Structure of Hadrons

gluons

Gluons are the exchange particles which couple to the **color charge**. They carry simultaneously color and anticolor.

What is the total number of gluons? According to SU_3, 3x3 color combinations form a singlet and an octet. The **octet** states form a basis from which all other color states can be constructed. The way in which these eight states are constructed from colors and anticolors is a matter of convention. One possible choice is:

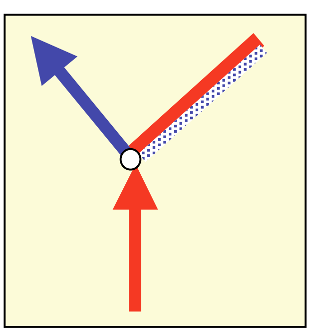
$$|R\overline{G}\rangle,\ |R\overline{B}\rangle,\ |G\overline{B}\rangle,\ |G\overline{R}\rangle,\ |B\overline{R}\rangle,\ |B\overline{G}\rangle,$$

$$\sqrt{1/2}\left(|R\overline{R}\rangle - |G\overline{G}\rangle\right),\ \sqrt{1/6}\left(|R\overline{R}\rangle + |G\overline{G}\rangle - 2|B\overline{B}\rangle\right)$$

The color singlet:

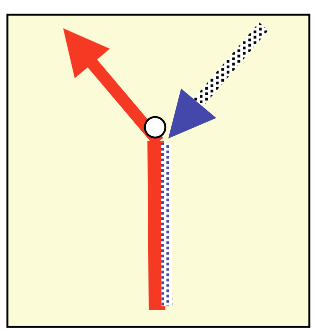
$$\sqrt{1/3}\left(|R\overline{R}\rangle + |G\overline{G}\rangle + |B\overline{B}\rangle\right)$$

is invariant with respect of a re-definition of the color names (rotation in color space). Therefore, it has no effect in color space and cannot be exchanged between color charges.



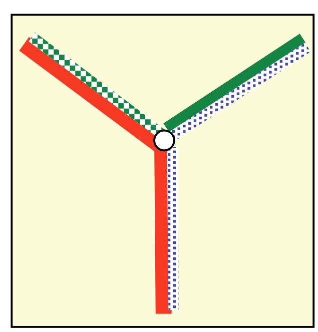
emission of a gluon by a quark

$q \rightarrow q + g$



splitting of a gluon into a quark-antiquark pair

$g \rightarrow q + \overline{q}$



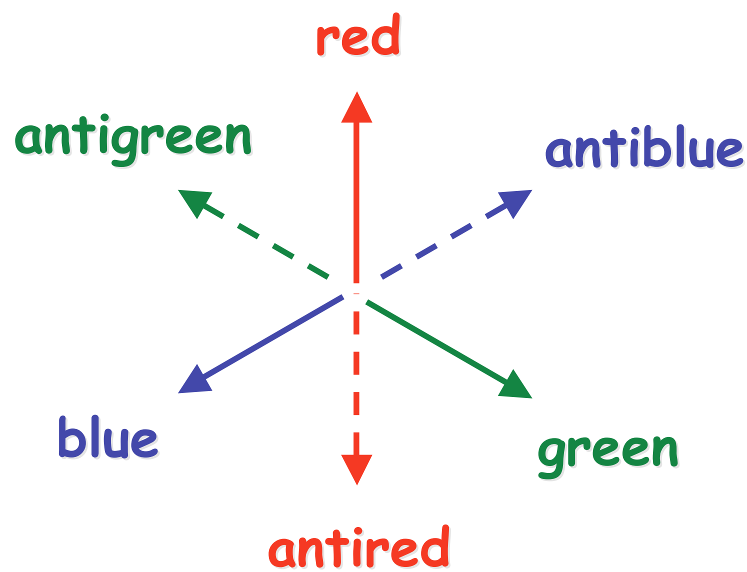
self-coupling of gluons

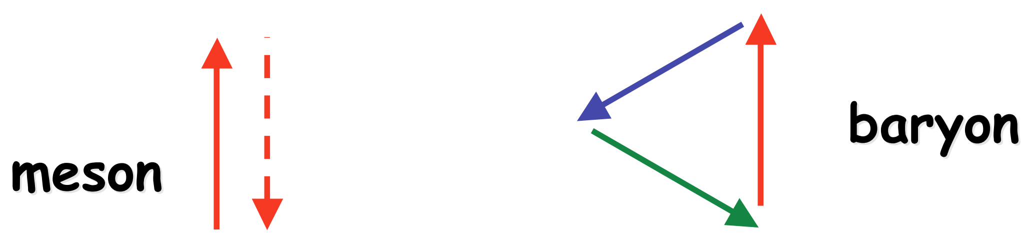
$g \rightarrow g + g$

$g + g \rightarrow g + g$

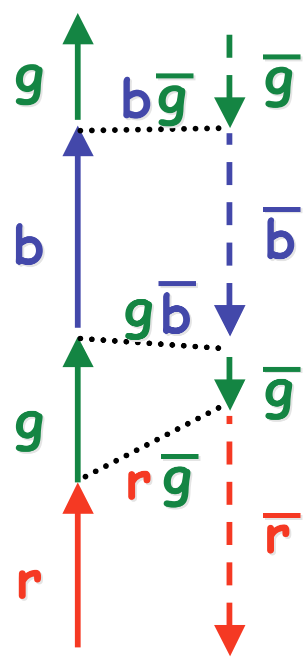
Structure of Hadrons

Hadrons as color neutral objects





$$\left|\square^{+}\right\rangle = \begin{matrix} \square & \left|u_R \bar{d}_R\right\rangle \\ \square & \left|u_B \bar{d}_B\right\rangle \\ \square & \left|u_G \bar{d}_G\right\rangle \end{matrix}$$



Meson can exist in three different color combinations. The actual pion is a **mixture** of these color states. By exchange of gluons, the color combination continuously changes.

Structure of Hadrons
QCD Lagrangian

First, QED Lagrangian...

$$\mathcal{L}_{QED} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}_e \gamma^\mu \left[\partial_\mu + ieA_\mu\right] \psi_e - m_e \bar{\psi}_e \psi_e$$

- $F_{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ EM field tensor
- A^μ four potential of the photon field
- γ^μ Dirac 4x4 matrices
- ψ_e Dirac four-spinor of the electron field
- $e = \sqrt{4\pi\alpha}, \quad 1/\alpha \approx 137, \quad \hbar = c = 1$

Now, QCD Lagrangian...

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha + \sum_{n=1}^{n_f} \bar{\psi}_n \gamma^\mu \left[\partial_\mu - igG^\alpha_\mu t_\alpha\right] \psi_n - \sum_{n=1}^{n_f} m_n \bar{\psi}_n \psi_n$$

- $G^{\mu\nu}_\alpha = \partial^\mu G^\nu_\alpha - \partial^\nu G^\mu_\alpha - gf^{\alpha\beta\gamma} G^\mu_\beta G^\nu_\gamma$ color fields tensor
- G^μ_α four potential of the gluon fields (α=1,..8)
- t_α 3x3 matrices; generators of the SU_3 color group
- $f^{\alpha\beta\gamma}$ structure constants of the SU_3 color group
- ψ_n Dirac four-spinor of the quark field (n=1,..6)
- $g = \sqrt{4\pi\alpha_s}\ (\hbar = c = 1)$ color charge

Structure of Hadrons

strong coupling constant

In quantum field theory, the coupling constant is an effective constant, which depends on four-momentum Q^2 transferred. For strong interactions, the Q^2 dependence is very strong (gluons - as the field quanta - carry color and they can couple to other gluons). A first-order perturbative QCD calculation (valid at very large Q^2) gives

$$\alpha_s\left(Q^2\right) = \frac{12\pi}{\left(22 - 2n_f\right)\cdot \ln\left(Q^2 / \Lambda^2_{\mathrm{QCD}}\right)}$$

running coupling constant!

number of quark flavors ~3-6

free parameter in QCD (0.1-0.5 GeV)

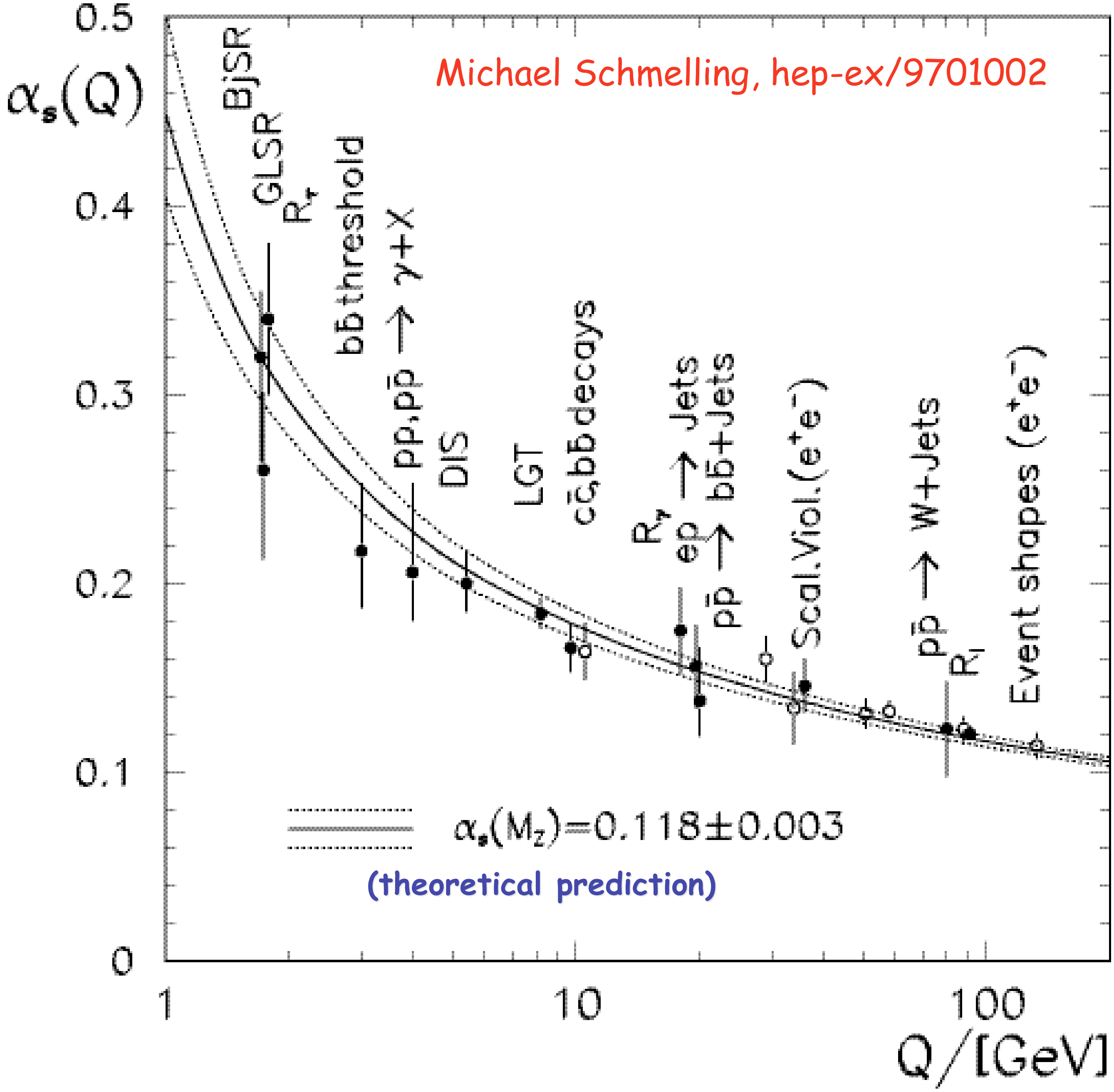
The spatial separation between quarks goes as

$$\lambda\!\!\!^{-} = \frac{\hbar}{\sqrt{Q^2}}$$

Therefore, for very small distances and high values of Q^2, the interquark coupling decreases, vanishing asymptotically. In the limit of very large Q^2, quarks can be considered to be “free” (**asymptotic freedom**). On the other hand, at large distances, the interquark coupling increases so it is impossible to detach individual quarks from hadrons (confinement).

Structure of Hadrons

strong coupling constant (cont.)

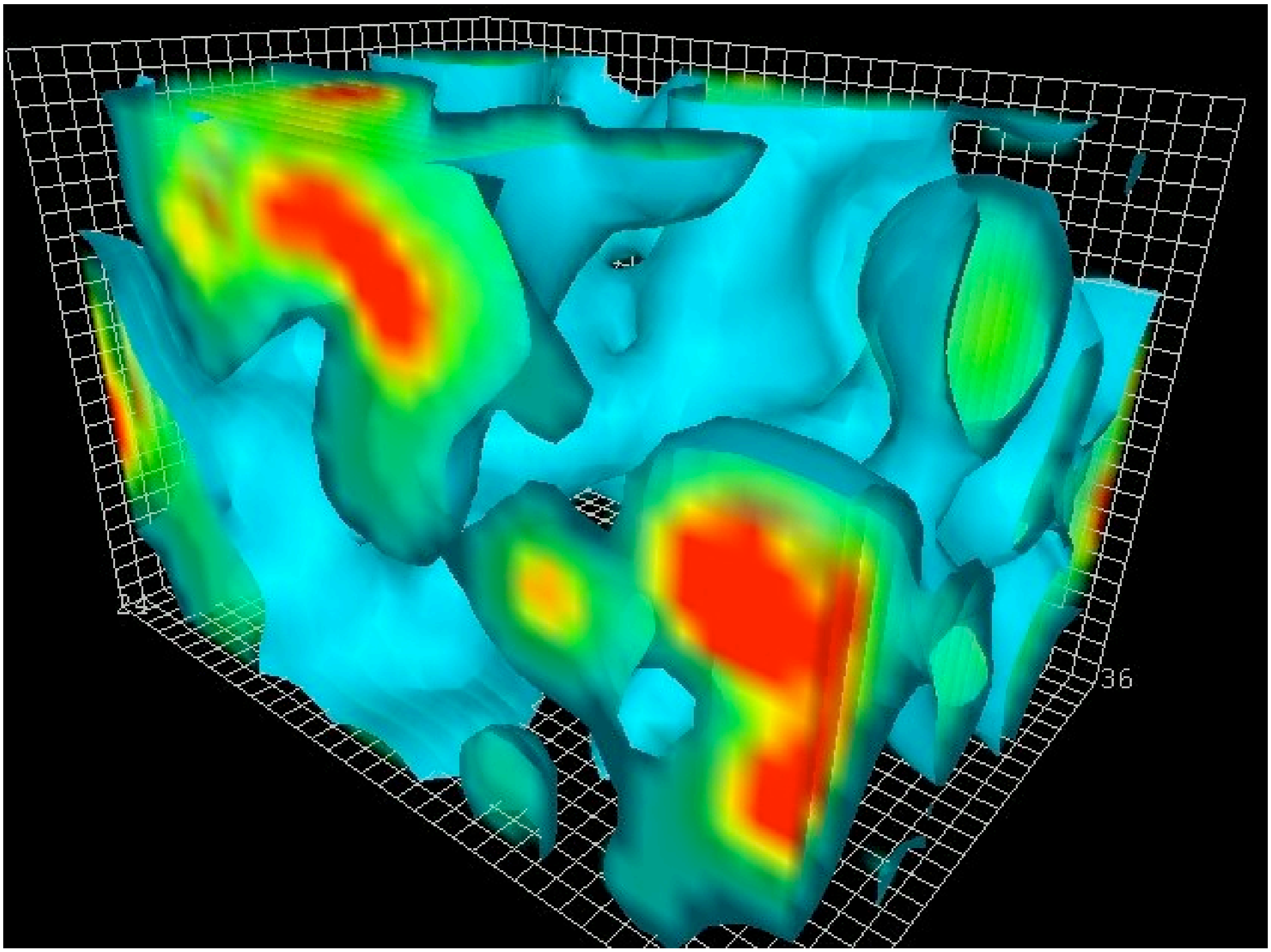


Structure of Hadrons

QCD vacuum

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/QCDvacuum/

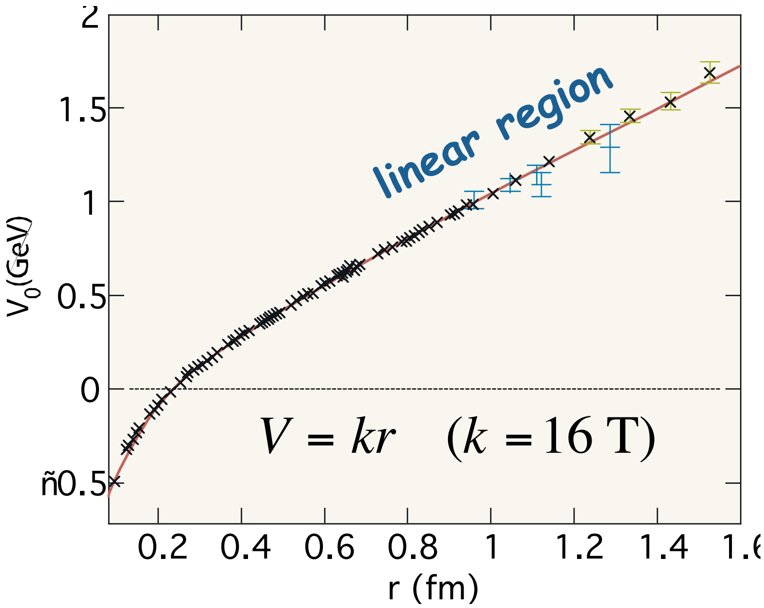
The quantum fluctuations of the QCD vacuum. The images have been created via supercomputer simulations of QCD on a $24^3 \times 36$ space-time lattice using a 128-node Thinking Machines CM5 (D.B. Leinweber, Adelaide)



According to the Standard Model, all space is filled with the QCD condensate. The interaction of particles with this background condensate gives rise to most of the mass that makes up "ordinary" hadronic matter. The computer simulation shown here is a snapshot of the gluon field that binds quarks together to make up particles such as protons and neutrons. The red color indicates areas of intense "action" in the gluon field, associated with winding of the field lines. The green and blue colors correspond to weaker gluon field strengths.

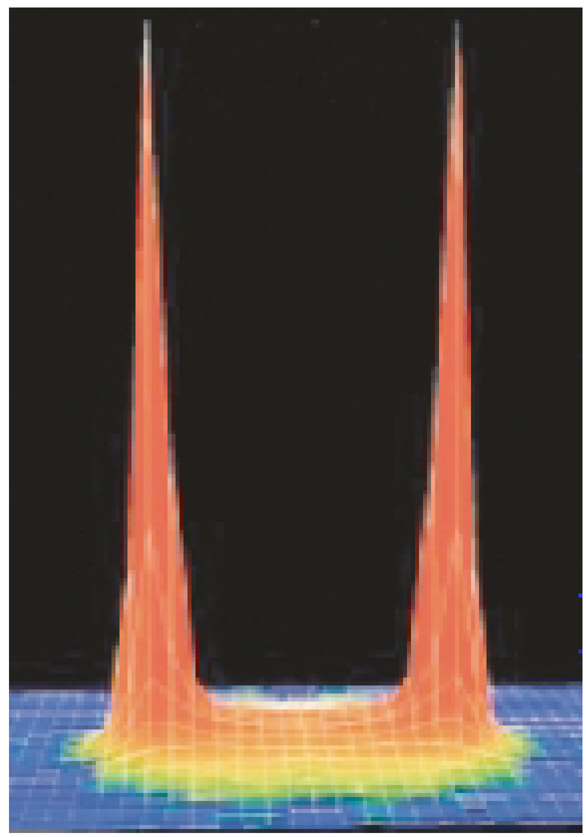
Structure of Hadrons

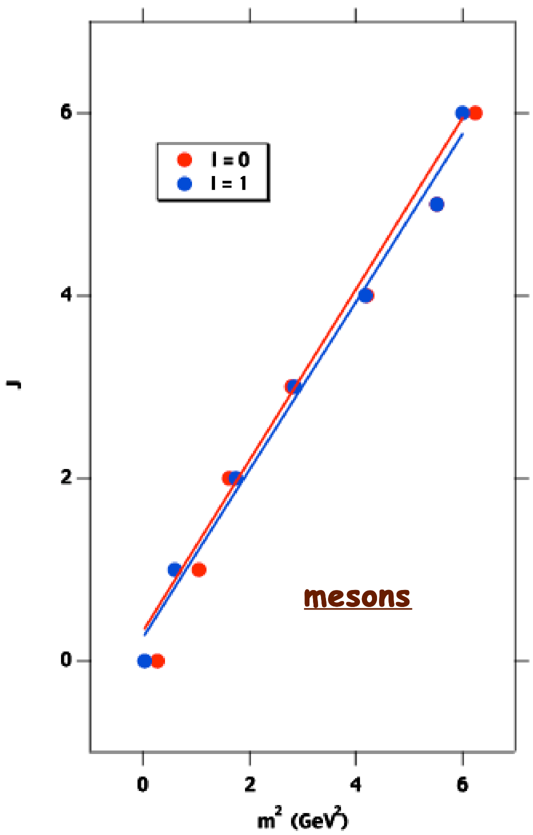
Fields of Color



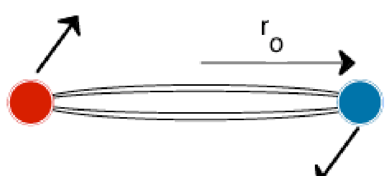
Lattice “measurement” of the quenched static potential

Bali et al.





Regge trajectories (suggested by Nambu 1970)



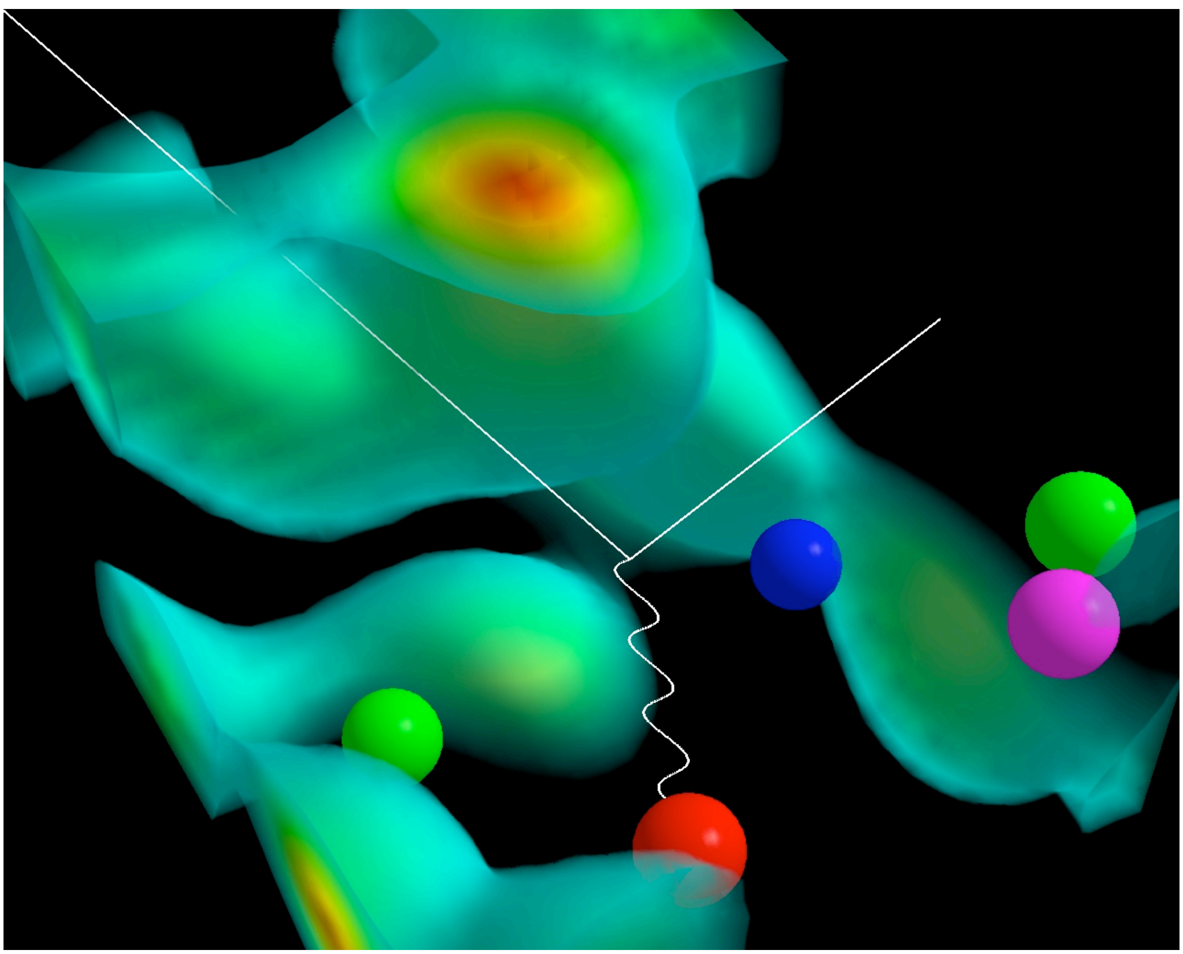
flux tubes/strings

Structure of Hadrons

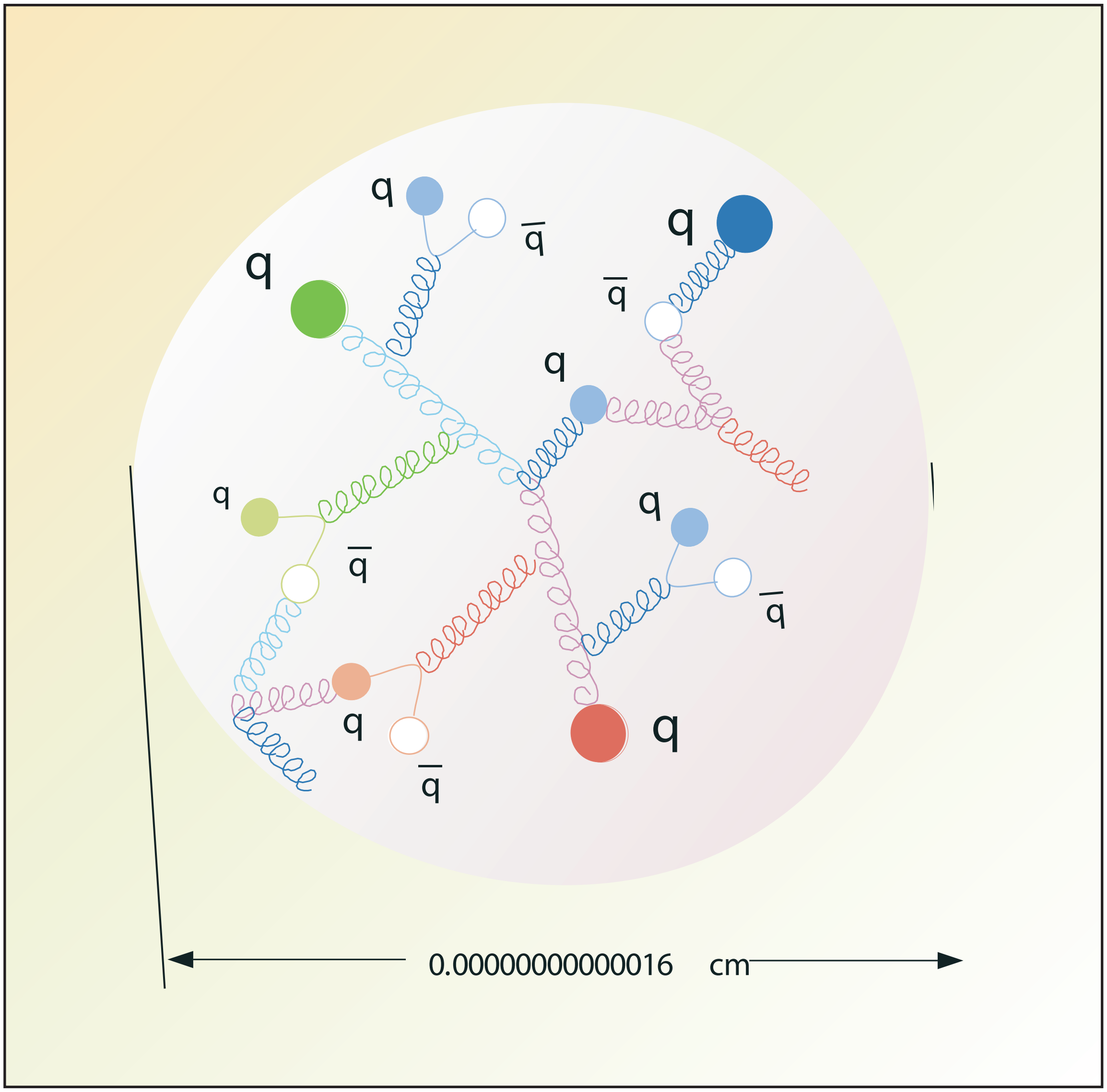
Structure of the proton

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/QCDvacuum/

- Three quarks indicated by red, green and blue spheres (lower left) are localized by the gluon field.
- A quark-antiquark pair created from the gluon field is illustrated by the green-antigreen (magenta) quark pair on the right. These quark pairs give rise to a *meson* cloud around the proton.
- The masses of the quarks illustrated in this diagram account for only 3% of the proton mass. The gluon field is responsible for the remaining 97% of the proton's mass and is the origin of mass in most everything around us.
- Experimentalists probe the structure of the proton by scattering electrons (white line) off quarks which interact by exchanging a photon (wavy line).



THE NUCLEON



Inside the nucleon. Within the theory of QCD, the nucleon has a complex internal structure, consisting of three valence quarks (large dots), which are continually interacting by the exchange of gluons (depicted as springs in this schematic picture). In contrast to the photons that are exchanged between electric charges, gluons interact not only with the valence quarks, but also with each other, creating and destroying gluons and quark-antiquark pairs (small dots).