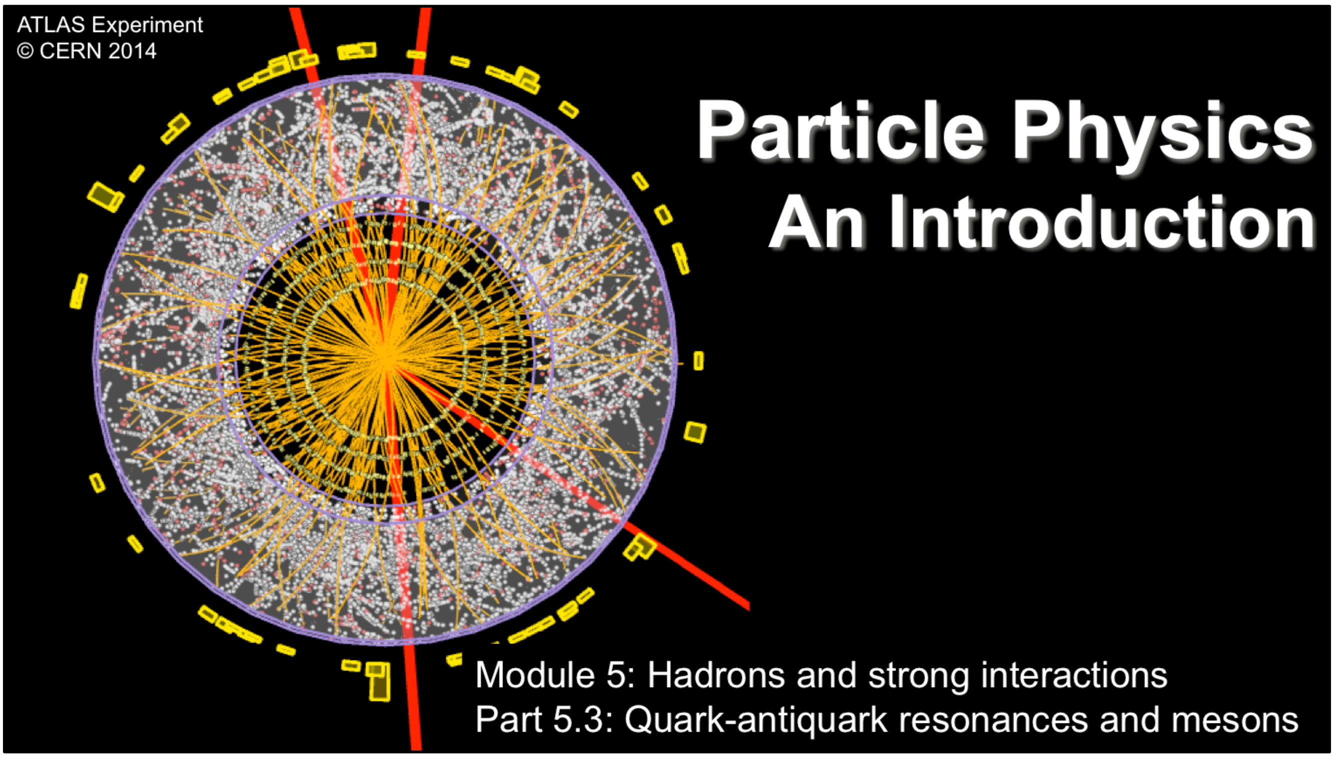
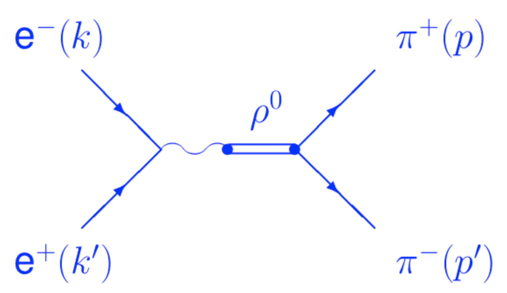


In this fifth module we are discussing the structure of hadrons and strong interactions.

In this 3rd video we discuss mesons, bound states between quarks and antiquarks.

After following this video you will know:

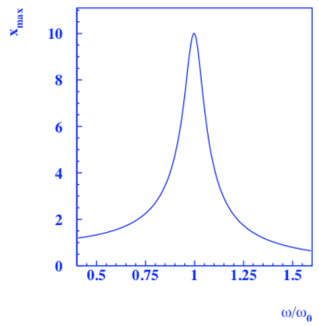
- The basic mechanisms that bind quarks and antiquarks, to form mesons;
- Their excited states and their spectra, which provide information about the nature of the binding force.

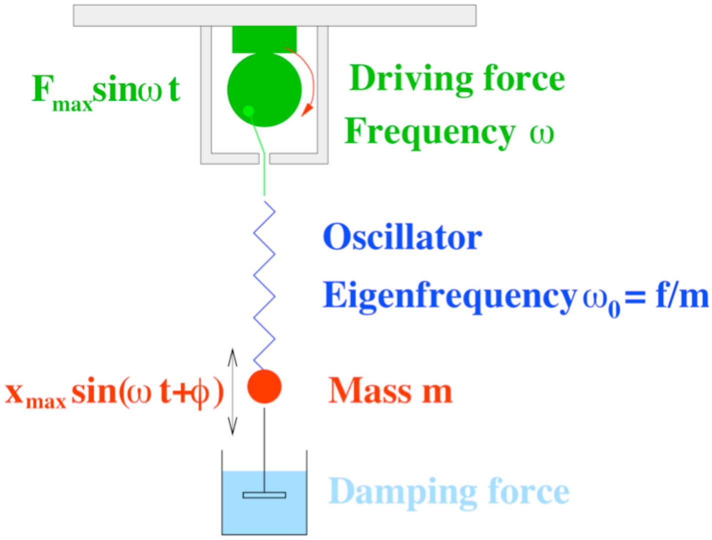


- In addition to the baryons and their resonances, which we treated in the previous video, there are **bound states between quarks and antiquarks, called mesons**. If their quantum numbers are right, they can be produced *in vacuo* by a virtual photon. An example is the production process of the ρ meson, a bound state between light quarks.
- For light quarks, their **mass** is dominated by the binding energy. For heavy quarks, their mass is slightly lower than the sum of masses of the corresponding quark.
- Resonances can also appear as intermediate states in **hadronic reactions**. In this case, there is more freedom regarding their quantum numbers.
- In general, bound states between quarks and anti-quarks have a rather **short life time**, especially if heavy quarks are involved. This is due to the substantial phase space available for their decay.

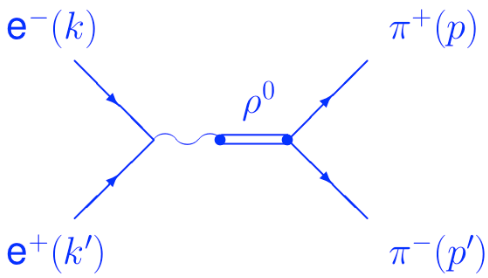
$$\sigma(\sqrt{s}) = \sigma\text{max}\frac{\Gamma^2/4}{(\sqrt{s}-M)^2+\Gamma^2/4}$$

$x^2_{max} \leftrightarrow$ cross section





- The energy dependence of the electron-positron cross section around a resonance generally follows a **Breit-Wigner function** shown here.
- *M* is the mass and *Γ* the width of the resonance. The cross section is reduced to half of its maximum value for $\sqrt{s} = M \pm \Gamma/2$. The **life time** of the resonance is $\tau = 1/\Gamma$.
- The form of the Breit -Wigner function resembles the squared amplitude of a **classical damped oscillator**. $\sqrt{s}$ corresponds to the frequency of the external periodic force, *M* to the resonance frequency and *Γ* to the damping factor. The cross section in this analogy appears as the squared amplitude of the oscillation.

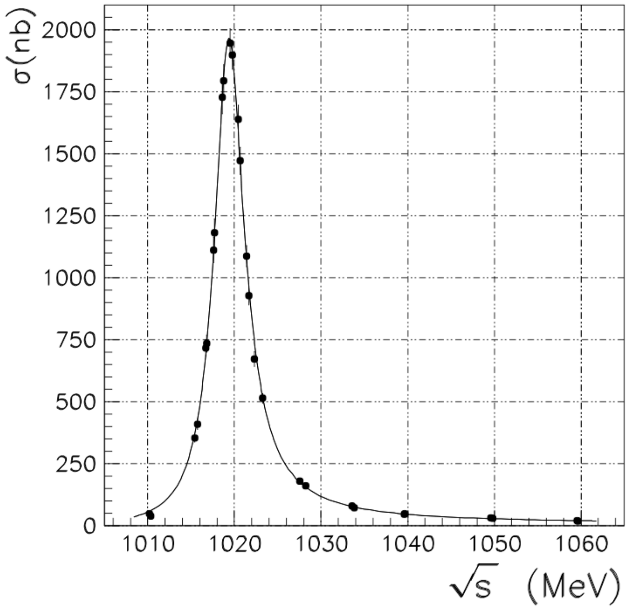


Particle name	Particle symbol	Antiparticle symbol	Quark content[3]	Rest mass (MeV/c^2)	Mean lifetime (s)	Commonly decays to (>5% of decays)
Charged rho meson[4]	$\rho^+(770)$	$\rho^-(770)$	$u\bar{d}$	775.4 ± 0.4	$\sim 4.5 \times 10^{-24}$	$\pi^\pm + \pi^0$
Neutral rho meson[4]	$\rho^0(770)$	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.49 ± 0.34	$\sim 4.5 \times 10^{-24}$	$\pi^+ + \pi^-$

https://en.wikipedia.org/wiki/Rho_meson

- For **resonances between light quarks**, such as ρ and ω, one observes widths from a few MeV to 150 MeV, corresponding to lifetimes between 10^{-22}s and 10^{-24}s.
- They are produced in a resonant manner by the intermediate photon, when the mass of the virtual photon is sufficiently close to that of the meson. When produced this way, they must obviously have **spin 1 and charge 0**. They decay into pions.

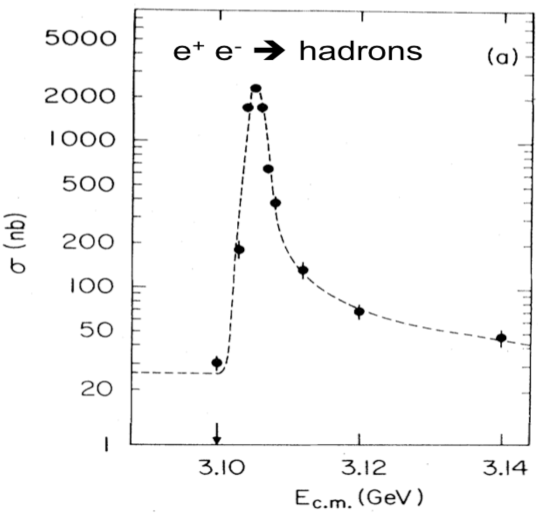
$$\phi \to K^+K^-, K^0\bar{K}^0$$



M.N. Achasov et al., Phys.Rev. D63 (2001) 072002

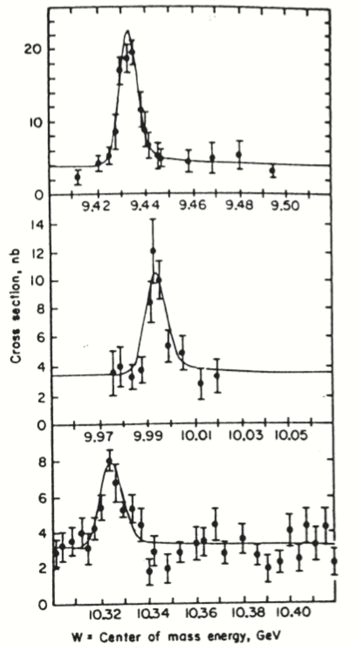
- Around a mass of about 1 GeV, one can produce the ϕ resonance, a **s-s-bar bound state**, which decays into strange particles. Its width is narrow, of the order of 4.4 MeV.

J/Ψ



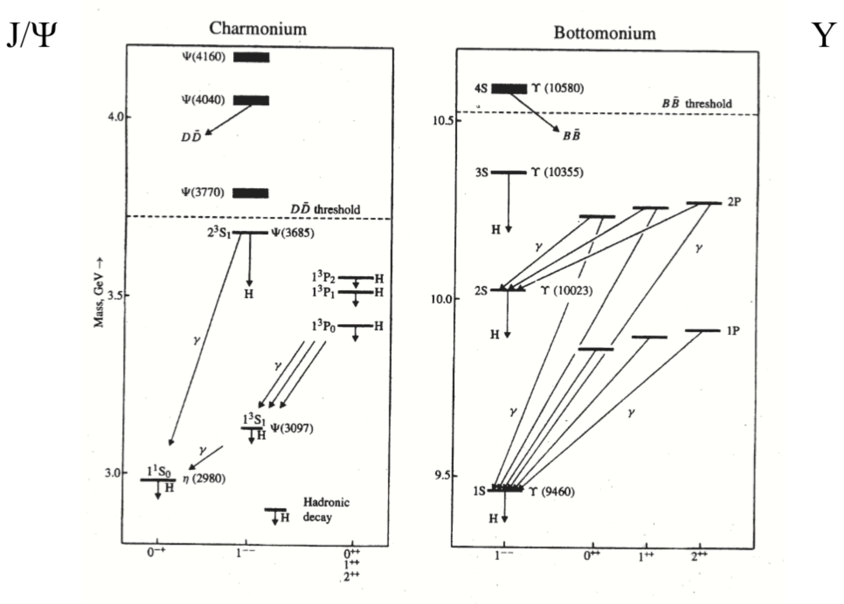
J.-E. Augustin et al., Phys. Rev. Lett 33 (1974) 1406

Y



D. Andrews et al., Phys. Rev. Lett. 45 (1980) 219

- Around 3 GeV, we find the **J/ψ resonance**, a **c-c-bar bound state,** as well as its excited states, the ψ mesons. Their widths are small, ~90 keV for J/ψ. Their **lifetime** is thus long and the $e^+ e^- \rightarrow$ hadrons **cross section is significantly enhanced** around the resonance energy, as shown in the left plot.
- Close to 10 GeV the **Y resonances** are produced, made of **b-b-bar pairs**. We see on the right the $e^+ e^- \rightarrow$ hadrons cross section around the Y(1s) resonance and its excited states Y(2s) and Y(3S), all mesons formed by b-b-bar pairs. The states are distinguished by the relative angular momentum of the two quarks. The spins are always parallel to produce a vector meson.



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

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

- The study of **resonant states**, especially those of heavy quarks, allows to better understand the **potential** generated by the strong force that binds quark-antiquark pairs in mesons, as well as the decay mechanisms for heavy quarks.
- As an example, the figure shows the **mass spectrum and decay scheme** of c-c-bar and b-b-bar resonances.
- The energy levels indicate that the potential between two quarks has **two terms**. The parameter $\alpha_s \approx 0.2$, is the strong interaction analogue of the electromagnetic fine structure constant. The first term **diminishes with distance**. The second term, on the contrary, **grows with distance** and keeps the two quarks from being separated. The constant in this confining term is $k \approx 1$ GeV/fm.
- In video 5.4 we will discuss in more detail the properties of the strong interactions, which provide the binding force.

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	Mean lifetime (s)	Commonly decays to (>5% of decays)
Charged rho meson[23]	$\rho^+(770)$	$\rho^-(770)$	$u\bar{d}$	775.11 ±0.34	$(4.41 \pm 0.02) \times 10^{-24}$	$\pi^{\pm} + \pi^0$
Neutral rho meson[23]	$\rho^0(770)$	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.26 ±0.25	$(4.45 \pm 0.03) \times 10^{-24}$	$\pi^+ + \pi^-$
Omega meson[24]	$\omega(782)$	Self	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	782.65 ±0.12	$(7.75 \pm 0.07) \times 10^{-23}$	$\pi^+ + \pi^0 + \pi^-$ or $\pi^0 + \gamma$
Phi meson[25]	$\varphi(1020)$	Self	$s\bar{s}$	1 019.461 ±0.019	$(1.54 \pm 0.01) \times 10^{-22}$	$K^+ + K^-$ or $K^0_S + K^0_L$ or $(\rho + \pi) / (\pi^+ + \pi^0 + \pi^-)$
J/Psi[26]	J/ψ	Self	$c\bar{c}$	3 096.916 ±0.011	$(7.09 \pm 0.21) \times 10^{-21}$	See J/ψ(1S) decay modes (http://pdg.lbl.gov/2014/listings/rpp2014-list-J-psi-1S.pdf)
Upsilon meson[27]	$\Upsilon(1S)$	Self	$b\bar{b}$	9 460.30 ±0.26	$(1.22 \pm 0.03) \times 10^{-20}$	See ϒ(1S) decay modes (http://pdg.lbl.gov/2014/listings/rpp2014-list-upsilon-1S.pdf)

https://en.wikipedia.org/wiki/List_of_mesons

- The peaks of the cross section around resonances invite to build **storage rings** for the mass production of the corresponding states.
- The collider **DAFNE** in Frascati/Italy is one such factory, dedicated to the production of ϕ resonances.
- The Beijing Electron Positron Collider **BEPC** produces J/ψ mesons.
- The **PEP-II** collider in the United States and **KEK-B** in Japan are factories for the Y and other b-b-bar mesons.
- The systematic decrease of the width with the mass of the resonance could make us believe that a **t-t-bar resonance** would be very narrow, and thus have a long life time and a significant cross section. This however is not the case at all.
- The top quark is so heavy, ~ 175 GeV, that the phase space for its decay becomes enormous. The **t quark lifetime is thus extremely short**, it decays before it can even form a bound state. Consequently, there will hardly be an increase in the e^+e^- cross section at the threshold for the production of pairs of top quarks.

- In the next video we will discuss what all of this means for the properties of strong interactions.