8 Confinement

Λ_{QCD} sets a natural scale in the theory. Well above Λ_{QCD} perturbation theory makes sense. Of course perturbative QCD at large enough energies describes a world of quasi-free quarks, interacting with Coulomb-like forces. We know very well that hadronic physics is a very different world with quarks are confined into colorless hadrons. As soon as $q^2 \sim \Lambda^2_{QCD}$ perturbation theory is unreliable. It simply cannot explain confinement.

What does confinement actually mean? One popular interpretation is that 'it is not possible to detect an isolated quark or gluon'. The problem with this definition of confinement is that in electromagnetism, which is certainly "not confining", it is not possible to detect an isolated electron either. Electromagnetism (as well as Quantum Chromodynamics) is long-range (mediated by a massless particle) and plagued (just as QCD) with infrared divergences. Both QED and QCD observables have to be inclusive enough. There is one difference, of course, and that is that photons have no $U(1)$ charge, while gluons do carry $SU(3)$ charges. Far away from the interaction point you can hope to be able to measure the electric charge carried by one particle (or rather what the experimental resolution defines as a particle which is actually the electron surrounded by a cloud of soft photons), but even if you were able to construct a detector that measured color you probably would not be able to identify in any way the color of the quark itself.

In fact, there is another definition of confinement that tells to you that the chances of actually seeing a (gluon-dressed) quark are small: 'there is a force between quarks that does not decrease with distance'. There is indeed phenomenological evidence (which is supported by lattice analysis) that the interquark potential in QCD is of the form

$$V(r) \sim a\Lambda^2_{QCD} r - \frac{b}{r} + \ldots \tag{166}$$

The first term is a confining quark potential. The constant a has to be ~ 1 because Λ^2_{QCD} is the only dimensional quantity at our disposal. The Coulombic part is called the Lüscher term and plays a crucial theoretical role even if it is not very important in heavy quark spectroscopy in practice.

We like this second definition of confinement better, because the first one is far too imprecise. In order to see that it is useful to recall a toy example suggested by Georgi. Imagine a world in which we tune Λ_{QCD} in such a way that $\alpha_s(1\text{GeV}) = 1/137$. Since the coupling constant is so small, perturbation theory works wonderfully at such energies. The proton would be a bound state of quarks (bound by Coulomb-like forces that is) with mass roughly $3m_q$. Its size would be dictated by the Bohr radius, about 1000 times the size it has in our world. The inhabitants of this world would certainly not understand the first definition of confinement. The reason is that using

$$\alpha_s(\mu) = \frac{-\pi}{\frac{\beta_1}{2}\log\frac{\mu^2}{\Lambda^2}} \tag{167}$$

we obtain that the confinement radius would be $\sim \Lambda^{-1} \sim 10^{21}$cm. They would see quarks as you see electrons.

Even in our world the situation is somewhat similar to that of the toy world for very heavy quarks. Indeed $\alpha_s(m_t)$ is small (say ~ 0.1). The Bohr radius is $r_0 \sim 10^{-2}$ fm, much smaller than Λ_{QCD}^{-1}. The coulombic part of the interquark potential largely dominates. (At such short distances the linearly rising potential is not at work, the leading confinement effects are $\sim r^3$, as discussed by Leutwyler some time ago, but they can be safely neglected at first approximation.)

Bottom and charm are in a somewhat intermediate position. $\alpha_s(m_b)$ is still relatively small. The Bohr radius is 10^{-1} fm, smaller but comparable to Λ_{QCD}^{-1}. Spectroscopy is basically perturbative, at least for the lowest levels, but some non-perturbative effects are visible. Charm is really no-man's land. Both perturbative and non-perturbative effects compete even for the ground state $n = 1$. For light quarks the Bohr radius is several fm and the confining potential is fully at work.

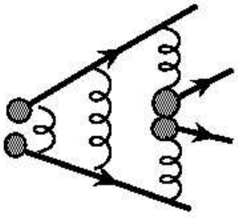

Figure 10: The QCD string.

The existence of a confining potential leads to very large multiplicities and jets. One can imagine a quark-antiquark being formed at a primary vertex then moving apart. Part of their kinetic energy is deposited in the interquark potential as they move away. Very quickly a separation r_m is reached where the energy deposited is enough to form a new quark-antiquark pair,

$$\Lambda_{QCD}^2 r_m \simeq 2m_q, \tag{168}$$

at that moment the quark-antiquark 'string' breaks and the process is repeated until the average relative momentum is small enough and hadronization takes place.

There is a lot of physics in the string picture. We can think of color forces being confined in some sort of tube or string joining the two moving quarks. The chromodynamic energy is thus stored in a relatively small region of space-time. If this picture is correct we should expect hadronization to take place in this region in preference to any other. This is indeed the case; in three jet events (which originate from $\bar{q}qg$, with a hard gluon) there is a clear enhancement of soft gluon and hadron production in the regions between color lines (representing the gluon by a double color line, or $\bar{q}q$ state), and a relative depletion in other regions. This phenomenon is called color coherence.