N_A} \left(-\frac{80}{9} + \frac{704}{3} \zeta_3 \right) + n_f \frac{d_F^{abcd} d_A^{abcd}}{N_A} \left(\frac{512}{9} - \frac{1664}{3} \zeta_3 \right) \\
& + n_f^2 \frac{d_F^{abcd} d_F^{abcd}}{N_A} \left(-\frac{704}{9} + \frac{512}{3} \zeta_3 \right)
\end{aligned}$$

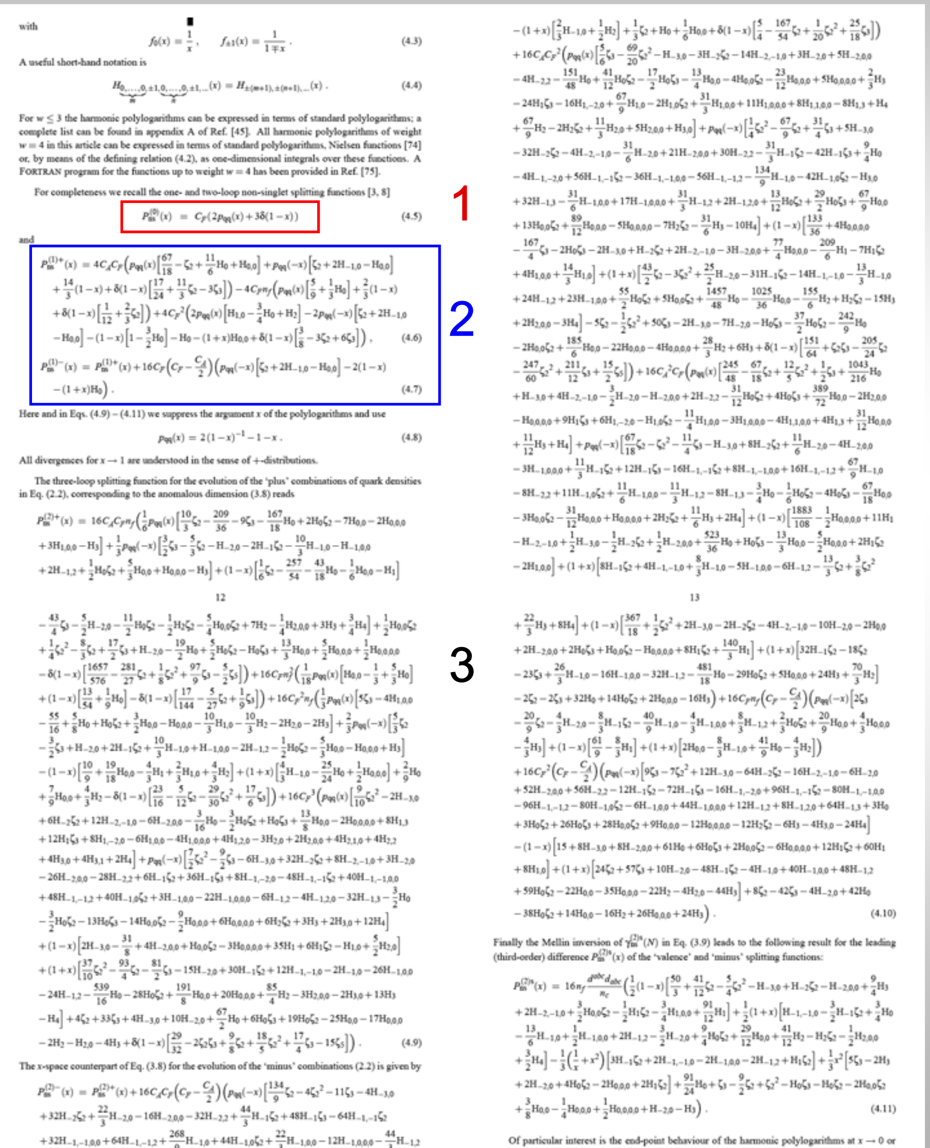
Nicht-triviale Struktur des QCD-Vakuums

reine SU(3)

Loops+Legs 2004



Störungstheorie

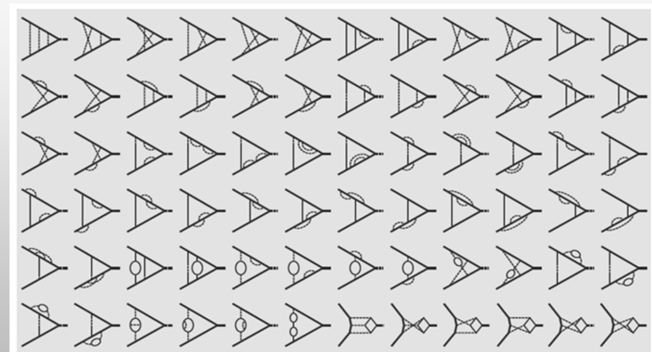


1-2-3 Loops: Next-to-Next-to-Leading Order:

- Splitting-Funktionen
- anomale Dimensionen
- Koeffizienten-Funktionen

~ 10.000 Feynman-Diagramme :

	tree	1-loop	2-loop	3-loop
$q\gamma$	1	3	25	359
$g\gamma$		2	17	345
$h\gamma$			2	56
qW	1	3	32	589
$q\phi$		1	23	696
$g\phi$	1	8	218	6378
$h\phi$		1	33	1184
sum	3	18	350	9607



> 100.000 Integrale …

S. Moch et al., The QCD Splitting Functions At Three Loops, Nucl.Phys.Proc.Suppl.135:137-146,2004. hep-ph / 0403192 + 0404111

M. Czakon, Kovalevskaya Preis 2004.

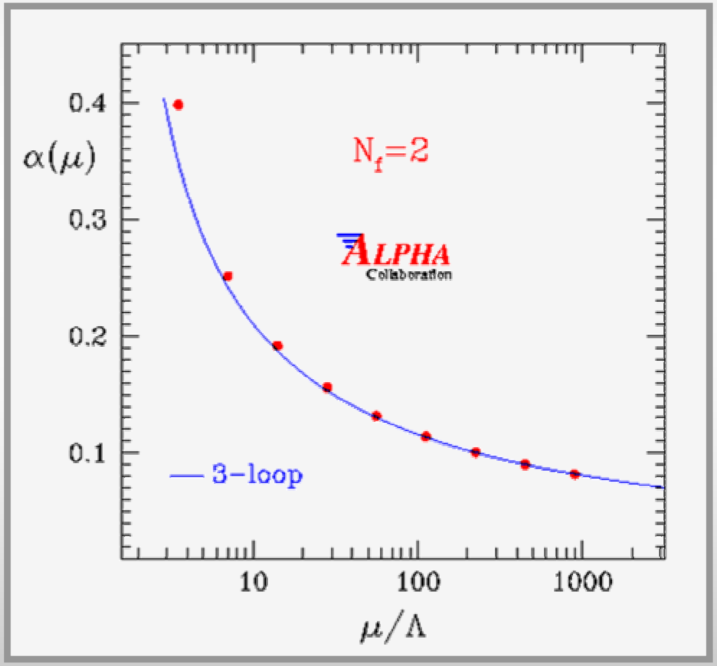
QCD auf dem Gitter

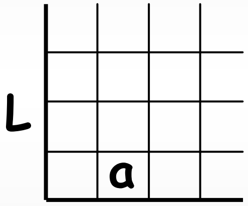
APE Gitter-Rechner

bei DESY Zeuthen
2005/6: 3 TFlop

Alternative:

- diskrete Raum-Zeit
- minimiere QCD Pfad-Integrale
- simuliere QCD auf dem Gitter :





L/a=16,32,…

- Freiheitsgrade: Color, Flavor, Quark-Massen

$\delta\alpha_S/\alpha_S$ = 1% ok mit Expt.+ 3-Loop

Der Weg zur Urkraft:

Vereint sind wir gleich stark !

Die Vereinigung der Kräfte

Große Vereinigung

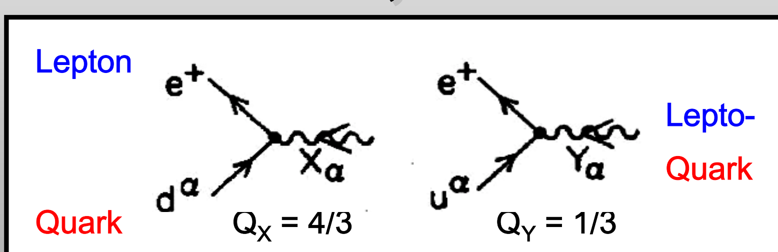
elm. schwach stark — vereinigt

$U(1) \otimes SU(2) \otimes SU(3) \subset SU(5)$ SYMMETRIEN

$\{ e^- \ \nu_e , \ \bar{d}_r \ \bar{d}_g \ \bar{d}_b \}_L$ — $\overline{\{5\}}$ MULTIPLETT

$\gamma \quad W^{\pm 0} \quad g_{ij}$ BOSONEN

X,Y



Kopplungen asymptot. frei + berechenbar.
Wo wird

$\alpha_{elm} = \alpha_{schwach} = \alpha_{stark}$?

Georgi, Glashow; Georgi, Quinn, Weinberg, 1974.

Große Vereinigung

- Quark-Lepton-Symmetrie:

  Quarks + Leptonen in ein Multiplett

$$\{ e^- \ \nu_e \ , \ \bar{d}_r \ \bar{d}_g \ \bar{d}_b \}_L$$

- Quantisierung der elektr. Ladung:

  $N_C\, Q_q - Q_e = 0 \ = \ 3 \times 1/3 - 1$

  bzw. $Q_p = Q_e$

- Vorhersage für elektro-schwachen Mischungswinkel:
  - $\sin^2\theta_W (M_X) \ = \ g'^2 / (g^2 + g'^2) \ = \ 3/5 / (1+3/5) \ = \ 3/8$
  - $\sin^2\theta_W (M_Z) \ = \ 0.20$ GUT
  - $\sin^2\theta_W (M_Z) \ = \ 0.22$ Expt.

- Leptonzahl-Verletzung:

  Neutrino-Massen u. -Oszillationen:

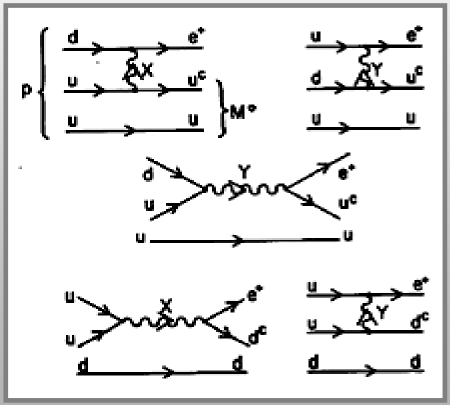
- Baryonzahl-Verletzung: Proton-Zerfall : $p \to e^+ \pi^0$

  $\tau_p \sim \ M_X^4 / \alpha^2 m_p^5$

Super-K 1998:	$\tau\ (p \to e^+\pi^0) > 5 \cdot 10^{33}$ a	$\tau\ (p \to K^+\nu) > 1.6 \cdot 10^{33}$ a
Hyper-K 201x+10:	$\tau\ (p \to e^+\pi^0) > 10^{35}$ a	$\tau\ (p \to K^+\nu) > 3 \ \cdot 10^{34}$ a

- SUSY GUT: $M_X \sim 10^{16}$ GeV :

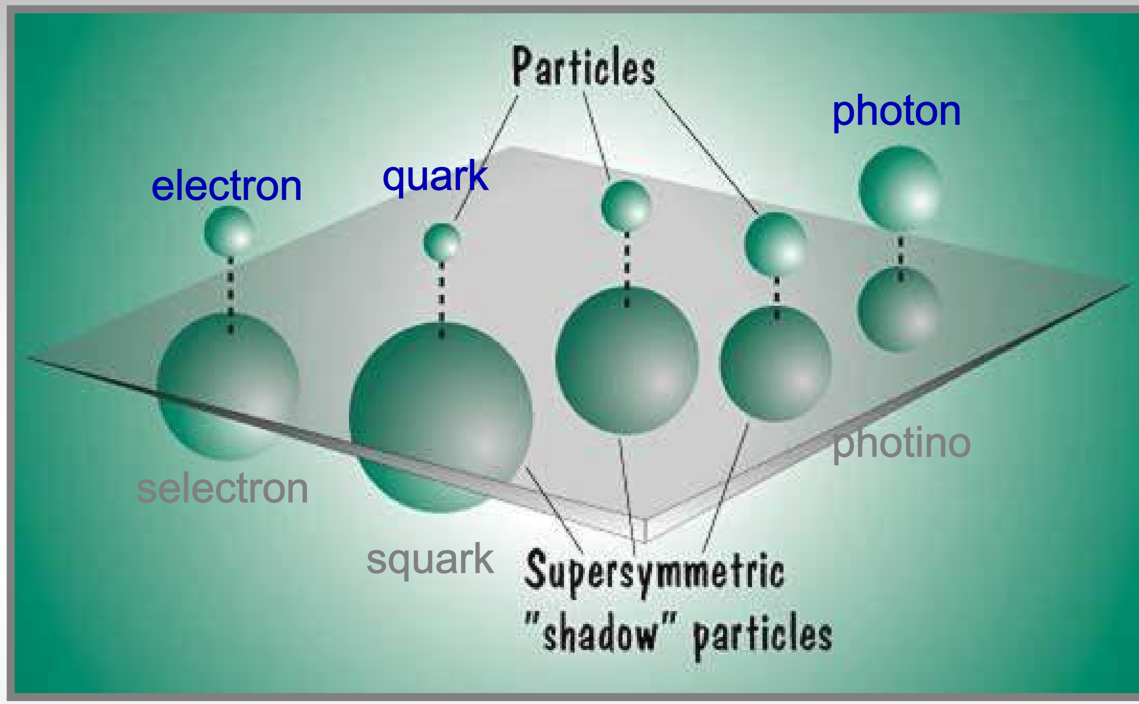
  $\tau\ (p \to e^+\pi^0) \sim 10^{35\pm1}$ a $\tau\ (p \to K^+\nu) \sim 10^{32\pm3}$ a



Super-Symmetrie

Fermion

Boson



Boson

Fermion

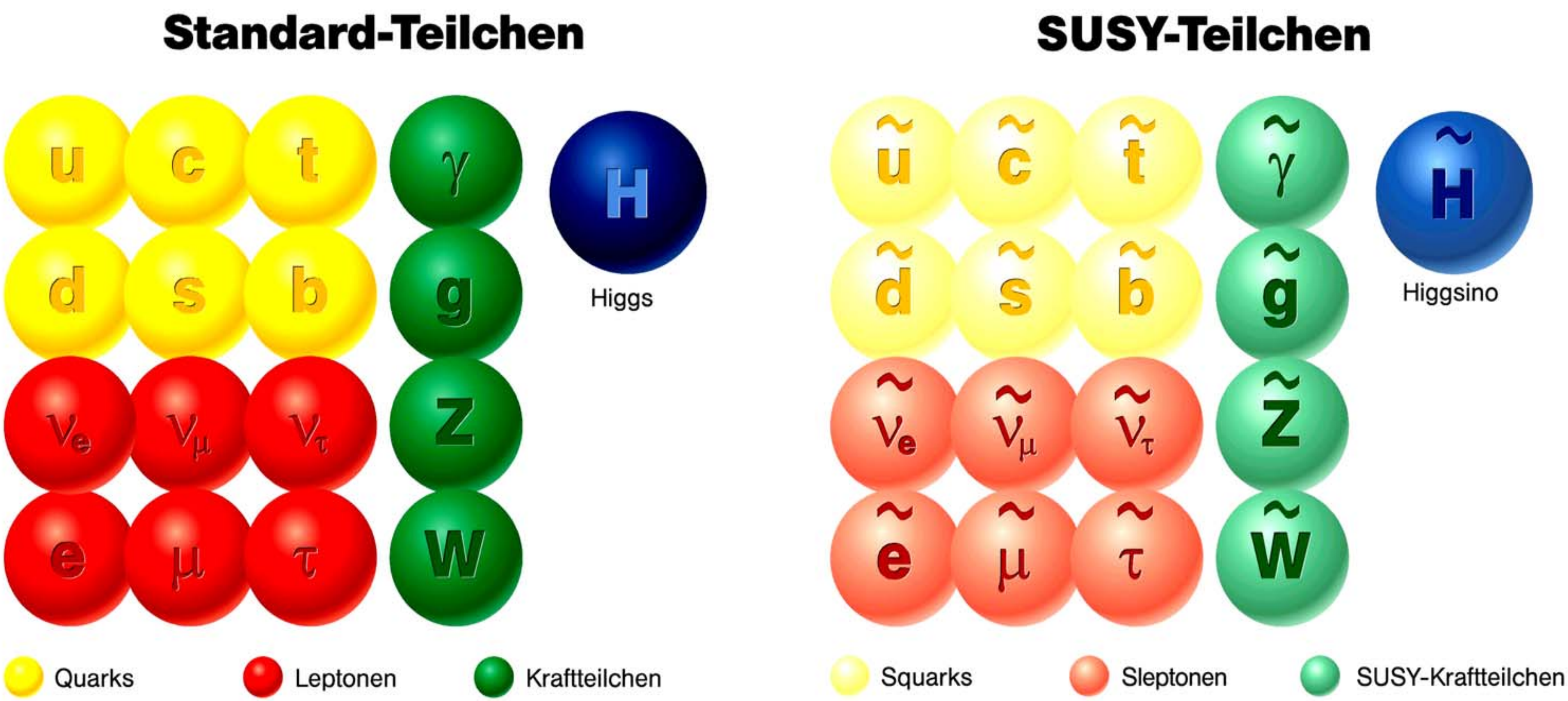
Super-Symmetrie

vereinigt

Bosonen mit Fermionen

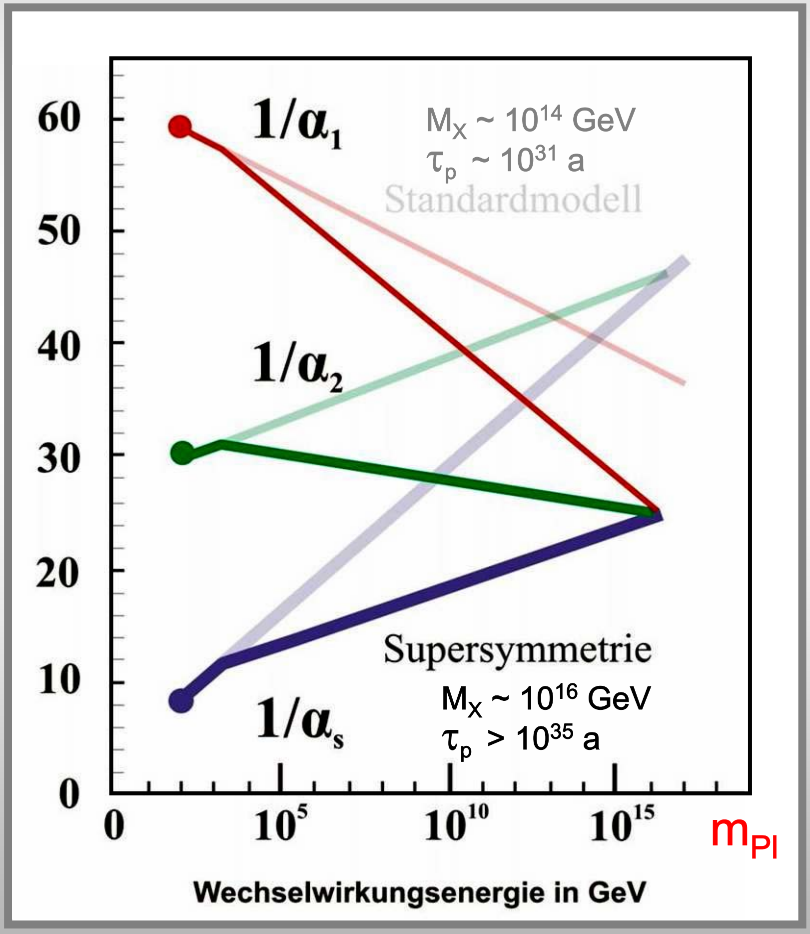
Kraft mit Materie

Super-Symmetrie



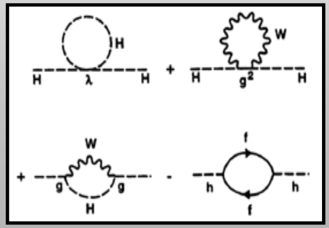
Super-Symmetrie

vereinigt Kräfte und Kopplungen



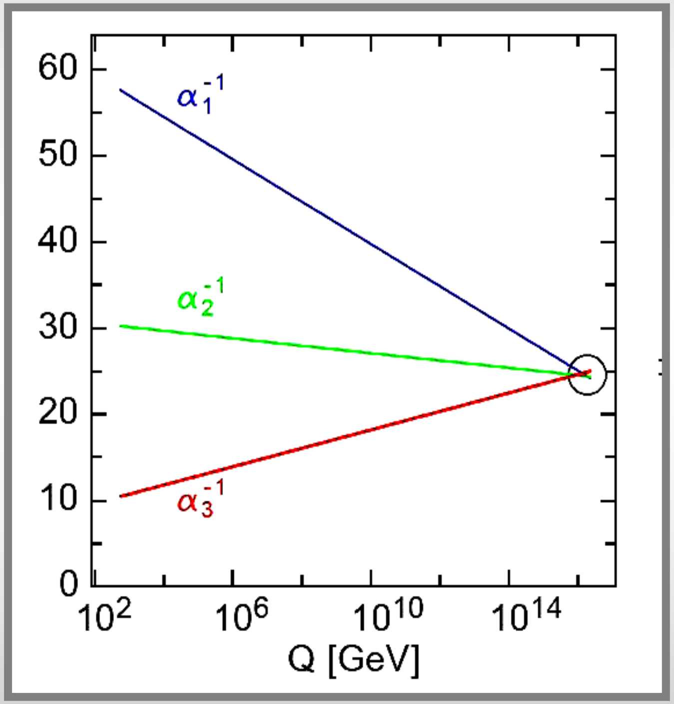
- ändert Energie-Abhängigkeit der Kopplungen:
  ein Vereinigungs-Punkt bei $M_X = 2 \cdot 10^{16}$ GeV !
- Proton-Lebensdauer > exptl. Limit
- Neutralino ($\bar{\gamma}$, $\bar{Z}$, $\bar{H}_{1,2}$): leichtestes SUSY-Teilchen
  Dunkle Materie im Universum !

- verbindet kontinuierl. Raum-Zeit-Symmetrie
  mit Spin-Statistik + Symmetrien
  $U(1) \otimes SU(2) \otimes SU(3) \supset SU(5), SO(10), E(6), \ldots$
- Eichfelder lokaler SUSY:
  Graviton (J=2) + Gravitino (J=3/2)
  Super-Gravitation !
- Higgs-Strahlungskorrekturen
  stabil:



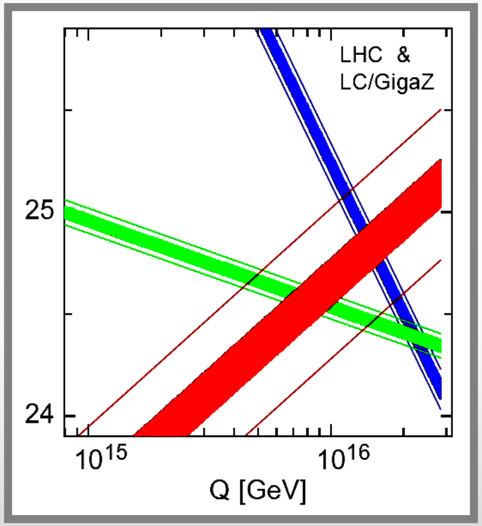
Super-Symmetrie

Vereinigung: Extrapolation über 10^{14}



Präzision der Startwerte:

$\delta\alpha\ /\ \alpha \sim 10^{-9}$ **elektromagnet.**
$\delta G_F/\ G_F \sim 10^{-5}$ **schwach**
$\delta G_N/\ G_N \sim 10^{-3}$ **Gravitation**
$\delta\alpha_s\ /\ \alpha_s \sim 10^{-2}$ **stark**



$\delta\alpha_s/\alpha_s$:

Experiment: ~1%

Theorie:

NLO	~4%
NNLO	~2% ?
Gitter	~1% ?

Was macht die Kernkraft stark ?

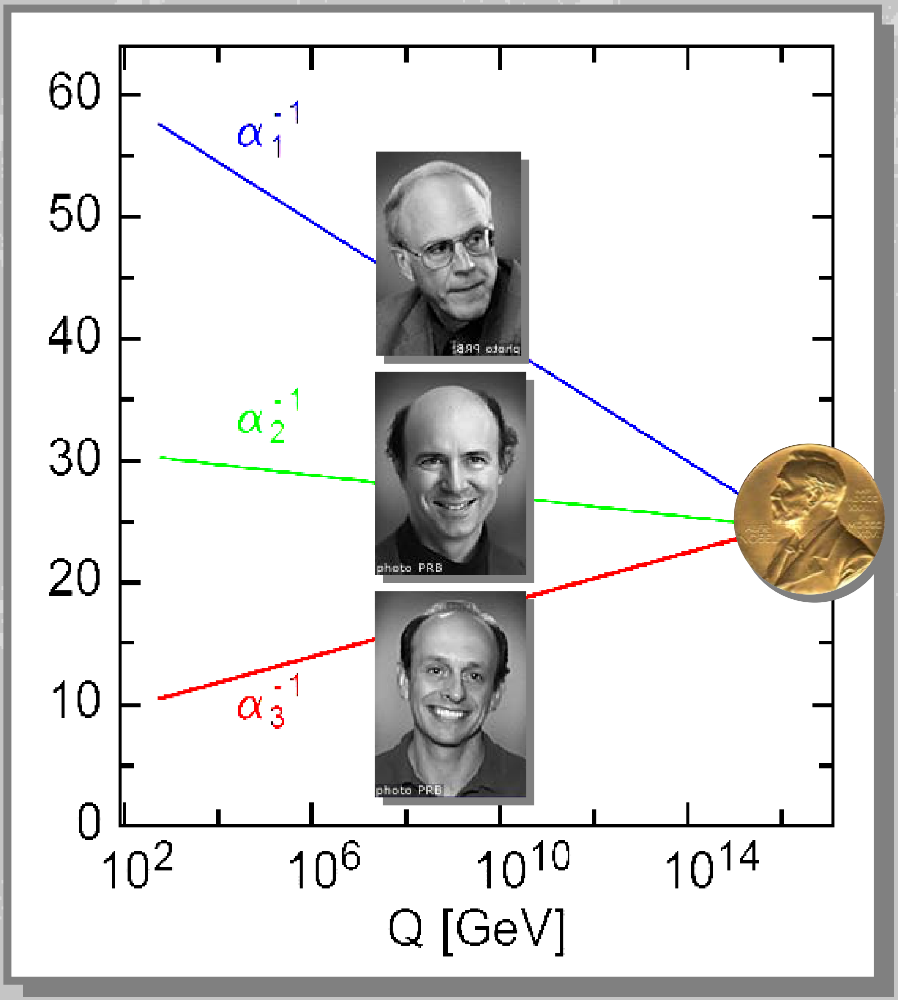
$$G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_i (i \gamma^\mu D_\mu + m_i) q_i$$

Was mich schwach macht,
macht mich stark !

$$G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$$

Selbstkopplung der Eichbosonen in nicht-abelschen Eichtheorien

Der Weg ist frei ...



zu einer

- **Feldtheorie** mit
  - korrekter Asymptotik +
  - Punkt-Wechselwirkung

- **zurück zum Urknall**

- **vorwärts zur Urkraft !**