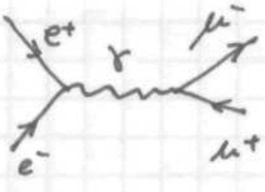
HADRONI I KVARKOVI

1. Evidencije (eksperimentalne + teorijske) za postojanje kvarkova

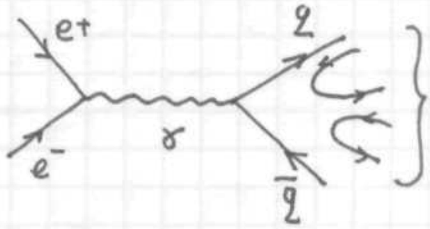
(a) $e^+ + e^-$ anihilacija : potvrda 'boje'

- $e^+ + e^- \rightarrow \gamma \rightarrow \mu^+ + \mu^-$



$$\sigma \propto \frac{\alpha^2}{(E_{CM})^2}$$

- $e^+ + e^- \rightarrow \gamma \rightarrow q + \bar{q} \rightarrow$ hadroni



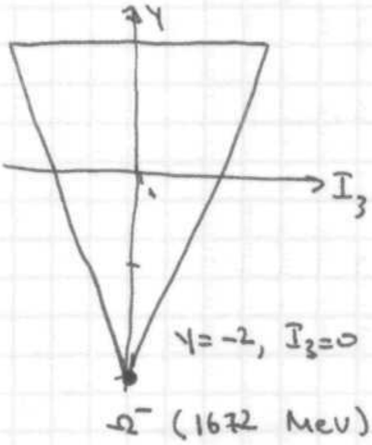
hadroni

$$R^{theor.}_{e^+e^-} \propto \frac{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}{\sigma(e^+e^- \rightarrow \text{hadroni})} \propto \sum_{\substack{\text{kvark.}\\ \text{'flavor'}}} Q^2_{\text{'flavor'}}$$

$$R^{exp}_{e^+e^-} \Big/ R^{th}_{e^+e^-} = N_C$$

$$\boxed{N_C = 3}$$

(b) Ω^- barion : potreba boje



spin-statistika teorem:

- bozoni := simetrična valna funkcija
- fermioni := antisimetrična valna funkcija

$\Omega := (sss)$

$$|\Omega^-\rangle = \underbrace{(s_\uparrow\ s_\uparrow\ s_\uparrow)}_{\text{spin } 3/2} \cdot \left(\text{Prostorna valna funkcija}(\vec{x}_1, \vec{x}_2, \vec{x}_3)\right)$$

$=$ (simetrična) $\cdot$ (simetrična) $\equiv$ simetrična !!

$\Longrightarrow$ • Fermion $\vec{J} = 3/2$ $\overset{!!??}{\Longrightarrow}$ simetrična v. funkcija

Uvođenje 'boje' $\alpha = 1,2,3$ ($\equiv B, R, G$ etc.)

$$(s_\uparrow\ s_\uparrow\ s_\uparrow) \longrightarrow \epsilon_{\alpha\beta\gamma}\,(s^\alpha_\uparrow\ s^\beta_\uparrow\ s^\gamma_\uparrow)$$

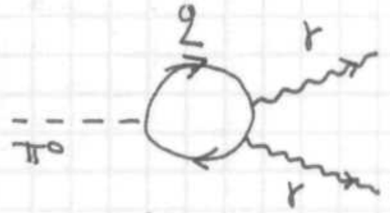
$\Longrightarrow$ $|\Omega^-\rangle =$ (antisimetrična) $\cdot$ (simetrična) $\equiv$

$\equiv$ antisimetrična

• Fermion $\vec{J} = 3/2$ $\Longrightarrow$ antisimetrična v. funkcija

(c) raspad $\pi^0 \to 2\gamma$: potvrda 'boje'

Γ_{th} (



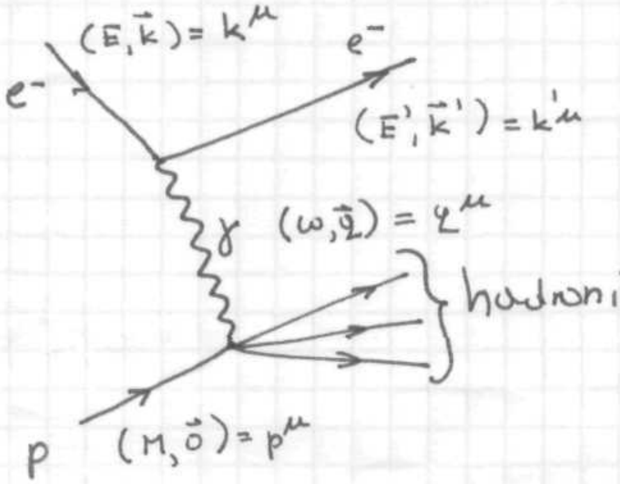
) $\simeq 7.87 \cdot \left(\frac{N_c}{3}\right)^2$ eV

$$\Gamma_{exp} \simeq 7.95 \text{ eV}$$

$$\boxed{N_c = 3} \implies \Gamma_{exp} \simeq \Gamma_{th}.$$

2. Dinamičke evidencije za postojanje kvarkova – Bjorken 'scaling'

- duboko neelastično raspršenje $e^- + p$



'momentum' transfer q^2:

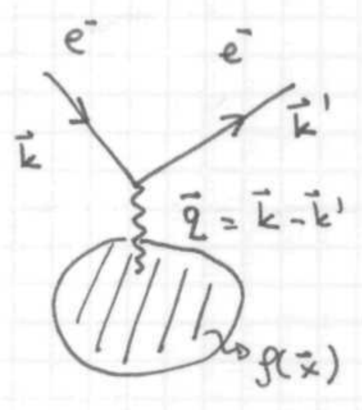
$$q^2 = |(k-k')^2| = 4EE'\sin^2\frac{\vartheta}{2}$$

- diferencijalni udarni presjek

$$\left(\frac{d^2\sigma}{d\Omega\, d\omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{point}_{Mott} \cdot \left[W_2(\omega, q^2) + \omega W_1(\omega, q^2) \cdot \mathrm{tg}^2\frac{\vartheta}{2} \right]$$

$W_{1,2} :=$ 'strukturne' funkcije

- Usporedite sa:



$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{point}_{Mott} \cdot \left| F(\vec{q}) \right|^2$$

$$F(\vec{q}) = \int \rho(\vec{x})\, e^{i\vec{q}\cdot\vec{x}}\, d^3x$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{point}_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth.} \left(1 - v^2 \sin^2\frac{\vartheta}{2}\right)$$

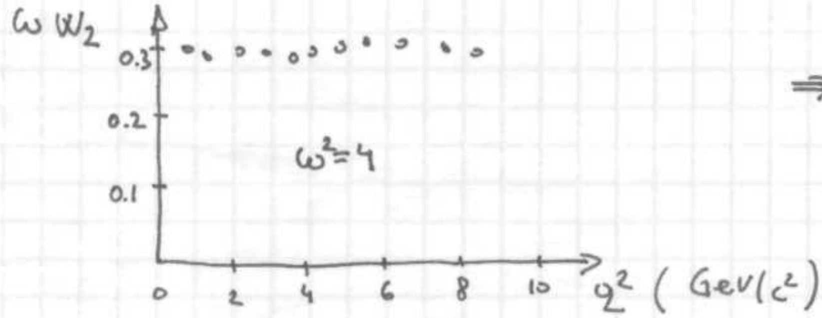
2. Bjorken 'scaling'

- uvedimo bezdimenzionu varijablu:

$$x = \frac{2M\omega}{q^2} = 2\,\frac{p\cdot q}{q^2}$$

$$y = \frac{1}{x} = q^2 / 2M\omega$$

- eksperimentalna činjenica



$\Rightarrow$ ne ovisi o q^2 !!

- teorijska predikcija (1969.)

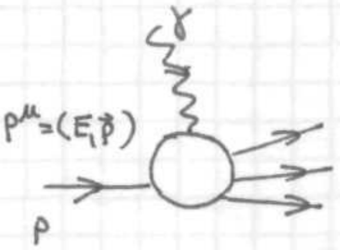
$$\lim_{\substack{q^2\to\infty \\ \omega\to 0 \\ y = \text{fiksno}}} W_1(\omega, q^2) \to F_1(\omega)$$

$$\lim_{\substack{q^2\to\infty \\ \omega\to 0 \\ y = \text{fiksno}}} \omega W_2(\omega, q^2) \to F_2(\omega)$$

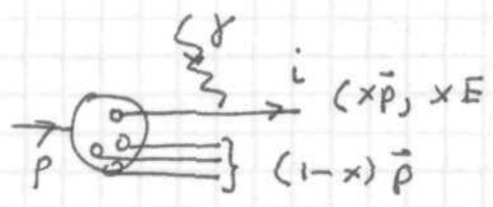
Bjorken 'scaling'

Interpretacija eksperimentalnih rezultata:

$\Rightarrow$ raspršenje e^- dešava se na točkastim konstituentima protona $\longrightarrow$ 'partonima' (Feynman)



$$:= \sum_i \int dx \; e_i^2 \Big\{ \quad \Big\}$$



$i :=$ različite vrste 'partona'

$x := 2m\omega / q^2$

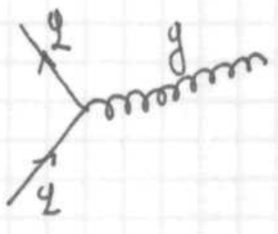
Ali: jesu li kvarkovi $\equiv$ 'partoni'?

Moderna slika:

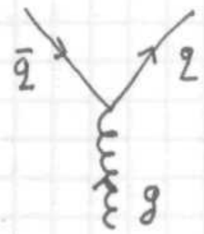
'partoni' = kvarkovi + gluoni

$\begin{cases} 50\% \text{ momenta odnose kvarkovi a} \\ 50\% \text{ gluoni} \end{cases}$

3 Interakcija kvarkova i gluona



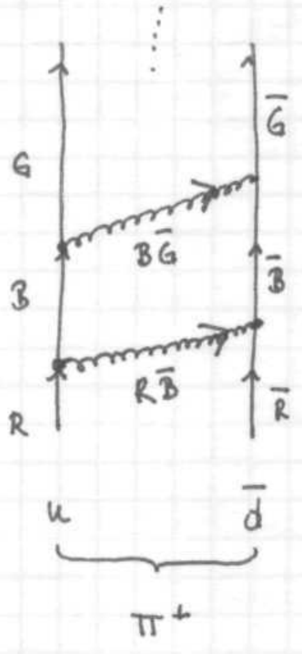
'emisija' gluona



'raspad' gluona u kvark-antikvark par

samointerakcija gluona

Primjeri:



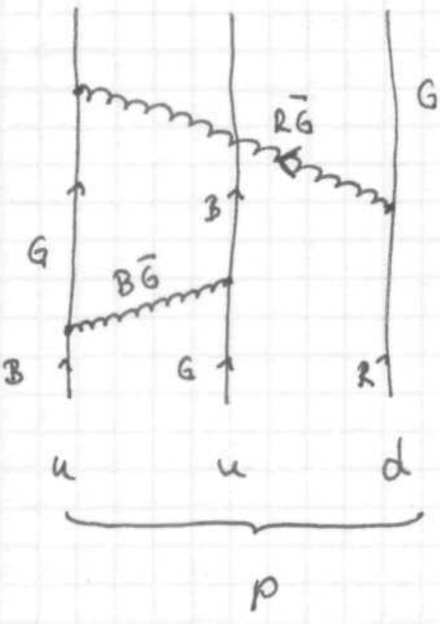


Fig. 7.11 Measurements of $R = \sigma_L/\sigma_T$ as a function of x from ep scattering. Q^2 (in GeV)^2): ●, 3; ○, 6; ▲, 9; ▽, 12; ■, 15; □, 18.

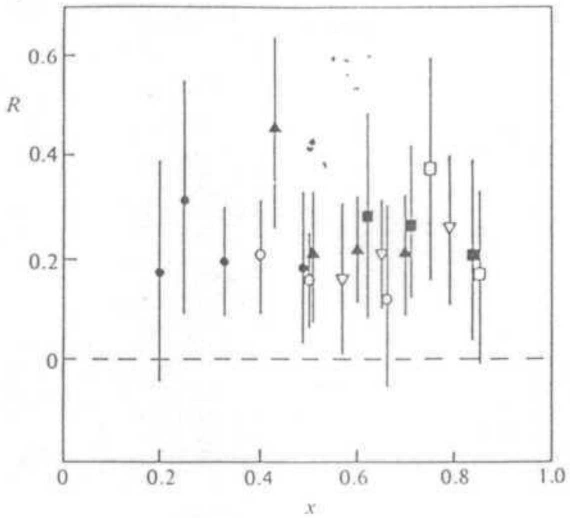
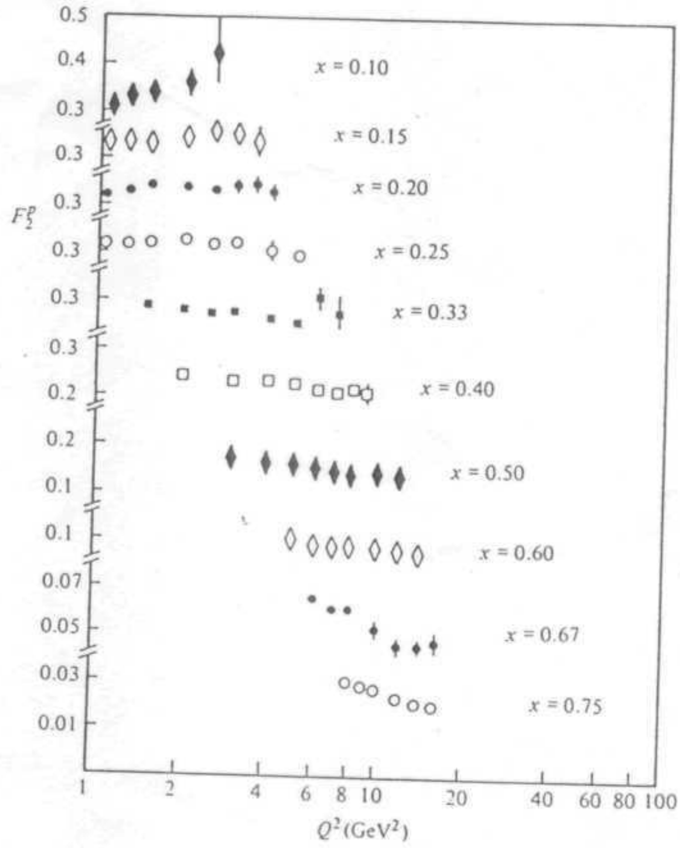


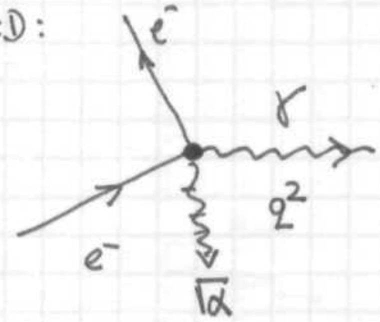
Fig. 7.13 Measurements of F_2^p versus Q^2, for different x values; from Bodek *et al.* (1979).



OVISNOST JAKOSTI INTERAKCIJA O ENERGIJI

(fenomen 'trčećih' konstanti veze)

1. QED:



$$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{4\pi}\frac{e^2}{\left(\frac{\hbar}{m_e \cdot c}\right)} \Big/ :(m_e \cdot c^2)$$

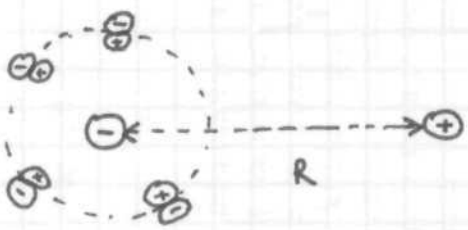
$(\epsilon_0 = 1,$ Heaviside-Lorentz!$)$

$$\alpha \simeq \frac{1}{137}$$

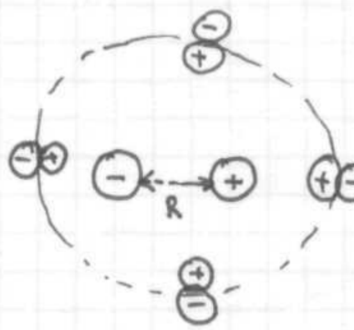
- Ali: α nije konstanta!! Ovisi o energetskoj skali tj. q^2:

$$\alpha \equiv \alpha(q^2) = \frac{\alpha_0}{1 + F(q^2)} = \frac{\alpha(q_0)}{1 + \text{const.} \ln\left(\frac{q^2}{q_0^2}\right)}$$

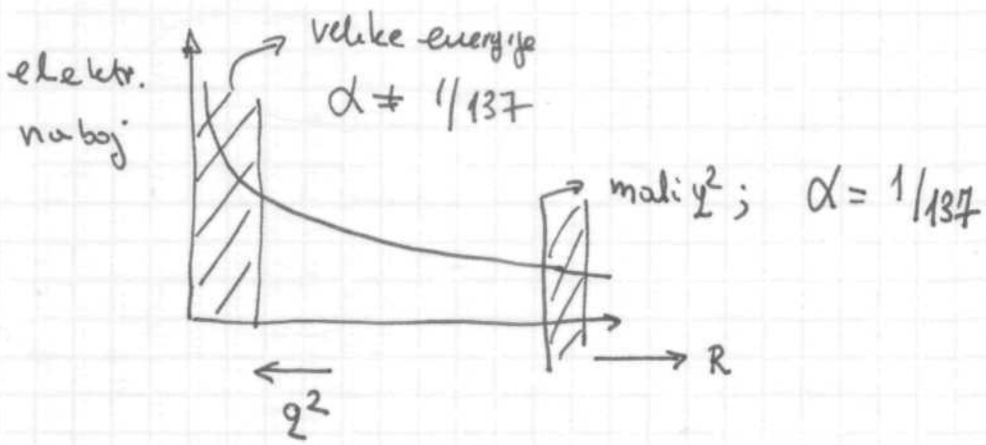
- 'Intuitivna' slika:



$R \gg$, $q^2 \ll$ } 'long distance' probe



$R \ll$, $q^2 \gg$ } 'short distance' probe



2. 'Trčeće' konstante veze

$$\alpha_k = \alpha_k(q^2) \qquad \begin{matrix} k=1 & (\text{ELM}) \ldots U(1)_Y \\ k=3 & (\text{Jaka}) \ldots SU(3)_C \end{matrix}$$

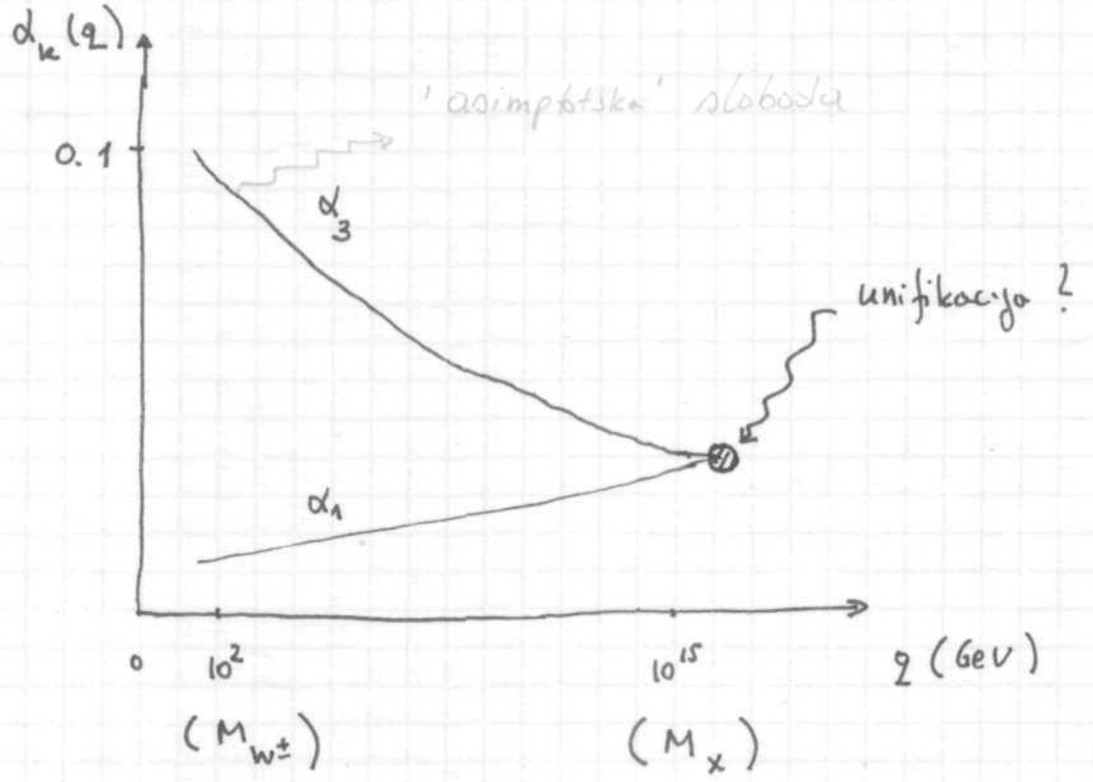
$$\alpha_k := \frac{1}{4\pi} g_k^2 = \left\{ \begin{matrix} \sim 0.16 & , k=3 \\ \sim 0.009 & , k=1 \end{matrix} \right\}_{M_{W^\pm}}$$

RGE:

$$\frac{1}{g_k^2(q)} = \frac{1}{g_k^2(M_X)} + 2 b_k \ln\left(\frac{M_X}{q}\right)$$

$$b_1 = \frac{1}{(4\pi)^2}\left(\frac{4}{3} N_G\right) , \quad N_G = \text{broj generacija}$$

$$b_3 = \frac{1}{(4\pi)^2}(-11) + b_1$$



```
In[11]:= α = A / Log[(q^2 / 0.06)]
```

Out[11]= $\frac{4\pi}{9\,\mathrm{Log}[16.6667\,q^2]}$

```
In[12]:= A = 12 Pi / (33 - 6)
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Out[12]= $\frac{4\pi}{9}$

```
In[13]:= α
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Out[13]= $\frac{4\pi}{9\,\mathrm{Log}[16.6667\,q^2]}$

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In[14]:= Plot[α, {q, 0.01, 100}]
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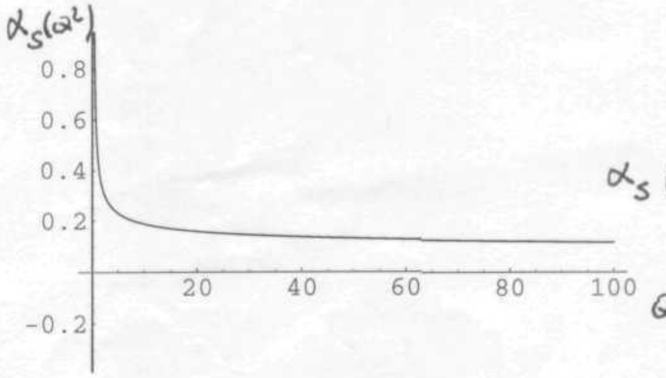

$\alpha_s(Q^2 \to \infty) \to 0$

asymptotic freedom!!

Out[14]= - Graphics -

```
In[15]:= Plot[α, {q, 0, 10}]
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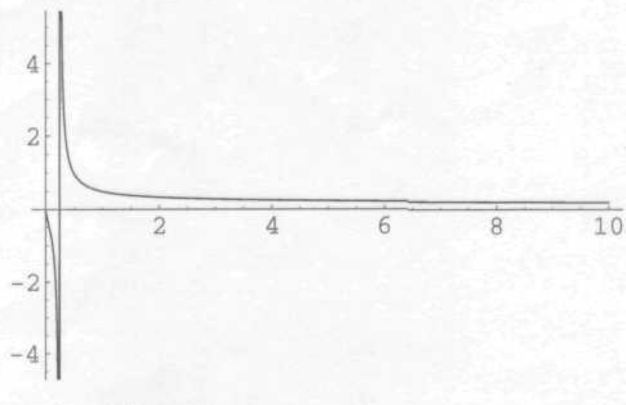


Out[15]= - Graphics -

3. 'Asimptotska' sloboda i 'zatočenje' kvarkova

$$\alpha_3(q^2) \propto \frac{1}{(33-2N_G)\cdot \ln\frac{q^2}{M_x^2}}$$

$N_G = 3$, $M_x = 250$ MeV/c

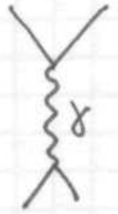
- ako je $\alpha_3 \ll 1$, perturbativni račun ('slaba' konstanta veze)
- ako je $\alpha_3 \gtrsim 1$, neperturbativni efekt ('jaka' konstanta veze)

⇒ (1) na velikim energijama (malim udaljenostima) α_3 je efektivno mala pa su kvarkovi 'slobodni'

(2) na niskim energijama (velikim udaljenostima) α_3 je efektivno velika i kvarkovi su 'zatočeni'

Razlog:

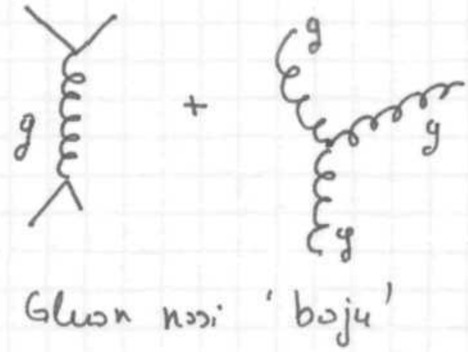
QED:



Foton 'ne nosi' U(1) naboj

(Abelova teorija)

QCD:



Gluon nosi 'boju'

(Ne-Abelova teorija)

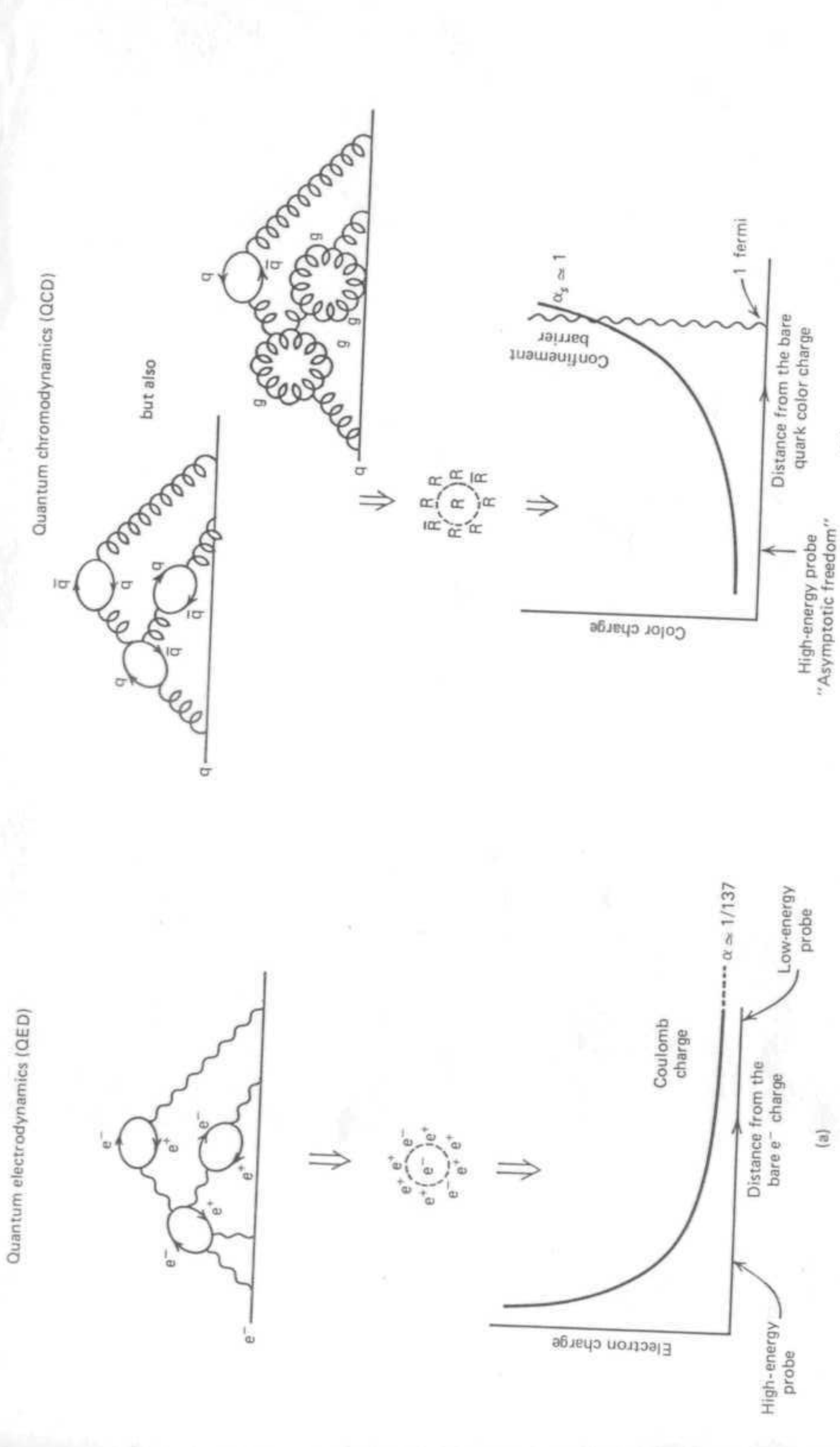


Fig. 1.5 Screening of the (a) electric and (b) color charge in quantum field theory.

place the test charge; when moving the test charge closer to the electron, we penetrate the cloud of positrons that screens the electron's charge. Therefore, the closer one approaches the electron, the larger is the charge one measures. In quantum field theory, the vacuum surrounding the electron has become a polarizable medium. The situation is analogous to that of a negative charge in a dielectric medium: the electron–positron pairs in Fig. 1.6 respond to the presence of the electron like the polarized molecules do in the dielectric. This effect is known as charge screening; as a result, the "measured charge" depends on the distance one is probing the electron; the result is shown pictorially in Fig. 1.5a. In QED, this variation of the charge is calculable by considering all possible configurations of the electron's charge cloud, only one of which is shown in Fig. 1.5a (see Chapter 7).

One can carry through the same calculation for the color charge of a quark. Color screening would be a carbon copy of charge screening if it were not for the new configurations involving gluons turning into pairs of gluons, as shown in Fig. 1.5b. The gluons, themselves carriers of color, also spread out the effective color charge of the quark. It turns out that the additional diagrams reverse the familiar result of quantum electrodynamics: a red charge is preferentially surrounded by other red charges, as shown in Fig. 1.5b. We now repeat the experiment of Fig. 1.6 for color charges. By moving our test probe closer to the original red quark, the probe penetrates a sphere of predominantly red charge and the amount of red