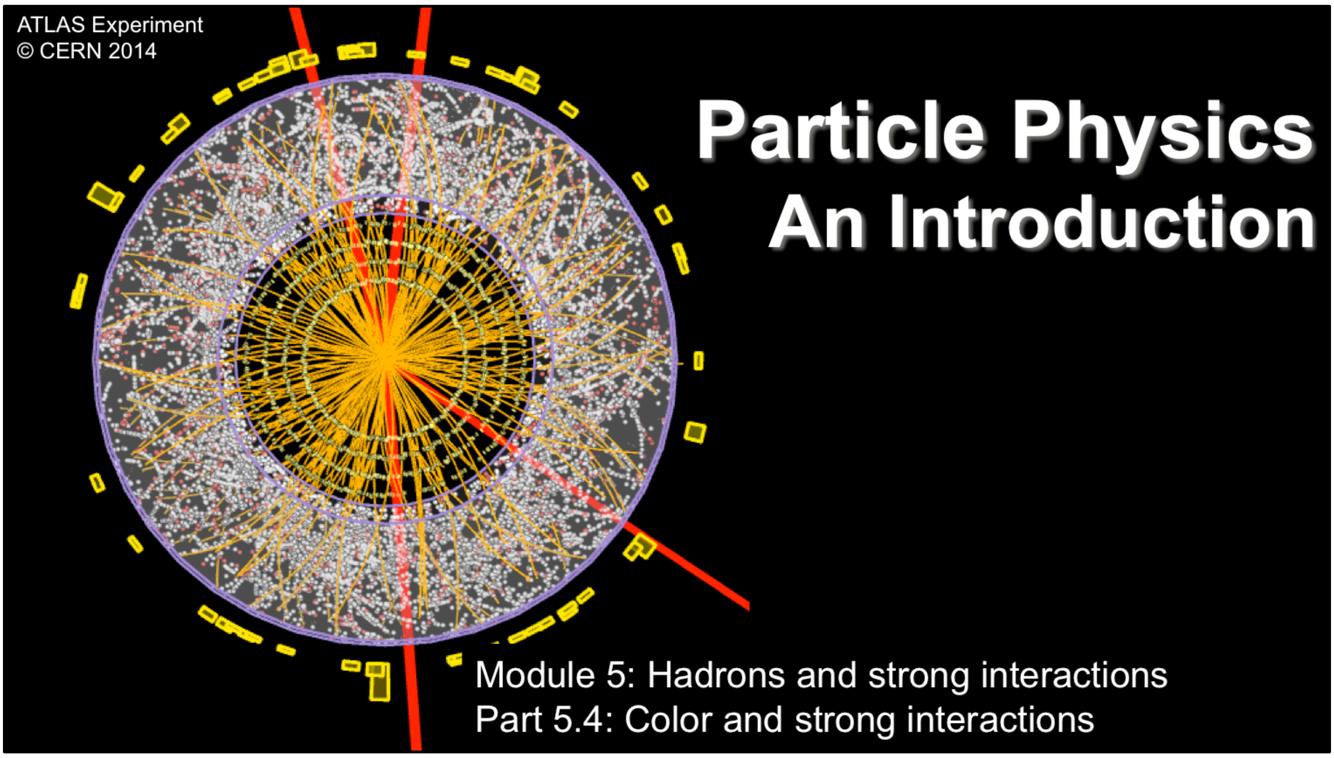


In this fifth module we are discussing the structure of hadrons and strong interactions.

We have seen several times that the strong interactions have special properties. Quarks behave as almost free particles at short distances inside hadrons. Nonetheless, free quarks have never been observed outside hadrons. This indicates that the strong force confines them within bound states and does not allow to separate them to large distances. In this 4th video we qualitatively discuss these seemingly incompatible properties.

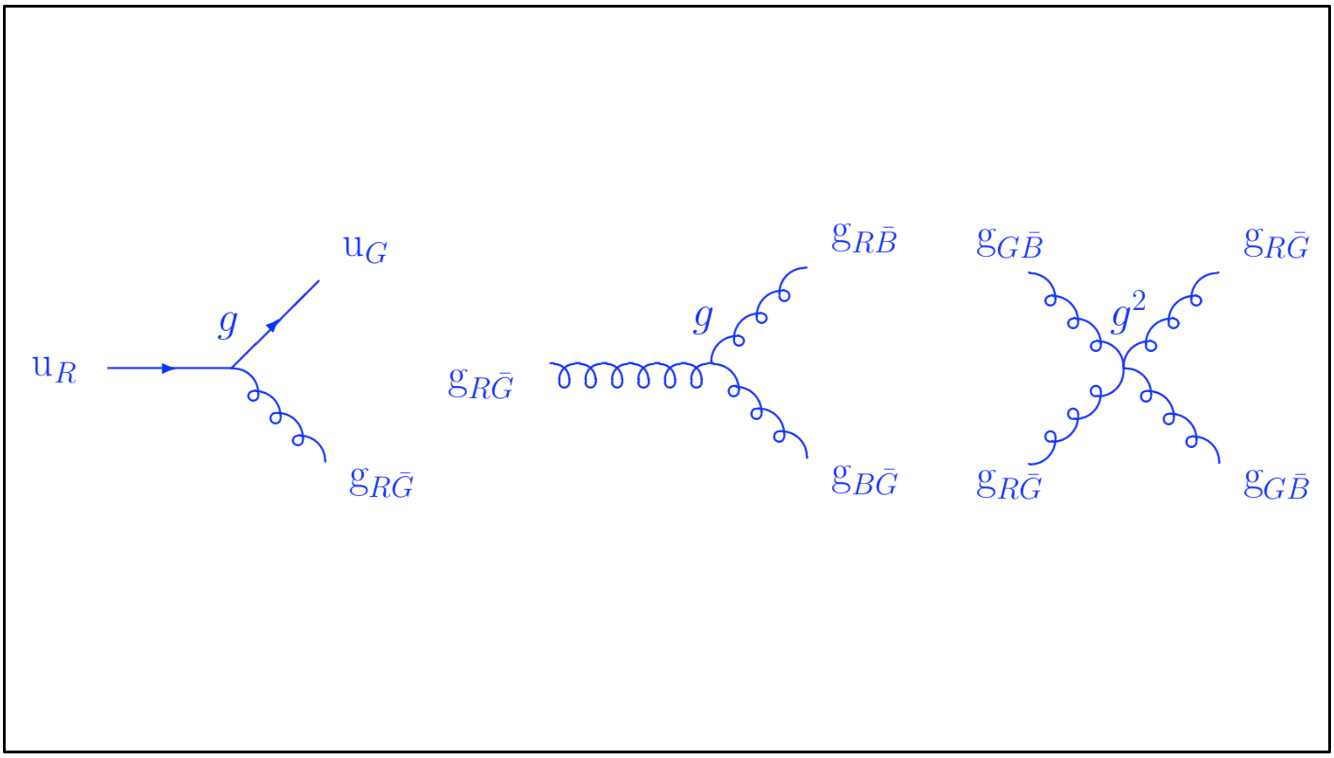
After following this video you will know:

- The main properties of strong interactions, including its different vertices in Feynman diagrams;
- Color charge, gluons and their role in binding quarks together;
- Vacuum polarization for electromagnetic and strong interactions.

- Colors red R, green G, blue B; anti-colors $\bar{R}$, $\bar{G}$, $\bar{B}$
- Quarks carry one color : u_R, u_G or u_B, antiquarks $\bar{\mathrm{u}}_{\bar{R}}$, $\bar{\mathrm{u}}_{\bar{G}}$ or $\bar{\mathrm{u}}_{\bar{B}}$
- Gluons carry a combination of color and anti-color:

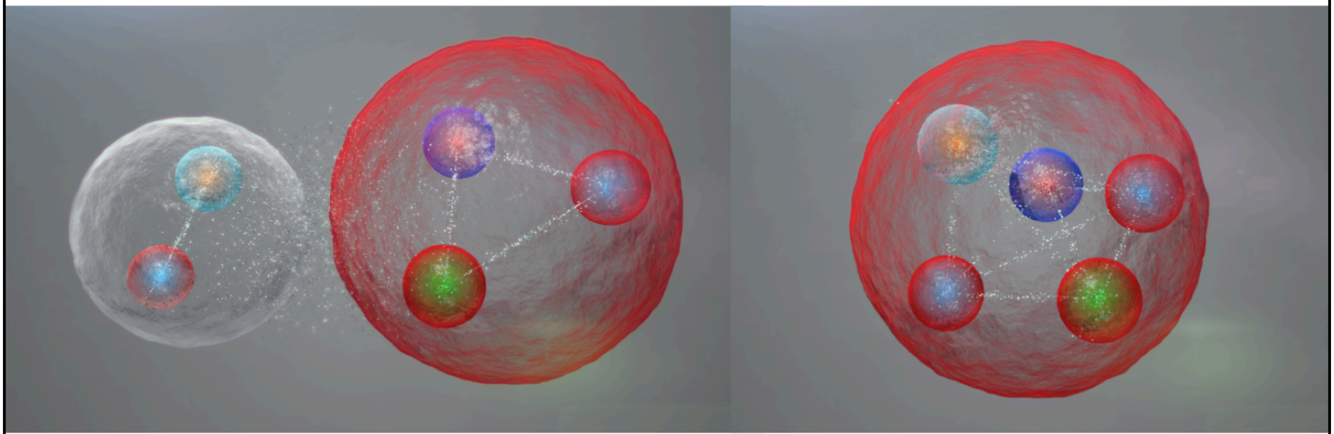
$$R\bar{G}, R\bar{B}, G\bar{B}, G\bar{R}, B\bar{R}, B\bar{G}, \frac{1}{\sqrt{2}}(R\bar{R} - G\bar{G}), \frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B})$$

- We already introduced the **three-component color charge** in video 1.1 as a quantum numbers of quarks. We also saw its immediate consequence to triple the cross section for $e^+ e^- \rightarrow$ hadrons in video 4.5.
- Color is the quark property responsible for their strong interactions. The formal theory of these interactions is **quantum chromodynamics, QCD**.
- Color can take **three different values**, say, red, blue and green for quarks. We indicate it by a lower index when appropriate. A quark can carry only one non-zero color. Antiquarks carry one anti-color.
- The interactions between quarks proceeds through the **exchange of color**. The intermediate vector bosons transmitting the strong force are the eight **gluons**, g. They carry **a color and an anti-color** and therefore are not color-neutral. This is in contrast to the photon, which couples to the electromagnetic charge, but does not carry one itself. For strong interactions there are eight gluons in total.
- With three colors and three anti-colors, one would expect a total of 3^2 combinations. One of them, the fully symmetric combination, (R R-bar + G-G-bar + B B-bar) has **no net color**. It thus does not participate in strong interactions and cannot be produced.
- The remaining eight **gluons are vector bosons,** they are electromagnetically neutral and have zero mass.



- The **basic vertex** of the strong quark interactions changes the color of a quark. The **coupling constant *g*** appearing at the vertex enters into the cross section through its square $\alpha_s = g^2/4\pi$, in analogy to the electromagnetic fine structure constant α.
- The interaction has the **same strength for the three colors** or any of their superpositions. So there is invariance under an overall rotations in color space. According to Noether's theorem, this requires **a conservation law for color**, the vertex conserves color. The corresponding amplitude is also **independent of the flavor of quarks** and their **electromagnetic charge**, which are both ignored and conserved by strong interactions.
- If **gluons** carry color, they should be able to **interact among themselves**. Because they carry even color and anti-color, there are two additional vertices. The color indices indicated here are only examples.
- The **three-gluon vertex** is proportional to *g* and has the same strength as the quark-gluon vertex. We must, in each calculation, consider the fact that there are many more different colors for gluons than for quarks. The **vertex with four gluons**, on the contrary, is proportional to g^2 and thus disfavored with respect to the others.

© CERN



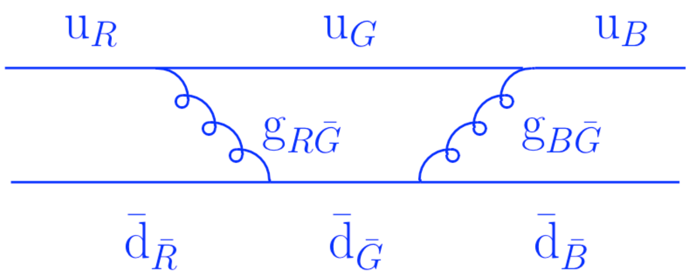
Meson + Baryon

Pentaquark

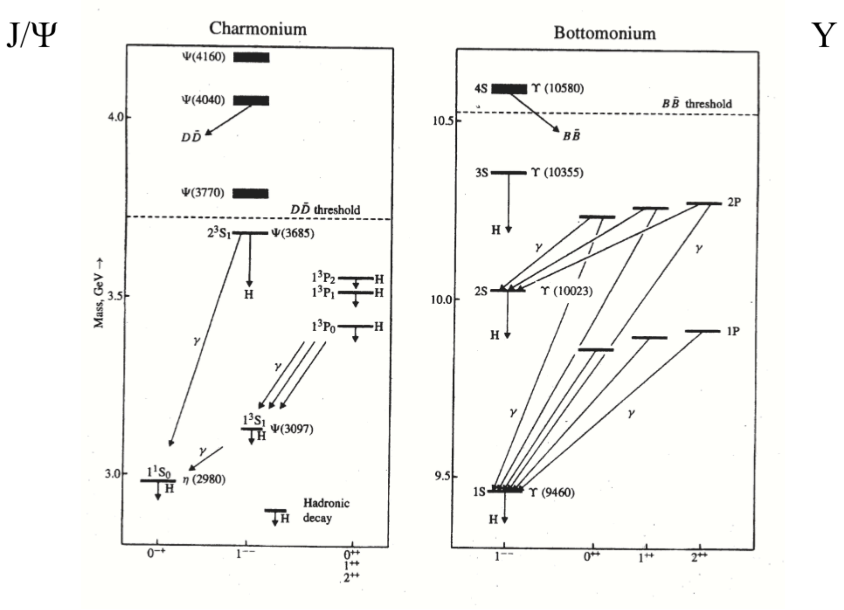
https://physics.aps.org/synopsis-for/10.1103/PhysRevLett.117.082003

http://phys.org/news/2016-07-physicists-family-tetraquarks.html

- Color does not show up as a quantum number in our characterization of **hadrons**, they **are white**. So far, all established mesons are q-q-bar states and all established baryons are three-quark states of neutral color.
- Recently, the LHCb collaboration has discovered two charmed **pentaquark** states, consisting of 5 quarks. However it is still unclear whether these are bound baryon-meson states, as shown on the picture on the left, or genuine compact multi-quark states as sketched on the right. LHCb has also confirmed the existence of a **tetraquark** state first observed by the Belle collaboration in Japan. Again the same reservation applies: it could still be a meson-meson bound state.



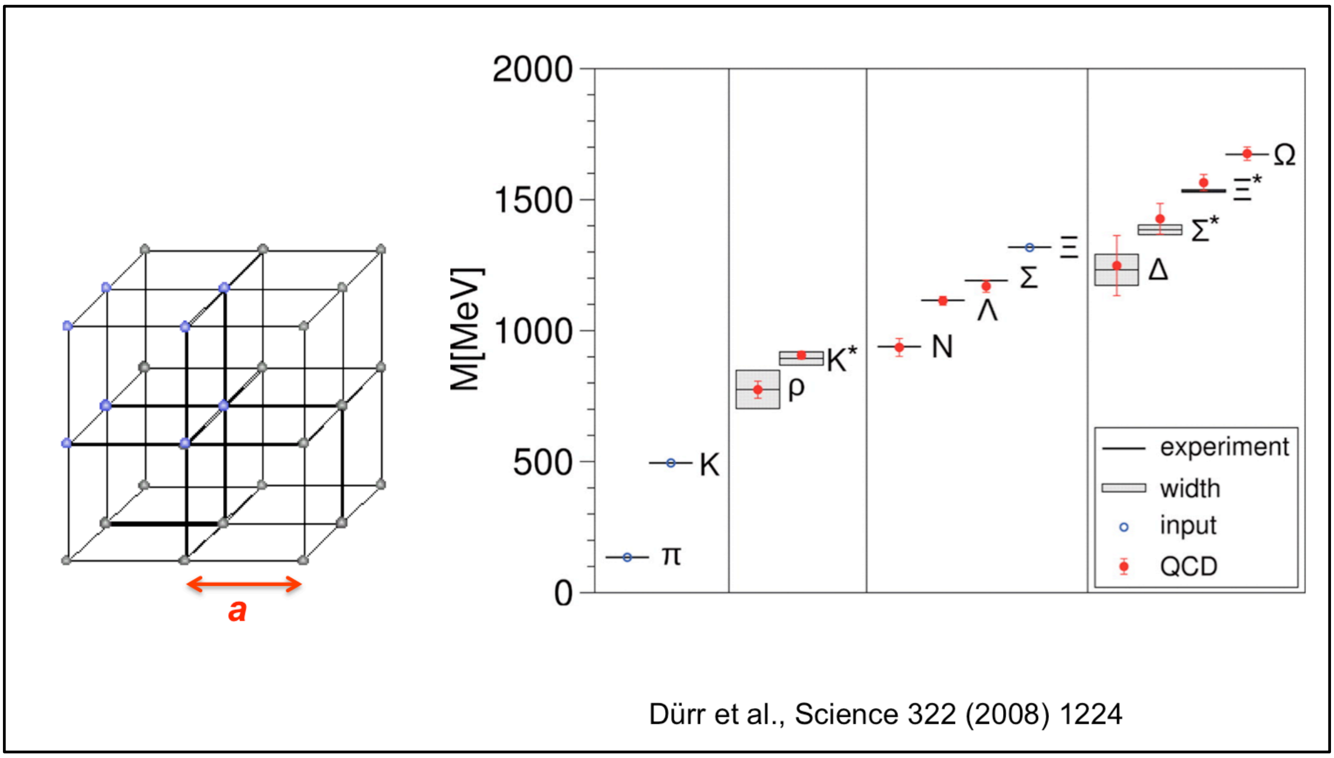
- Mesons contain a superposition of **quark-antiquark pairs**, with all colors in equal proportions. An snapshot is shown here for the interior of a π^+.
- **Gluons** are constantly exchanged between quarks to maintain binding, changing the color of quarks as in this sketch, while keeping the overall hadron white. The same mechanism works inside baryons.
- **Between hadrons**, for example in a nucleus, objects of neutral color are exchanged to create binding, except at very short distances.
- It follows that an *ab initio* description of the **nuclear force** stays very difficult, although we dispose of a well established quantum field theory for the interaction between quarks and gluons, namely QCD.



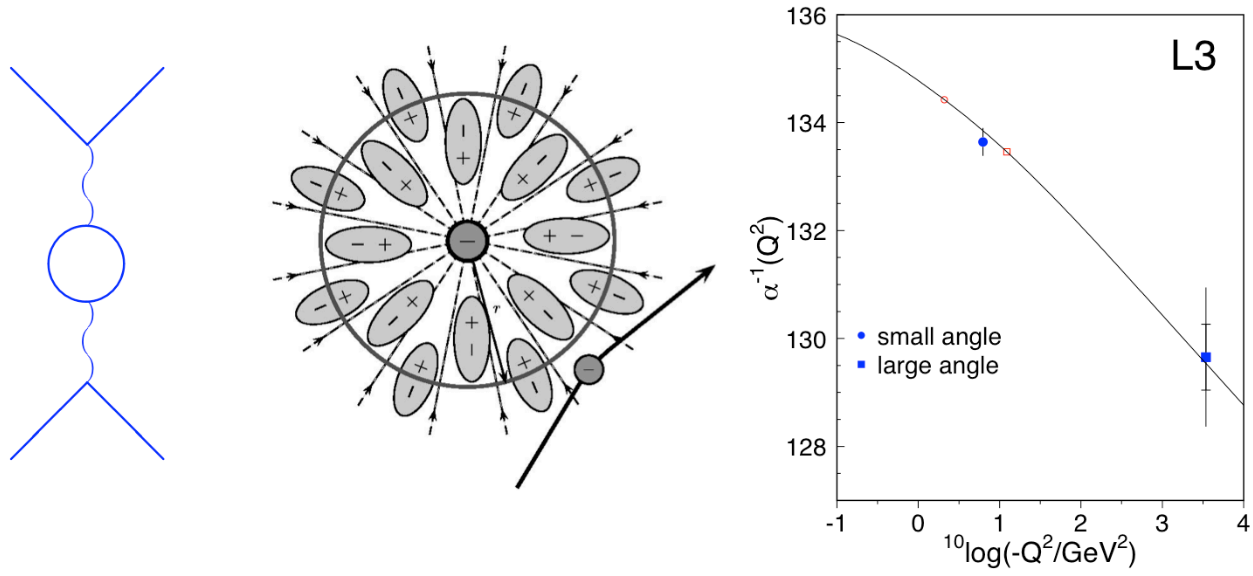
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$
$$\alpha_s \simeq 0.2$$

D.H. Perkins, Introduction to High Energy Physics, Cambridge University Press, 2000

- At **short distances** comparable to the hadron size, the exchange of gluons produces a potential between quark and anti-quark, which is similar to the one established by photons in a positronium bound state. This potential varies with distance as *1/r*, like the Coulomb potential.
- At **larger distances**, there is a different behavior: the potential becomes larger with distance. We already saw a potential that fits the description of the spectra of J/Ψ and Y states in video 5.3.
- The second term determines the behavior of the long-range potential with a constant $k \approx 1$ GeV/fm. This corresponds to a **constant long distance force** equivalent to the one required to lift a weight of 16 tons!
- The second term is created by the **interaction between gluons**. In terms of a chromostatic language, the additional force between gluons concentrates the color field along a corridor that connects the two color charges. Because of the particular shape of the field, one also calls this a **string** that connects the colors. The potential ~*kr* does not allow color and anti-color to be separated, but confines them to distances of the order of 1 fm.

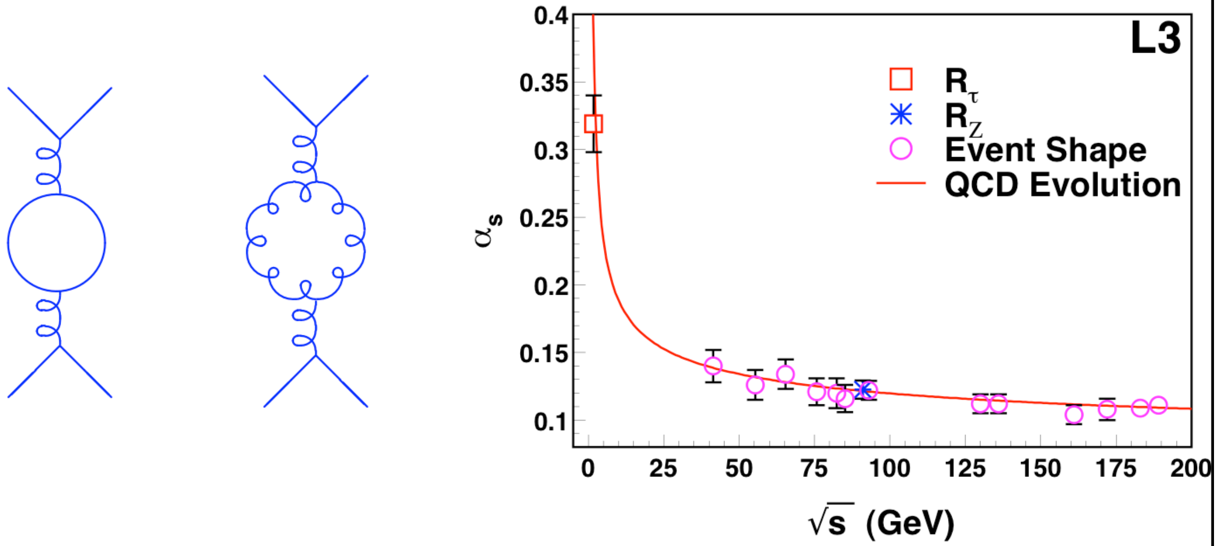


- The potential inside hadrons ought to be generated **dynamically** by the interaction between quarks and gluons.
- Obtaining results is complicated by difficulties which are both **conceptual and technical:**
    - Both the **confinement** of color at large distance and the relativistic and **quasi-free movement** of quarks must be incorporated.
    - One must treat states with **multiple quarks and gluons**.
    - The evolution of the **strong coupling constant** α_s with four-momentum transfer q^2 must be taken into account. We'll talk about this effect in a moment.
- Calculation techniques are considerably simplified if one replaces the space-time continuum by a **mesh of equidistant discrete points**, similar to a crystal lattice with cell size a. One defines the quark fields on the sites of the lattice, gluon fields on the links. The continuous space-time is recovered in the limit of an infinitely large lattice with $a \rightarrow 0$. The discretization introduces a lower limit on momentum transfer of the order of $1/a$ and thus regularizes the divergences inherent in perturbative QCD.
- **Numerical calculations** of this kind require tremendous computing resources, they are performed on the most powerful supercomputers.
- With this non-perturbative method one arrives for example at results for the **spectrum of light hadrons**. The calculated masses are the average for the different particle types, like $M_N = (M_p + M_n)/2$. Parameters of the calculation are the strong coupling constant α_s and the masses of light quarks, $m_u = m_d$ and m_s. They are fixed using the measured masses of π, K and Ξ as reference. This results in a pretty impressive understanding of the hadron spectrum, suggesting that QCD is indeed the correct theory for strong interactions also at larger distances.



L3 Collab., M. Acciarri et al., Phys.Lett. B476 (2000) 40.

- **Distance laws** for electromagnetic and strong interactions are fundamentally different:
    - The electromagnetic potential decreases as *1/r* at any distance;
    - The strong potential increases at long distances proportional to *r*.
- To understand this difference we must consider **quantum corrections** to the **photon and the gluon propagators**.
- A significant correction to the photon propagator is the one, which introduces an **electron-positron loop**. This loop creates additional electric charges between the projectile and target. We call this phenomenon vacuum polarization. In electrostatic language we can say that these additional charges **screen the target charge**.
- Therefore, the **effective charge decreases with distance**, i.e. it increases with growing momentum transfer q^2. This is indeed what we find experimentally.
- For electrodynamics this is a **small effect**. To see a change of α of a few percent, we have to compare momentum transfers of almost zero (very large distances), where $\alpha \approx 1/137$ is measured (see the example of the Penning Trap in video 4.3), to energies of the Large Electron-Positron Collider at CERN, $q^2 \approx 10^4$ GeV^2 (very short distances).



L3 Collab., M. Acciarri et al., Phys.Lett. B489 (2000) 65

- For **strong interactions**, the effect of vacuum polarization is much more pronounced. Because of the very size of the strong coupling, the vacuum polarization and the change in the net charge with distance are more important. In addition, the sign of the effect is reversed: the **strong force becomes stronger with distance**.
- This is because there are two types of vacuum polarization graphs for gluons. The analogue of the electromagnetic polarization introduces **quark-antiquark loops** in the gluon propagator, which **shield the color charge**.
- But in addition, the coupling of gluons between them introduces **gluon loops**, which have the opposite sign. In a chromostatic language we could say that the gluons loops introduce additional color-anticolor charges, which are attractive. **This reinforces the color charge** of the target instead of shielding it.
- Because of the large number of gluons and their zero mass, **gluons loops dominate** the strong vacuum polarization.
- Consequently, the **color charge of the target increases with distanc**e, proportional to the inverse of the momentum transfer. Indeed, one experimentally finds that this effect is more significant than its electromagnetic counterpart.

- In the next video we'll see how these properties of strong interactions keep us from seeing free quarks.