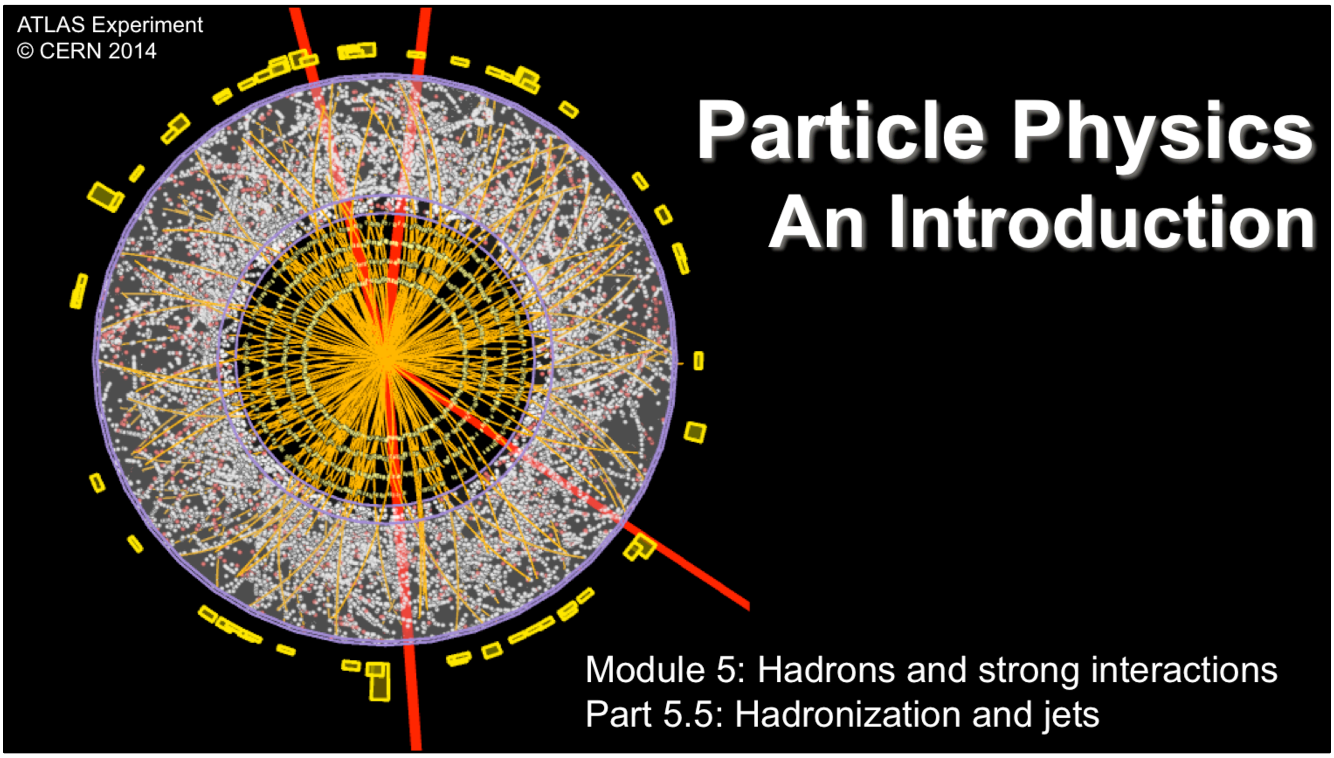
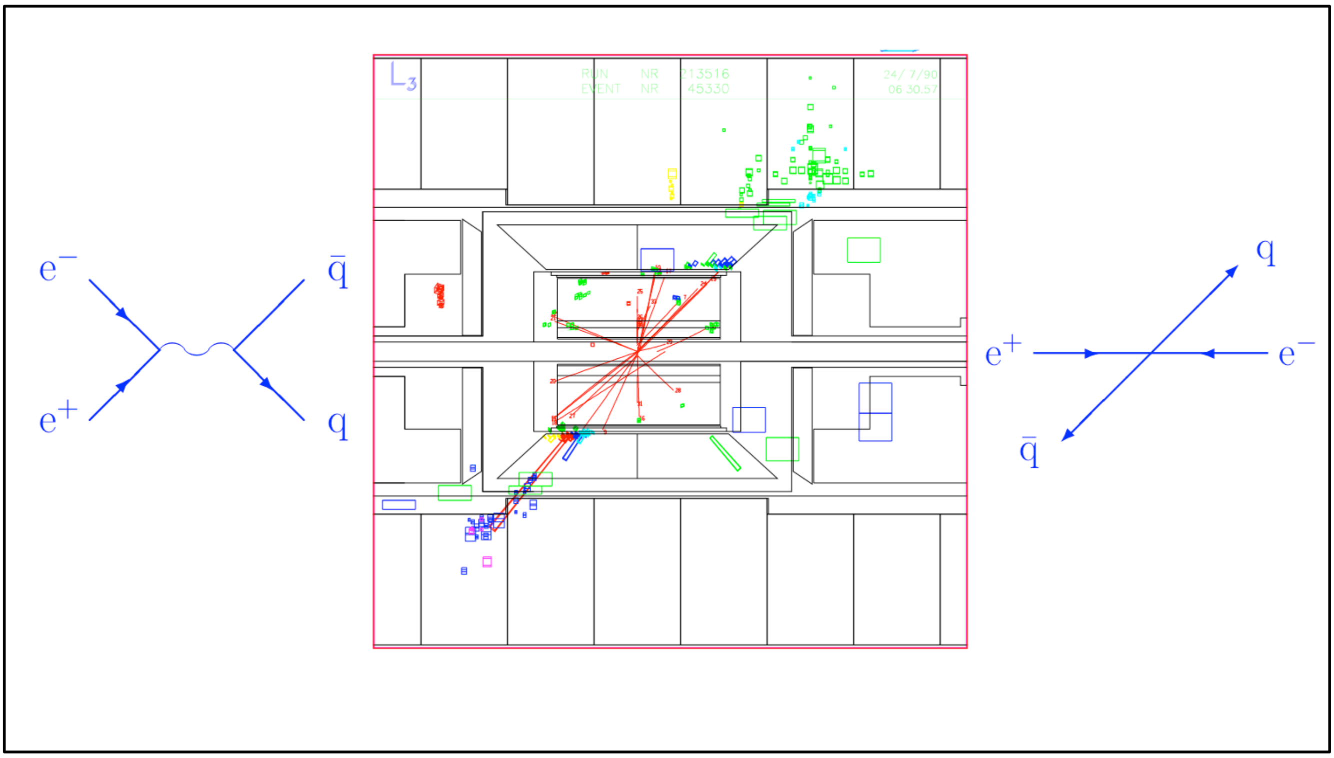


In this fifth module we are discussing the structure of hadrons and strong interactions.

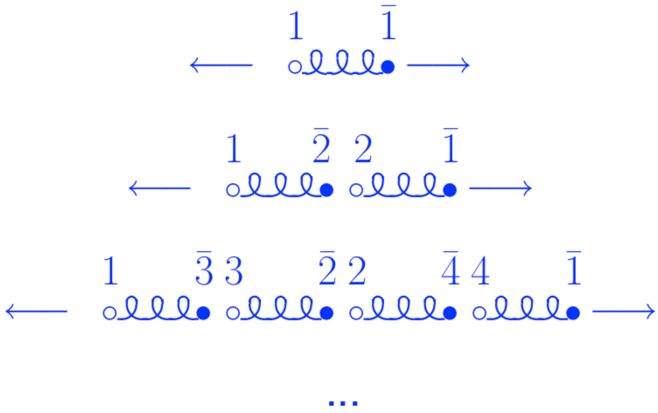
In this 5th video, we will examine the consequences of the fact that strong interactions become stronger with distance.

After having watched this video, you will understand:

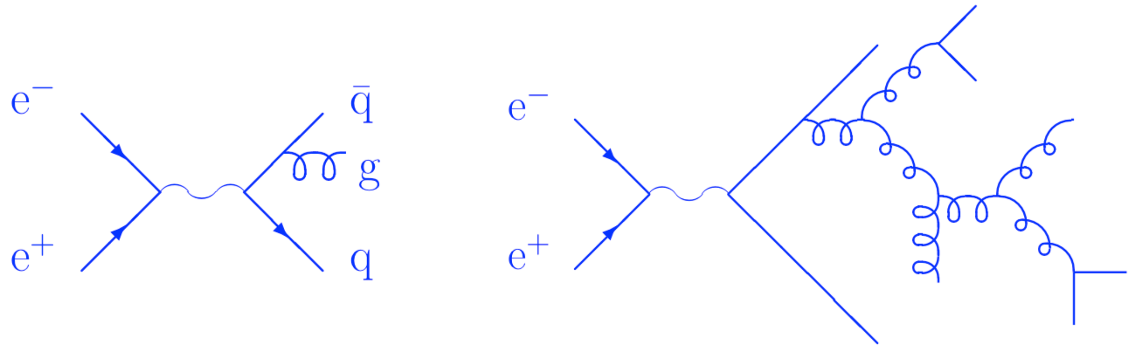
- Why one cannot observe free quarks;
- What happens when a quark-antiquark pair is created *in vacuo*.



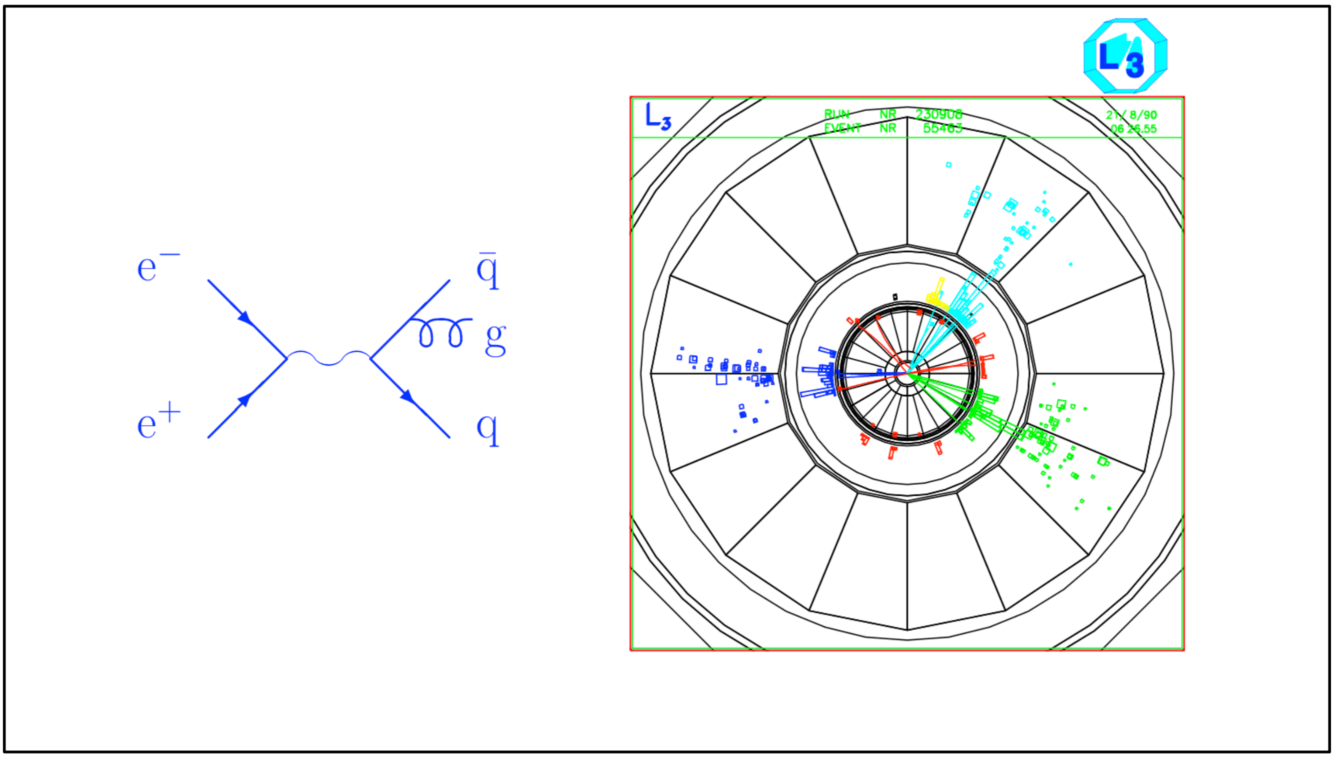
- Because of the enormous amount of energy stored in a **color field** at large distances, separated color charges will create **additional particles** instead of becoming free quarks or gluons. A dynamic separation occurs for example in the **e^+e^- annihilation into quark-antiquark pairs** at high energies, far above threshold.
- The left figure shows the Feynman diagram, the right figure the kinematics in the center-of-mass frame. The central figure is an example of an event of this kind, showing **multiple hadrons in the final state**.
- Again there are two approaches to qualitatively understand the process of hadron formation in the final state, a **chromostatic** one and a **chromodynamic** approach.



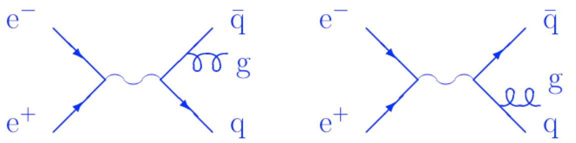
- In the **chromostatic approach**, the quark-antiquark pair creates further quark-antiquark pairs as soon as the original pair is separated by of the order of 1 fm. At this distance, the **stored field energy** is large enough to do this.
- This process continues until the relative momentum of the quarks is sufficiently moderated to permit the **formation of bound states**.
- Hadron formation occurs along "**strings**", a kind of elastic band connecting color charges, thus with limited transverse momenta. The hadrons thus form **jets**, which approximately follow the initial direction of the quark and the antiquark.



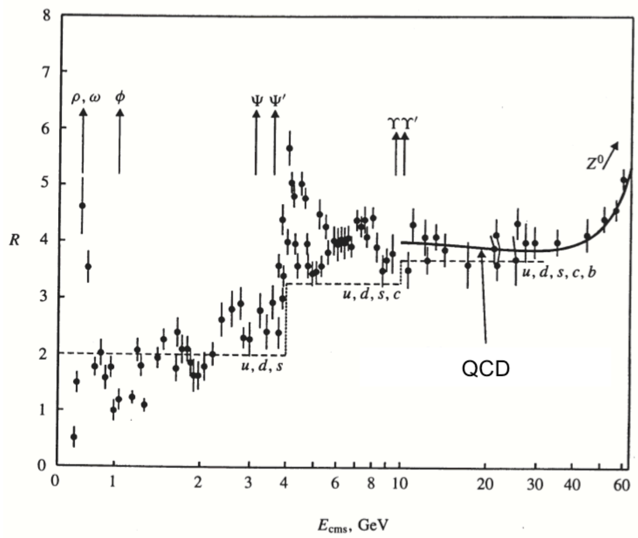
- In a more **chromodynamic** approach, the process can be visualized in terms of a **quark-gluon cascade.**
- It starts with the **emission of a gluon** by the quark or the antiquark.
- This gluon can produce either a quark-antiquark pair, or a pair of gluons, according to the elementary vertices of QCD. Because there are more gluons that quarks, **splitting into gluons** is more probable.
- The **strong coupling** will become the larger, the more the invariant mass q^2 of the virtual particles involved diminishes. At the end of the cascade, the quarks will form **colorless bound states**.
- It is clear that this approach can not be used up to the end of the **hadronization process**. At small q^2, the coupling constant become so large, that a perturbative expansion in powers of the coupling constant will no longer converge.
- In this domain, collective effects take over, which will end up by the formation of mesons and baryons. They must be described by **phenomenological models**.



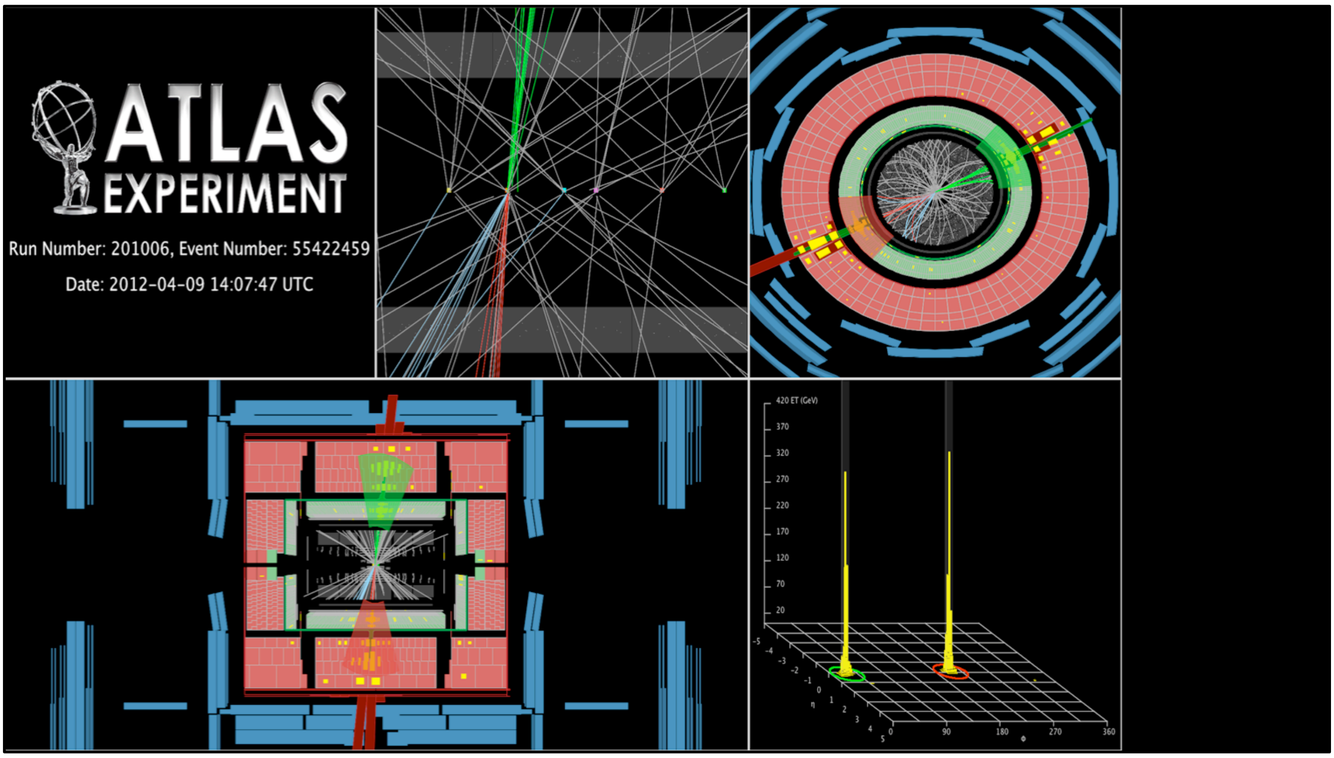
- The hadrons are formed ***in vacuo*** at the end of the quark-gluon cascade, their **transverse momenta** with respect to the original quark direction are thus limited by Heisenberg's principle to some 300 MeV. Hadrons are thus concentrated around the initial quark direction and form **jets**. Their transverse momentum is small and independent of the quark momentum. Thus jets become **more and more collimated** as the quark energy increases.
- If the **first gluon** emitted in the cascade has sufficient transverse momentum with respect to the natural width of jets, a **third hadron jet** will become visible along the gluon direction. One thus observes an event with **three jets**, as shown on the right. These events can be attributed to the reaction $e^+ e^- \rightarrow$ q q-bar g.



$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq 3 \sum_i Q_i^2 \left(1 + \frac{\alpha_s}{\pi}\right)$$



- The **cross section** for the process $e^+ e^-$ ➔ q q-bar g is calculated using the Feynman diagrams shown.
- The gluon emission from a quark has all the characteristics of a **bremsstrahlung process**. Its amplitude has two **divergences**: it becomes very large for the emission of a low energy gluon, which is an **infrared divergence**; it also blows up for a very forward emission, by a **collinear divergence**. In both cases, the quark and gluon jets will merge.
- Two- as well as three-jet events are counted among the hadronic final states. In the calculation we must thus add their cross sections to obtain the **total hadronic cross section** we introduced in video 4.5.
- One thus obtains a better approximation for the **ratio R** at high energies, in better agreement with the experimental data.



- **Jets** appear without exception, whenever a high energy quark or gluon converts into hadrons.
- This means first of all that the **probability of the hadronization process** is 1, it is inevitable.
- Second, the conservation of energy-momentum and the limitation of transverse hadron momenta by Heisenberg's principle mean that **jets follow the direction and represent the energy of the initial quark or gluon**. And this with a more and more **narrow collimation** as the energy increases.
- This event picture shows a final state with **two energetic jets** produced in a **proton-proton collision** at the LHC. On the top you see a zoom on the inner detector and the calorimeters. On the left, you see multiple vertices; the high luminosity of the collider causes **multiple reactions** at the same bunch crossing.
- The two regions with most of the deposited energy, colored in red and green, show **two back-to-back jets** which are strongly collimated. The bottom image on the right shows a histogram of the directional distribution of energy; the two narrow peaks correspond to the direction and energy of the two jets.

- This concludes our short discussion of strong interactions. In the next module, we will deal with weak interactions and the Higgs mechanism.