Kuantum renk dinamiği

T. M. Aliev
ODTÜ

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Quantum chromodynamics (QCD)

- Quark model (Gell-Mann, Zweig)
  Particles (baryon and mesons) build from quarks
- At present time

u,	c,	t	(up type)
d	s	b	(down type)

- Quarks are fermions, with spin 1/2 in electric charges $\frac{2}{3}$ or $-1/3$ +e unit.
- Problem of quark model
  ∴ 1964 discovered Ω baryon with $S = 3/2$ and according quark model its quark content

$$s \quad s \quad s$$

- Three identical fermions
  ∴ Contradict Pauli exclusion principle.
  ∴ Solution: Introduce new quantum number: <u>COLOR</u>

- Question: HOW MANY color numbers are needed?

  .. Answer: 3

- Follows from $\pi^0 \to 2\gamma$

  Experim: $\Gamma(\pi^0 \to 2\gamma) = 7.77 \text{ keV}$

  Theoretically: $|\pi^0\rangle = \frac{1}{\sqrt{2}}\left[\,|u\bar{u}\rangle - |d\bar{d}\rangle\right]$

$$\Gamma \simeq A N \left[\left(\frac{2}{3}\right)^2 - \left(-\frac{1}{3}\right)^2\right] = A N_c \, \tfrac{1}{3}$$

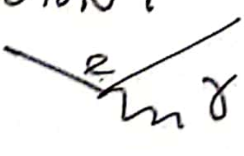
$$\frac{\Gamma_{theor}}{\Gamma_{exp}} = \frac{N_c}{3} \Rightarrow \boxed{N_c = 3}$$

COLOR IN QCD

- The theory of the strong interaction QCD, is very similar to QED, but with „3" conserved color charges

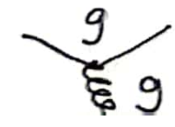
QED

the electron one unit of charge $-e$
the position $+e$
" the force is mediated by a massless" gauge boson the photon!



QCD

- quarks carry color charge r, g, b
- antiquark carry anti-color $\bar{r}, \bar{g}, \bar{b}$
- The force mediated by massless gluons



- In QCD the strong interaction is invariant under rotations in color space

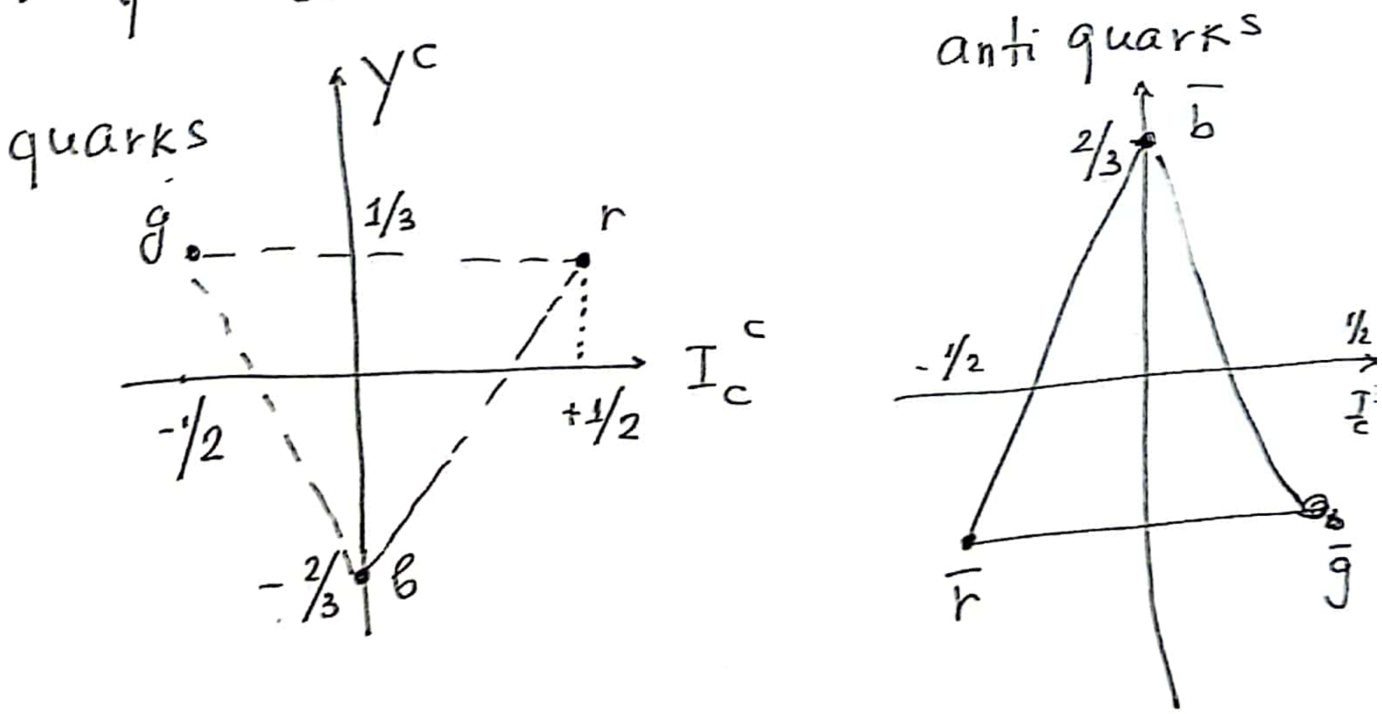
$$r \leftrightarrow b, \quad r \leftrightarrow g, \quad b \leftrightarrow g$$

$\downarrow$ SU(3) color symmetry (exact)!

- Color states represents by

$$r = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad g = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad b = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

- Color states characterized by two quantum numbers:
  - I_3^c color isospin
  - Y^c color hypercharge



Color confinement

- It is belived (not yet proven) that all observed free particles are colorless
  - ⇒ renk yükü taşiyan serbest parcacık gözlenemez (serbest quark)
  - Kuarkları ancak bagli renksiz hadronlarda bulmak mümkün
- Renk konfainment hypotezi:
  - Ancak renke gore „singlet" durumlar serbest parcacıklar olabilır

⇒ Tüm hadronlar „ color singlet olmali

Color singlet

- Color singlet ne anlama geliyor
- iki spin $1/2$ parcacıktan oluşan sistemin spin durumlarına bakalım:
- Mümkün ~~durumlar~~ spin combinasyonları

$$\uparrow\uparrow,\ \uparrow\downarrow,\ \downarrow\uparrow,\ \downarrow\downarrow$$

- Spin durumları S^2, S_z operatorların degerleri ile ifade dunurlar

$$|1,+1\rangle = \uparrow\uparrow$$
$$|1,0\rangle = \frac{1}{\sqrt{2}}\left[\uparrow\downarrow + \downarrow\uparrow\right]$$
$$|1,-1\rangle = \downarrow\downarrow$$

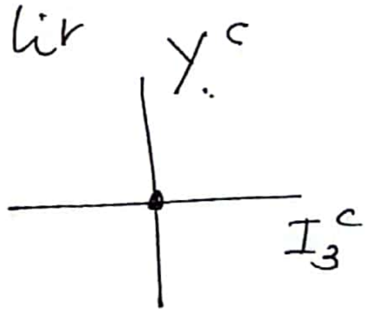
$\Big\}$ spin triplet $(S=1)$

$$|0,0\rangle = \frac{1}{\sqrt{2}}\left[\uparrow\downarrow - \downarrow\uparrow\right]$$ spin singlet $(S=0)$

$$2 \otimes 2 = 3 \oplus 1$$

- ~~The~~ Spin singlet $(S=0)$ SU(2) spin dönüşümlerine gore değişmez ve spin ladder $S_\pm|0,0\rangle = 0$

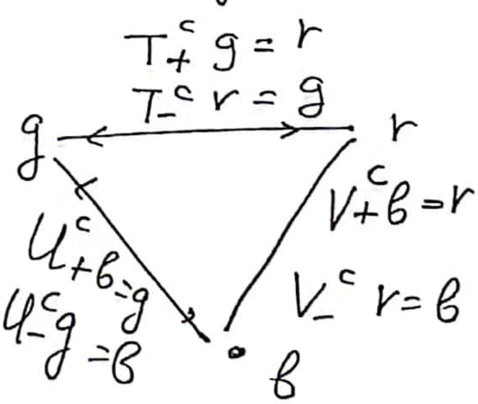
- Tamamile benser yolla color singlet durumlari elde edinebilir
- Onlar $I_3^c = 0$ $Y^c = 0$
- SU(3) color donuş. gore inv.
- Ladder operatorlar



$$T_\pm,\ U_\pm,\ V_\pm\ |\text{color singl.}\rangle = 0$$

Ladder operatorlar

flav.
$u \leftrightarrow r$
$d \leftrightarrow g$
$s \leftrightarrow b$



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$$\begin{cases} T_\pm = \frac{1}{2}(\lambda_1 \pm i\lambda_2) \\ V_\pm = \frac{1}{2}(\lambda_4 \pm i\lambda_5) \\ U_\pm = \frac{1}{2}(\lambda_6 \pm i\lambda_7) \\ I_3 = \frac{1}{2}\lambda_3 \qquad Y = \frac{1}{\sqrt{3}}\lambda_8 \end{cases}$$

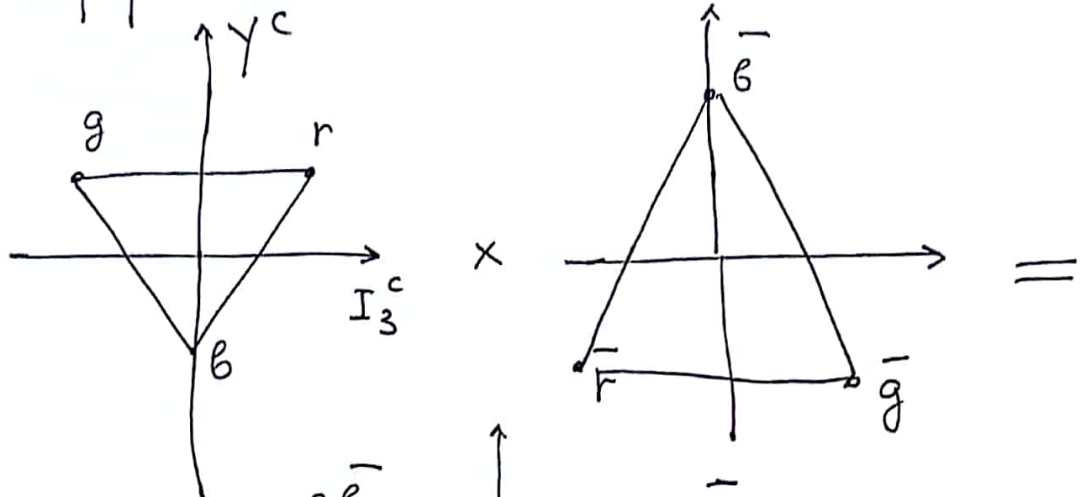
$$\lambda_1 = \begin{pmatrix} \sigma_1 & 0 \\ 0 & 0 \end{pmatrix} \qquad \lambda_2 = \begin{pmatrix} \sigma_2 & 0 \\ 0 & 0 \end{pmatrix} \qquad \lambda_3 = \begin{pmatrix} \sigma_3 & 0 \\ 0 & 0 \end{pmatrix}$$

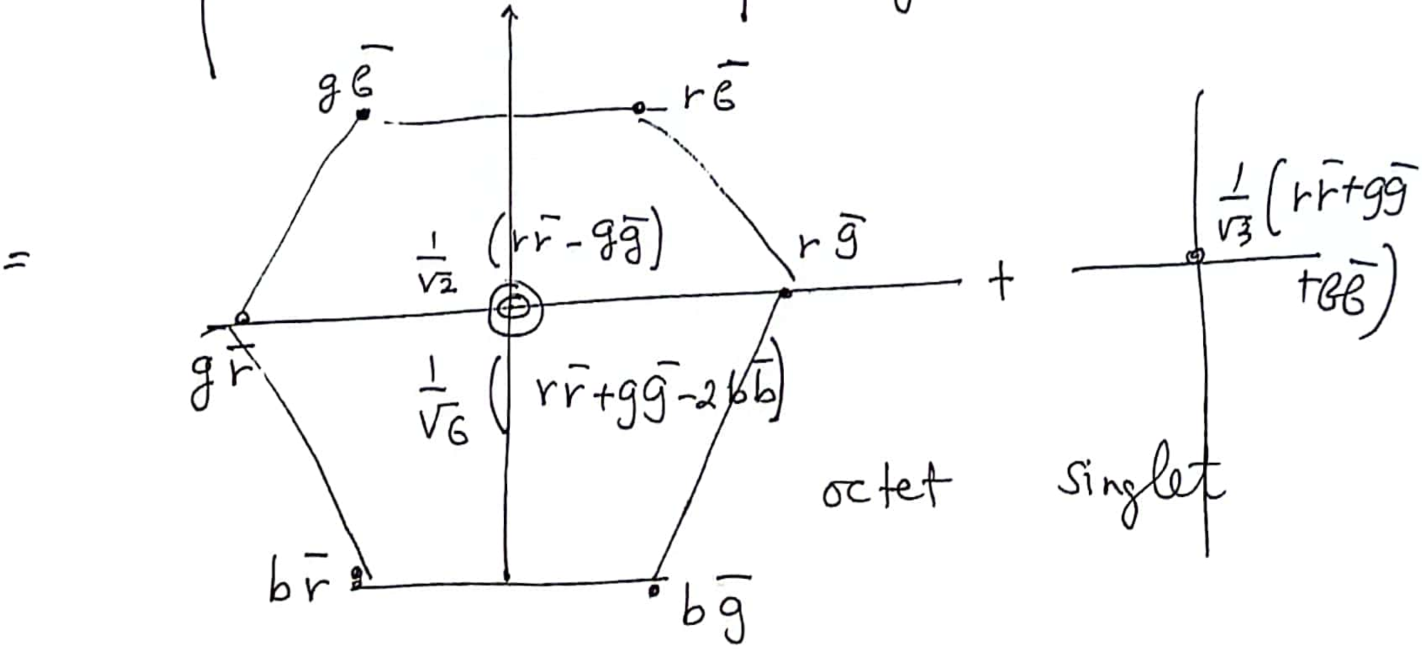
$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \qquad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

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

Meson Color WF

- $q\bar{q}$ WF





- $3 \times \bar{3} \equiv (8+1)$
- $\psi_c^{q\bar{q}} = \frac{1}{\sqrt{3}}(r\bar{r}+g\bar{g}+b\bar{b})$ $(I_3^c = 0 \;\; Y_3^c = 0)$
- $qq\bar{q}$ durumu mümkün mü!
  (Yani $q\bar{q}$ bir quark ekleye bilir miyiz)
- Hayır. $\Rightarrow$ $qq\bar{q}$ bağlı durumu doğada olamaz !!!

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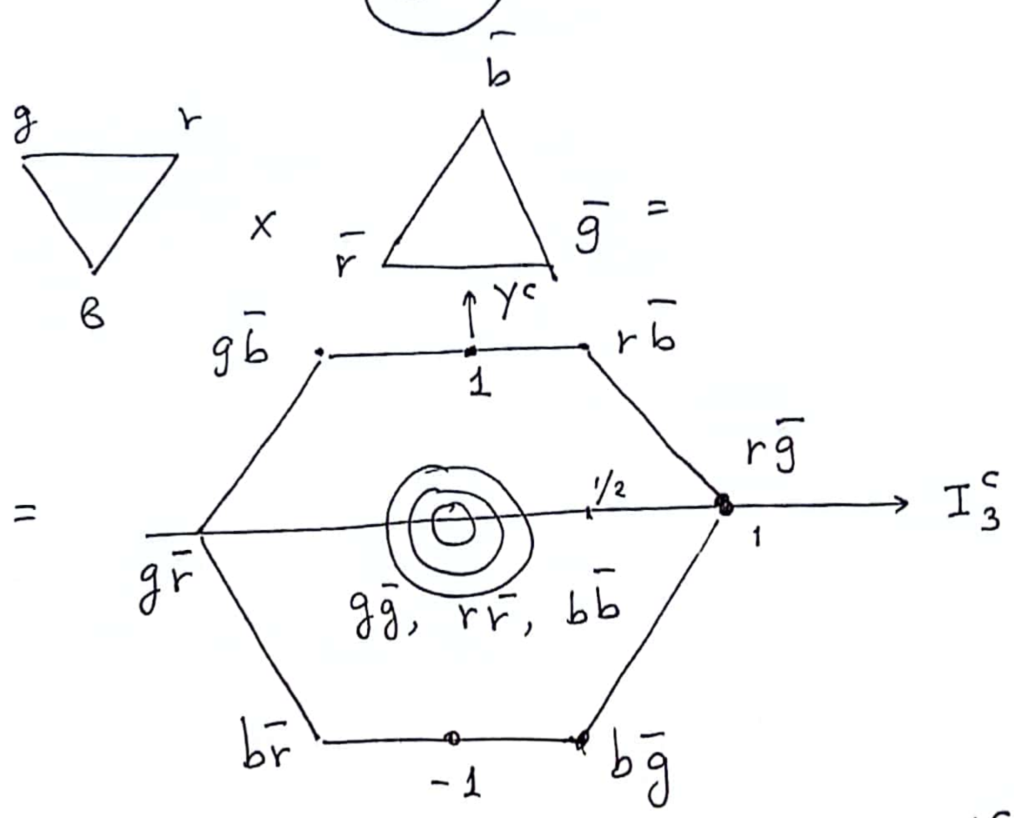

- Three states have $I_3^c = 0$ $Y_c = 0$ can be obtained by using the ladder operators and orthogonality. Starting ou ther states:

$$T_+|g\bar{r}\rangle = (|r\bar{r}\rangle - |g\bar{g}\rangle)$$

$$T_-|r\bar{g}\rangle = |g\bar{g}\rangle - |r\bar{r}\rangle$$

$$V_+|b\bar{r}\rangle = |r\bar{r}\rangle - |b\bar{b}\rangle$$

$$V_-|r\bar{b}\rangle = |b\bar{b}\rangle - |r\bar{r}\rangle$$

$$U_+|b\bar{g}\rangle = |g\bar{g}\rangle - |b\bar{b}\rangle$$

$$U_-|g\bar{b}\rangle = |b\bar{b}\rangle - |g\bar{g}\rangle$$

- Only two of six states are linearly independent.

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- But we have 3 states with $Y^c = 0$, $I_3^c = 0$. Therefore one of state cannot belong to this multiplet i.e. cannot be reached ~~by~~ with ladder operators.
- First form two linearly independent orthogonal states from:

$$|r\bar{r}\rangle - |g\bar{g}\rangle ; \qquad |r\bar{r}\rangle - |b\bar{b}\rangle ;$$
$$|g\bar{g}\rangle - |b\bar{b}\rangle$$

- choose: $$\psi_1 = \frac{1}{\sqrt{2}}\left[|r\bar{r}\rangle - |g\bar{g}\rangle\right]$$

- The second state can be obtained by taking the linear combination of other two states

$$\psi_2 = \alpha\left[|r\bar{r}\rangle - |b\bar{b}\rangle\right] + \beta\left(-|g\bar{g}\rangle + |b\bar{b}\rangle\right)$$

- Orthogon. cond.

$$\langle \psi_1 | \psi_2 \rangle = 0 \qquad \langle \psi_2 | \psi_2 \rangle = 1.$$

$$\alpha + \beta = 0$$

$$\cancel{2\alpha^2 + 2\beta^2 =}$$

$$\alpha\left(\langle r\bar{r}| - \langle b\bar{b}|\right) + \beta\left(-\langle g\bar{g}| + \langle b\bar{b}|\right)$$
$$\alpha\left(|r\bar{r}\rangle - |b\bar{b}\rangle\right) + \beta\left(-|g\bar{g}\rangle + |b\bar{b}\rangle\right)$$

$$\Rightarrow 2\alpha^2 + 2\beta^2 - 2\alpha\beta = 1$$

$$4\alpha^2 + \cancel{6}\alpha^2 = 1 \qquad \alpha = \frac{1}{\sqrt{6}}$$

6***

$$\beta = -\frac{1}{\sqrt{6}}$$

$$\Rightarrow \quad \psi_2 = \frac{1}{\sqrt{6}}\left\{ |r\bar{r}\rangle - |b\bar{b}\rangle + |g\bar{g}\rangle - |b\bar{b}\rangle \right\}$$

$$= \frac{1}{\sqrt{6}}\left\{ |r\bar{r}\rangle + |g\bar{g}\rangle - 2|b\bar{b}\rangle \right\}$$

$$\psi_3 : \quad \alpha\left[|r\bar{r}\rangle - |b\bar{b}\rangle \right] + \beta\left[|b\bar{b}\rangle - |g\bar{g}\rangle \right] + \gamma\left[|g\bar{g}\rangle - |r\bar{r}\rangle \right]$$

$$\langle \psi_1 | \psi_3 \rangle = 0 \qquad \alpha - \beta + \gamma = 0$$

$$+\alpha + 2\alpha + \beta(-2-1) + \gamma(1-1) = 0$$

$$\alpha = \beta ;$$

$$\psi_3 = \alpha|r\bar{r}\rangle + \beta|g\bar{g}\rangle + \gamma|b\bar{b}\rangle$$

$\langle \psi_3 | \psi_3 \rangle = 1 ;$ $\qquad \alpha^2 + \beta^2 + \gamma^2 = 1$

$\langle \psi_1 | \psi_3 \rangle = 0$ $\qquad \alpha - \beta = 0$

$\langle \psi_2 | \psi_3 \rangle = 0$ $\qquad \alpha + \beta - 2\gamma = 0$

$\alpha = \beta = \gamma$

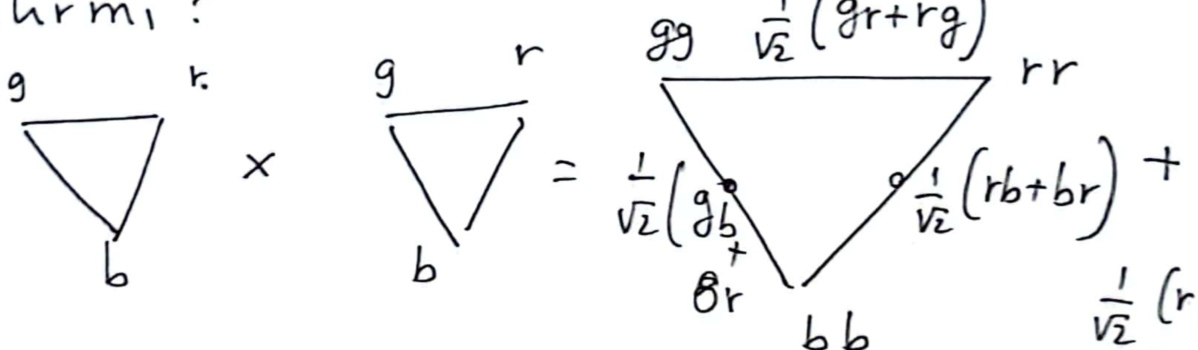
$\alpha = \beta = \gamma = \frac{1}{\sqrt{3}}$

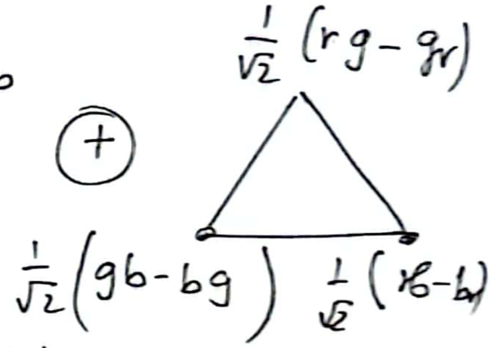
$$\boxed{|\psi_3\rangle = \frac{1}{\sqrt{3}}\left\{ |r\bar{r}\rangle + |g\bar{g}\rangle + |b\bar{b}\rangle \right\}}$$

Color Singlet!

(See p. 6)

BARYON Color WF

- $q\bar{q}$ bağlı durumu mümkün mü! Başka sözle: iki color triplet durumlardan color singlet oluşturulabilir mi?
- 



- qq color singlet durumu yok!
- Color confainment ⇒ qq bağlı durumu yok!!
- Üç quarkdan color singlet durumu oluşturmak mümkün

$$\psi_c^{qqq} = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr)$$

- Check: ~~ind~~ Bu durum doğrudan color singlettir.

$I_3^c = 0 \quad Y^c = 0$ (necess. but not sufficient)

$$T_+ \psi_c^{qqq} = \frac{1}{\sqrt{6}}(rrb - rbr + rbr - rrb + brr - brr) = 0$$

(Recall: $T_+ g = r$)

- Benzer yolla $T_- \psi = 0$

$V_\pm \psi_c = 0 \quad U_\pm \psi_c^{qqq} = 0$

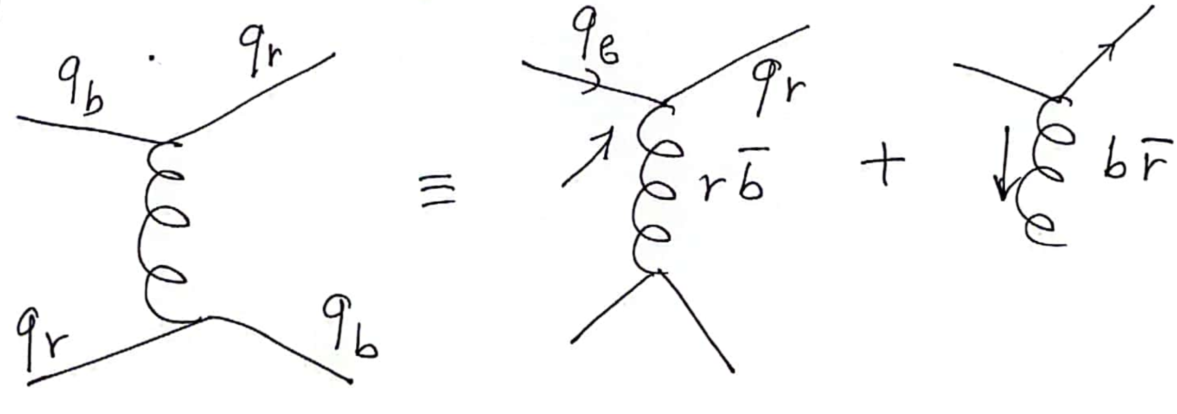
Sonuç: qqq bağlı durum mümkün

$\Rightarrow$ Anti symmetric color WF.

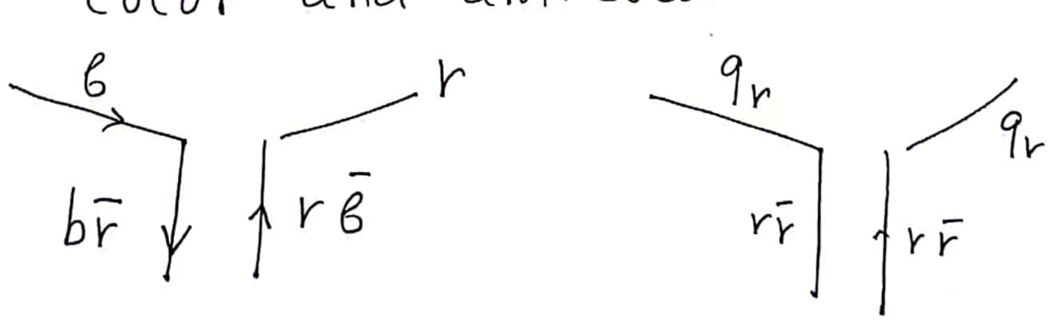
- Olabilecek hadronlar: (color singlet)
- $q\bar{q}$, qqq (Meson ve baryonlar)
- $q\bar{q}q\bar{q}$ $qqqq\bar{q}$ (tetraquarks, pentaquarks..)

Gluonlar:

- QCD etkileşme virtual kütlesiz gluonları değiş-tokuşu ile oluyor.



- Gluons color and anticolor i.e.



- WF similar for meson

i.e. Octet + Colorless Singlet!

- 9 physical gluons beklenebilir

Octet: $r\bar{g}$, $r\bar{b}$, $g\bar{r}$, $g\bar{b}$, $b\bar{r}$, $b\bar{g}$,

$$\frac{1}{\sqrt{2}}(r\bar{r}-g\bar{g}),\ \frac{1}{\sqrt{6}}(r\bar{r}+g\bar{g}-2b\bar{b})$$

Singlet: $\frac{1}{\sqrt{3}}(r\bar{r}+g\bar{g}+b\bar{b})$

- Color confainement hypotesi:

Serbest parcacık color singlet olmalı $\Rightarrow$ Color singlet gluon unconfined. Ona gore o güclü etkileşmede fotona benzer olabilir $\Rightarrow$ ∞ range güclü etkileşme !!!

- Deneylerde: Güclü etkileşme "short" range. Ona gore fiziksel gluon confined. $\Rightarrow$ Color singlet gluon dogada var olamaz!!

LOCAL gauge (phase) invariance

$$\psi \to \psi'(x) = e^{i\alpha(x)}\,\psi(x) \qquad (1)$$

- $\mathcal{L}(\psi(x), \partial_\mu \psi(x))$

$$\partial_\mu \psi(x) \Rightarrow e^{i\alpha(x)}\left[\partial_\mu \psi(x) + i\partial_\mu \alpha\, \psi\right]$$

- $\mathcal{L}$ is not invariant under (1)
- Question ~~Introduce "local U(1) symmetry~~

Is it possible to Modify $\mathcal{L}$ such that it obeys local U(1) symmetry of α

Answer: Yes, but we need to introduce new field, so called gauge field

→ covariant derivative

Rule: $\partial_\mu \to \mathcal{D}_\mu = \partial_\mu + iq A_\mu(x)$

and require that A_μ should transform in specific way!

It achived by requiring ψ and $\mathcal{D}_\mu \psi$ transforms in a same way, i.e.

$$\psi \to \psi' = e^{i\alpha(x)}\,\psi$$

$$\mathcal{D}_\mu \psi \to \mathcal{D}'_\mu \psi' = e^{i\alpha(x)}\,\mathcal{D}_\mu \psi$$

$$(\partial_\mu + iqA'_\mu)\,e^{i\alpha(x)}\psi = e^{i\alpha(x)}\left[\partial_\mu + iqA_\mu\right]\psi$$

$$(i\partial_\mu \alpha + iqA'_\mu) = iqA_\mu$$

$$\boxed{A'_\mu = A_\mu - \frac{1}{q}\,\partial_\mu \alpha}$$

Lie groups.

Definition: Lie groups are groups with ∞ numbers of elements. All groups have an identity element $\mathbb{1}$. Any group element continuously connected to the identity can be written as

$$\mathcal{U} = e^{i\theta_\alpha T^\alpha}\,\mathbb{1}.$$

θ_α → group params. T^α → group generators

- The generators of a Lie group T^a form a Lie algebra. The Lie algebra is defined through its commutation relation

$$[T^a, T^b] = i\underbrace{f^{abc}}_{\text{structure constants}} T^c$$

(Remember for abelian group $f^{abc} = 0$)

- For SU(2) group $f^{abc} \equiv \epsilon^{abc}$

Yang-Mills Theories.

- Exp. properties of p and n are same (except charge)

$$\mathcal{L} = \bar{p}(i\gamma^\mu \partial_\mu - m)p + \bar{n}(i\gamma^\mu \partial_\mu - m)n$$

$$\Rightarrow \bar{\psi}(i\gamma^\mu \partial_\mu - mI)\psi$$

$$\psi = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \boxed{\text{isospin space}}$$

Problem: Find field strength tensor for $U(1)$ and $SU(n)$ group.

$$\left[\begin{array}{l} \psi \to \psi' = G\psi \\ \mathcal{D}_\mu \psi \to \mathcal{D}'_\mu \psi' = G\mathcal{D}_\mu \psi \quad (1) \end{array}\right.$$

$$\mathcal{D}'_\mu \psi' = G\mathcal{D}_\mu \psi$$

$$\mathcal{D}'_\mu [G\psi] = G\mathcal{D}_\mu \psi$$

Acting left and right sides by $\mathcal{D}'_\nu$

$$\mathcal{D}'_\nu \mathcal{D}'_\mu \psi' = \mathcal{D}'_\nu \mathcal{D}'_\mu (G\psi) =$$

$$= \mathcal{D}'_\nu (G\mathcal{D}_\mu \psi) = G\mathcal{D}_\nu \mathcal{D}_\mu \psi$$

From (1) $\quad G^{-1}\mathcal{D}'_\mu \psi' = \mathcal{D}_\mu \psi$

$$G^{-1}\mathcal{D}'_\mu (G\psi) = \mathcal{D}_\mu \psi$$

$$G^{-1}\mathcal{D}'_\mu G\psi + \underbrace{\mathcal{D}'_\mu \psi}$$ $$= \mathcal{D}_\mu \psi$$

$$G^{-1}\mathcal{D}'_\mu G = \mathcal{D}_\mu$$

$$\mathcal{D}'_\mu = G\mathcal{D}_\mu G^{-1}$$

Consider $\quad [\mathcal{D}'_\mu, \mathcal{D}'_\nu] = \mathcal{D}'_\mu \mathcal{D}'_\nu - \mathcal{D}'_\nu \mathcal{D}'_\mu$

$$= G\mathcal{D}_\mu G^{-1} G\mathcal{D}_\nu G^{-1} - G\mathcal{D}_\nu G^{-1} G\mathcal{D}_\mu G^{-1}$$

$$= G[\mathcal{D}_\mu \mathcal{D}_\nu] G^{-1}$$

- $\mathcal{U}(1)$ case

$$[\mathcal{D}_\mu \mathcal{D}_\nu]\psi = [\partial_\mu + iqA_\mu, \partial_\nu + iqA_\nu]\psi$$

$$= iq[\partial_\mu, A_\nu]\psi + iq[A_\mu \partial_\nu]\psi$$

$$= iq[\partial_\mu(A_\nu\psi) - \underline{A_\nu \partial_\mu}\psi + A_\mu \partial_\nu \psi - \partial_\nu(A_\mu\psi)$$

$$= iq[\cancel{A_\nu \partial_\mu} + (\partial_\mu A_\nu)\psi + \cancel{A_\nu \partial_\mu \psi} - \cancel{A_\nu \partial_\mu \psi}$$

$$+ \cancel{A_\mu \partial_\nu \psi} - (\partial_\nu A_\mu)\psi - \cancel{A_\mu \partial_\nu \psi}]$$

$$= iq[\partial_\mu A_\nu - \partial_\nu A_\mu]\psi$$

$$\Rightarrow \boxed{[\mathcal{D}_\mu \mathcal{D}_\nu] = iqF_{\mu\nu}}$$

Non abelian case

matrix valued!

$$[\mathcal{D}_\mu \mathcal{D}_\nu]\psi = [\partial_\mu + igB_\mu, \partial_\nu + igB_\nu]\psi$$

$$= ig[\partial_\mu B_\nu]\psi + ig[B_\mu \partial_\nu]\psi - g^2[B_\mu B_\nu]\psi$$

$$= ig[\partial_\mu B_\nu \psi + \cancel{B_\nu \partial_\mu \psi} - \cancel{B_\nu \partial_\mu \psi} + \cancel{ig B_\mu \partial_\nu \psi} - ig\partial_\nu B_\mu \psi - \cancel{ig B_\mu \partial_\nu \psi}]$$

$$\mp g^2[B_\mu B_\nu]\psi$$

$$\Rightarrow [\mathcal{D}_\mu \mathcal{D}_\nu] = ig[\partial_\mu B_\nu - \partial_\nu B_\mu] - g^2[B_\mu B_\nu]$$

$$B_\mu = \vec{b}_\mu \frac{\vec{\tau}}{2}$$

$$B_\mu B_\nu = \frac{1}{4} b_{\mu i} b_{\nu j} \underbrace{[\tau_i \tau_j]}_{2i\varepsilon_{ijk}\frac{\tau_k}{2}} = \frac{i}{2}[\vec{b}_\mu \times \vec{b}_\nu]\cdot\vec{\tau}$$

so
$$[\mathcal{D}_\mu \mathcal{D}_\nu] = ig\frac{\vec{\tau}}{2}[\underbrace{\partial_\mu \vec{b}_\nu - \partial_\nu \vec{b}_\mu - g(\vec{b}_\mu \times \vec{b}_\nu)}_{\vec{F}_{\mu\nu}}]$$

$$\boxed{\vec{F}_{\mu\nu} = \partial_\mu \vec{b}_\nu - \partial_\nu \vec{b}_\mu - g(\vec{b}_\mu \times \vec{b}_\nu)}$$

New two type vertices

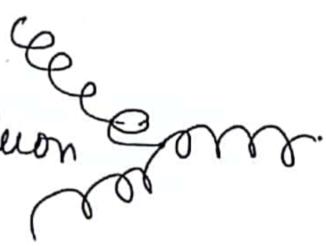
- 3 vector vertices $\quad g(\partial_\mu \vec{b}_\nu - \partial_\nu \vec{b}_\mu)(\vec{b}_\mu \times \vec{b}_\nu)$
- four vector vertices $\quad g^2(\vec{b}_\mu \times \vec{b}_\nu)^2$

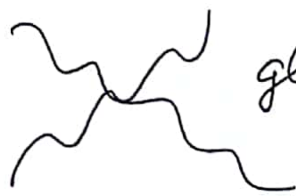
Gluon- Gluon interaction

- In QED the photon does not carry the charge of the EM interaction (photons are electrically neutral)
- In QCD, gluons do <u>carry color charge</u>

  $\Rightarrow$ gluon self interaction
- Two new vertices (no analog in QED)

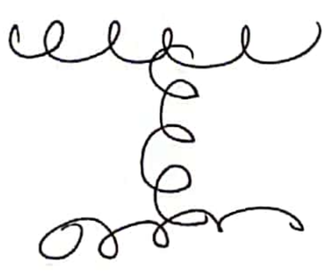
triple gluon vertex

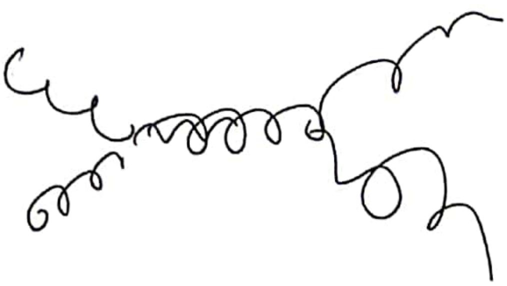




quartic gluon vertex

- In addition to quark- quark ~~inte-raction~~ scattering, therefore exist gluon-gluon scattering





Gluon self interactions and confinement

- Gluon self interactions are belived to give rise color confinement

- QUALITATIVE picture
  - Compare QED with QCD

In QCD "gluon self interactions squeeze lines of force into a flux tube"

- What happens when we try to separate two colored objects i.e. $q\bar{q}$

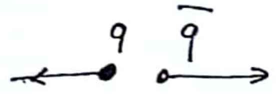
~ In tube energy density ~ $\underline{V(r) \approx \lambda r}$.

- ∞ energy require to separate colored objects to infinity
- Colored quarks and gluons confined within colored states.
- In this way QCD explained the confinement.

Hadronization and Jets

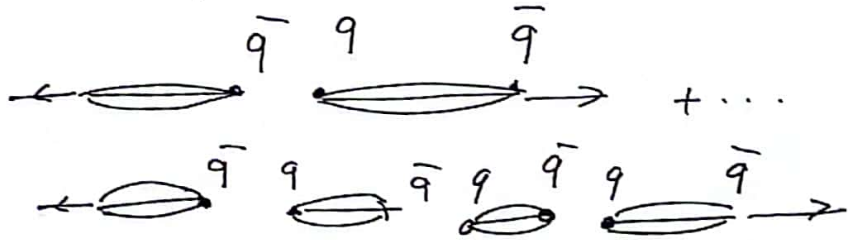
- Consider $q\bar{q}$ produced in some reaction

1) initially quarks separate at high velocity



2) Color flux tube forms between quarks

3) Energy stored in the flux tube sufficient to produce $q\bar{q}$ pair

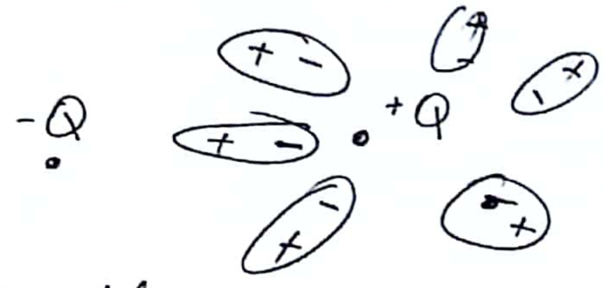


IV) Process continues until quarks pair up into jets of colorless hadrons

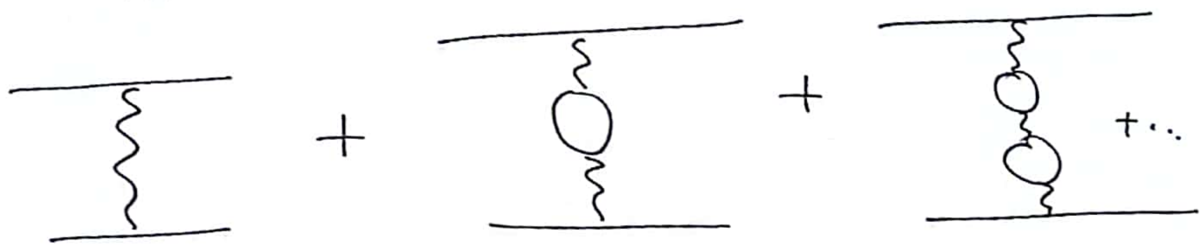
This process is called hadronization
(This process not (yet) calculable).

Running Coupling constants

- QED
  - "bare" charge of electron screened by virtual e^+e^- pairs

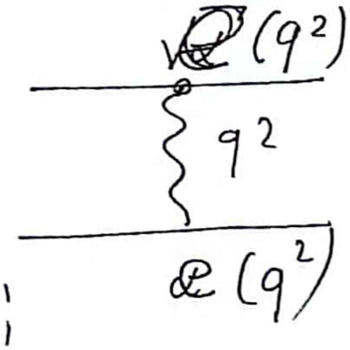


- Behaves like a polarisable dielectric

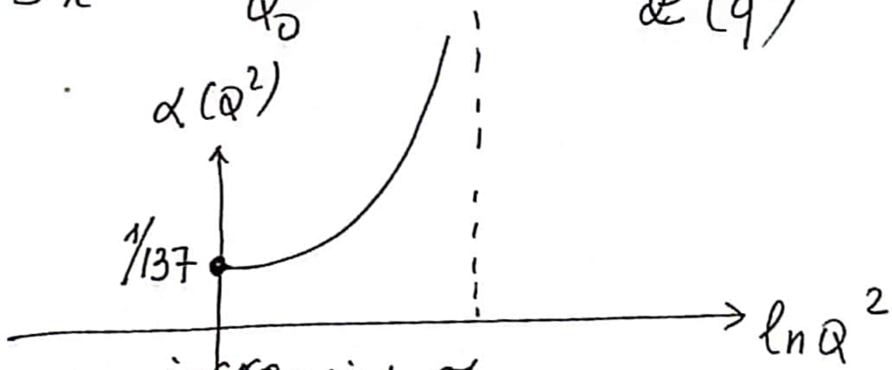


- Summation of all diagrams is equivalent to a single diagram with "running" coupling constant

$$\alpha(Q^2) = \frac{\alpha(Q_0^2)}{1 - \frac{\alpha(Q_0^2)}{3\pi} \ln \frac{Q^2}{Q_0^2}}$$



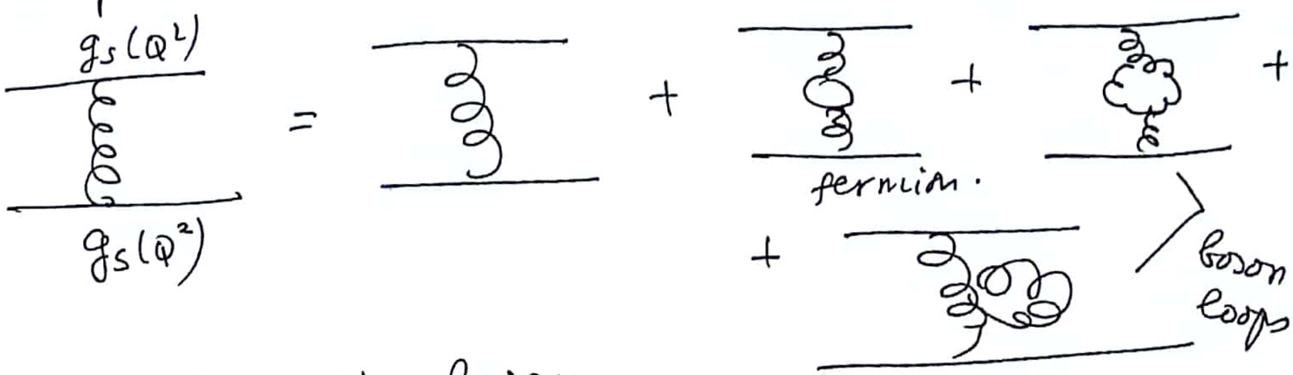
$(Q^2 \gg Q_0^2)$



- $\alpha(Q^2)$ increase with Q^2 increasing of i.e.
  - At small distance $\alpha(Q^2)$ is large
  - At large distance $\alpha(Q^2)$ is small.

Running of α_s

- Similar to QED but also have gluon loops



- Fermion and Boson loops give contributions with different sign.

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{\left[1 + B\,\alpha_s(Q^2)\ln\frac{Q^2}{Q_0^2}\right]}$$

$$B = \frac{11N_c - 2N_f}{12\pi} \qquad N_c = 3 \qquad N_f = 6$$

$$B > 0$$

- $\alpha_s(Q^2)$ decreases with Q^2;

- $\alpha_s(Q^2)$ decrease with increasing Q^2

i.e.

$\alpha_s(Q^2)$ is small at small distance
$\alpha_s(Q^2)$ is large at large distance

$\boxed{\text{Asymptotic freedom}}$

SONUC

- QCD similar to QED
- But gluon self-interactions are believed to result in color confinement
- All hadrons are color singlet which explains why only observe mesons and Baryons.

- A low energies $\alpha_s \sim 1$
  - Can't use perturbative theory
    NON perturbative regime
- α_s smaller at higher energy scales
  $\alpha_s(100\ \text{GeV}) \sim 0.1$
  - Can use perturbation theory.