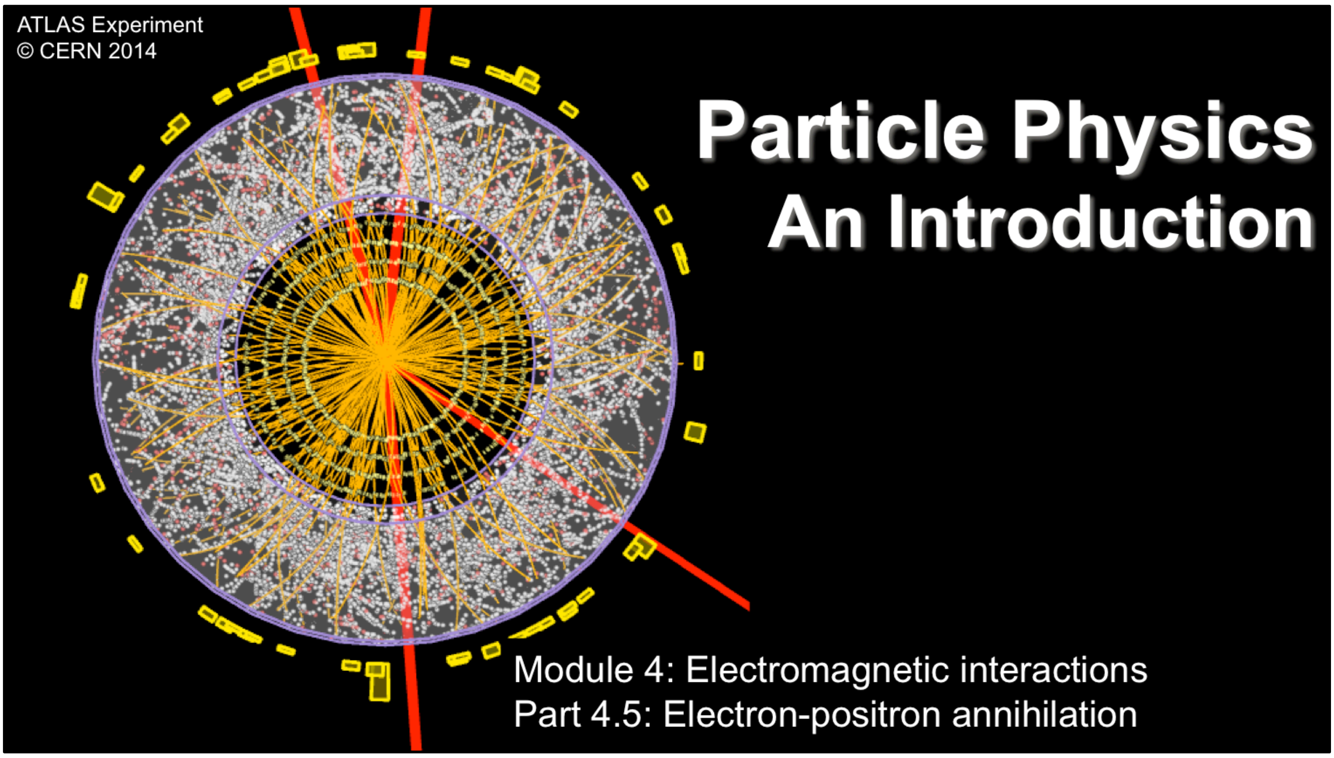
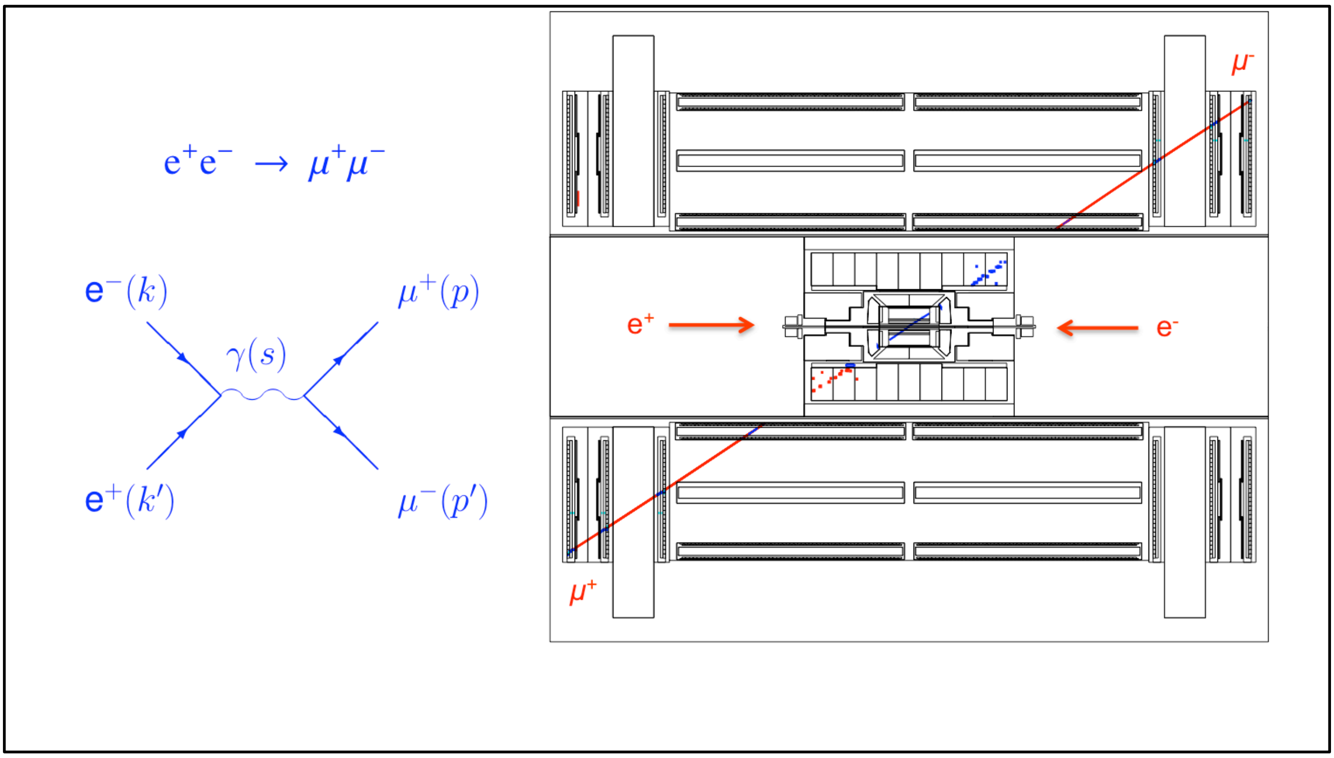


During this fourth module, we go into more details about the properties of electromagnetic interactions.

In this 5th video we discuss the annihilation of electron-positron pairs into pairs of fermions.

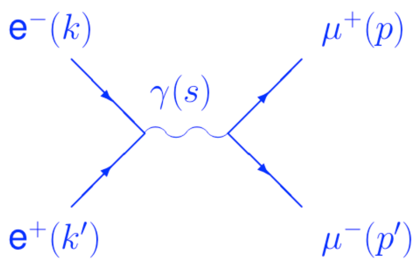
After following this video you will know:

- The main properties of the process of e^+e^- annihilation into lepton pairs;
- The peculiarities of the annihilation into hadrons.

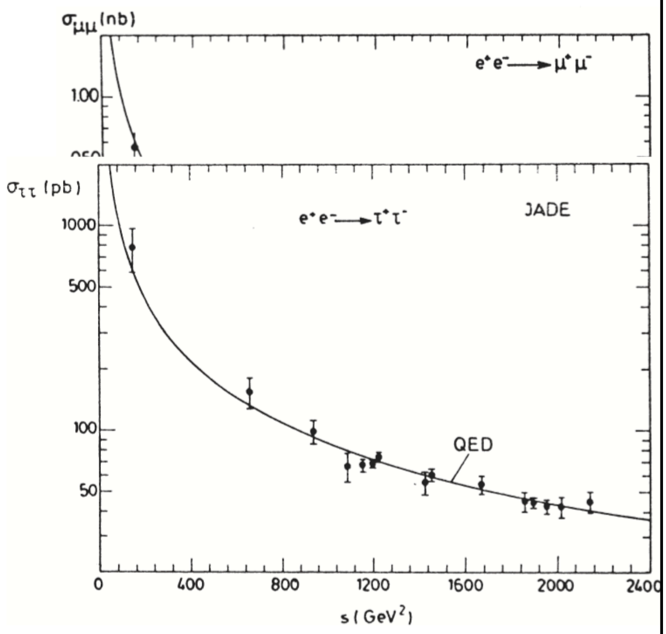


- The annihilation of electron-positron pairs into pairs of photons that Mercedes introduced in the previous video is not the only e^+e^- annihilation reaction. There is a whole class of reactions $e^+ e^- \rightarrow f$ anti-f , that is to say of **electron-positron annihilations into fermion-antifermion pairs**.
- We will **not include** here the reaction $e^+ e^- \rightarrow e^+ e^-$, which is complicated by a second scattering diagram, where the two electrons exchange a photon rather than annihilate.
- Let us take the creation of **pairs of muons as a prototype**. In the center-of-mass frame, the final state is characterized by two muons with equal and opposite momenta. Having no strong interaction and being too heavy to cause electromagnetic showers, muons penetrate all the material of the detector just losing energy by *dE/dx*.

$$e^+e^- \rightarrow \mu^+\mu^-$$
$$e^+e^- \rightarrow \tau^+\tau^-$$



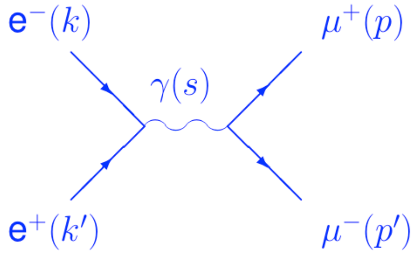
$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$



B. Naroska, Phys. Rept. 148 (1987) 67

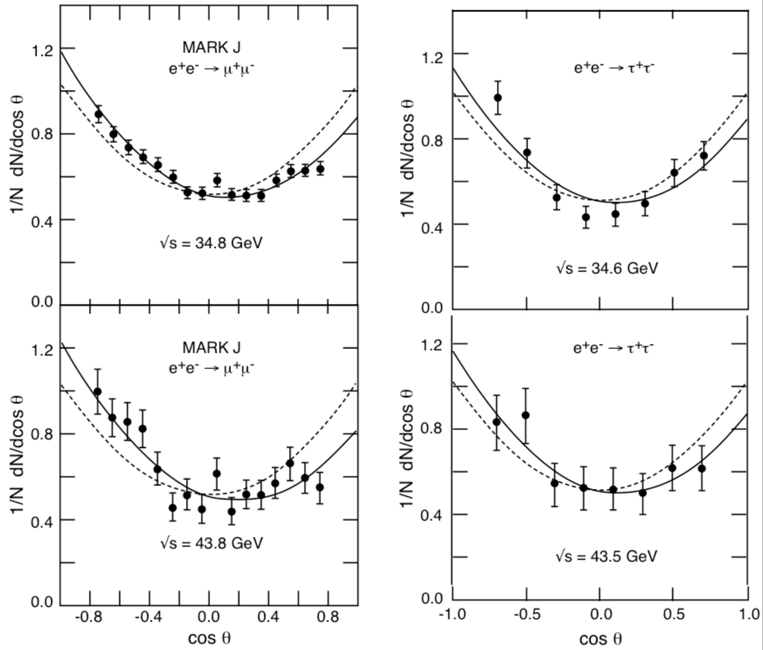
- The **total cross section** again exhibits the well-known factors, α^2 and $1/s$, which are characteristic for electromagnetic reactions between point-like particles.
- The cross section for the **tau production**, $e^+ e^- \rightarrow \tau^+ \tau^-$, is the same far from threshold, at $s >> 4\, m_\tau^2$.

$$e^+e^- \rightarrow \mu^+\mu^-$$
$$e^+e^- \rightarrow \tau^+\tau^-$$



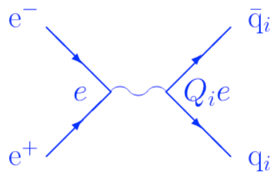
$$\left.\frac{d\sigma}{d\Omega}\right|_{cm} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$



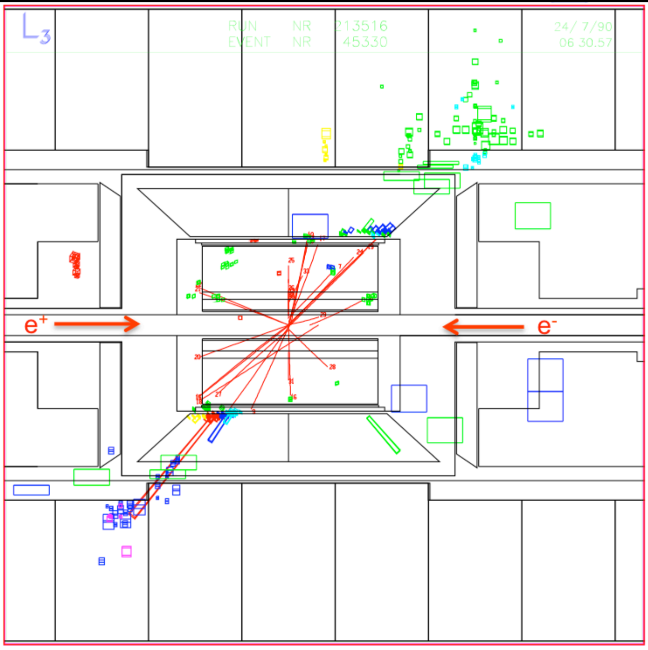
- The **differential cross section** is symmetric with respect to the sign of the scattering angle ϑ, if one neglects the masses, at $s >> 4\ m_\mu^2$.
- The figure shows the **angular distributions at high energy**. The dashed lines indicate the shape of the symmetric distribution predicted by QED. The solid lines include an asymmetric term that comes from **electroweak interference**. The angular distribution in fact shows a deviation from symmetry that increases with energy. It is due to the interference with weak interactions that we will treat in Module 6.
- This prototype cross section applies to **all annihilation reactions** which produce a fermion pair of negligible mass and charge *±e*, the coupling constant which is hidden in the fine structure constant, α.
- Again, an **identical angular distribution** is observed for the reaction $e^+ e^- \rightarrow \tau^+ \tau^-$ at $s >> 4\ m_\tau^2$.

$$\sigma(\mathrm{e^+e^-} \to \mathrm{q_i\bar{q}_i}) = 3Q_i^2\sigma(\mathrm{e^+e^-} \to \mu^+\mu^-) \quad ; \quad i = \mathrm{u, d, c, s, t, b}$$



$$\begin{aligned}\sqrt{s} &> 2m_c \simeq 3.7\ \mathrm{GeV}\\ \sqrt{s} &> 2m_b \simeq 10\ \mathrm{GeV}\\ \sqrt{s} &> 2m_t \simeq 350\ \mathrm{GeV}\end{aligned}$$

- As far as the **pair production of quarks** is concerned, one must consider two important changes.
- First, quarks carry **electric charges** Q_u = 2/3 for (u, c, t) and Q_d = -1/3 for (d, s, b), relative to the elementary charge *e*. As the quark charge comes in at one of the two vertices, we must introduce a factor Q_i^2 in the cross section.
- Second, quarks are produced with **three color charges** (r, g, or b), charges responsible for their strong interactions, to which electromagnetic interactions are insensitive. The color of quarks is another example for a property which is observable only in principle: we have no way to measure it, but it distinguishes nevertheless final states corresponding to different colors. We must therefore add the $|M_i|^2$ or the cross sections. They are obviously independent of color and for each flavor we obtain a cross section, which depends only on electric charge, but is **3 times larger** than for objects without color.
- The mass of quarks is negligible for u, d and s, but not for the **heavy quarks** c, b, and especially t. For them there are **production thresholds** as indicated. In the inclusive cross section $e^+ e^-$ ➔ q anti-q, there are steps at these thresholds.



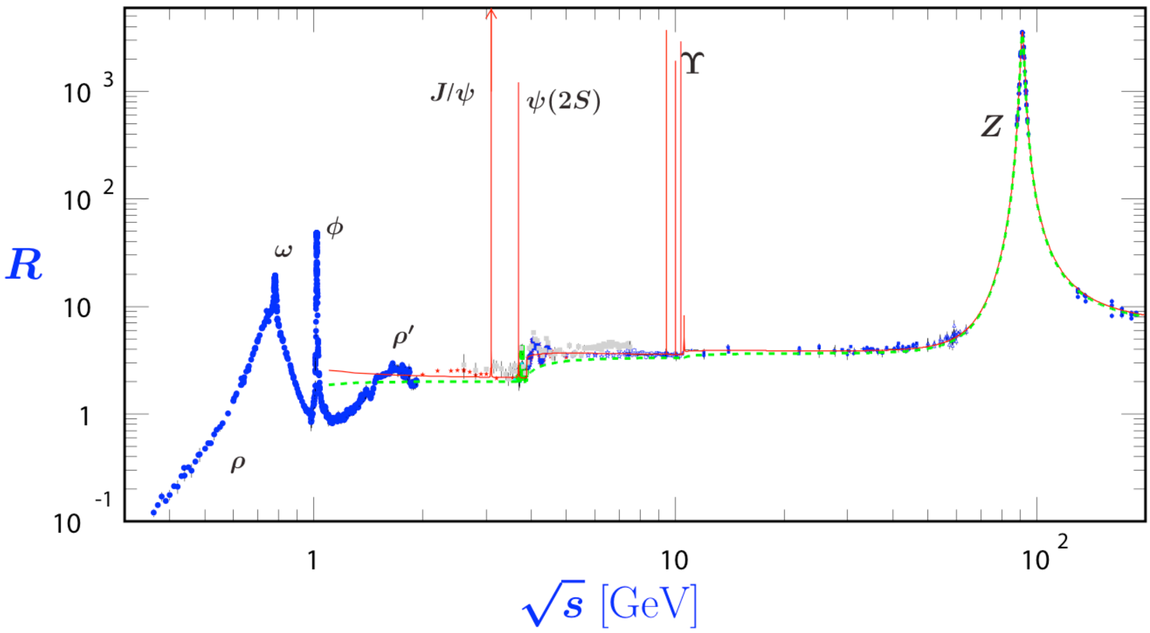
- Quarks in the final state are not observed as such because of their strong interaction, which starts acting as soon as they are produced. The **color field** that is established between them is so energetic that additional quark-antiquark pairs spontaneously pop up and cluster around the primordial quark as **hadronic jets**.
- These jets follow the **initial directions** of the quarks, their **total energy** is that of the quarks. The multiplicity of charged and neutral particles is high. Each quark forms **at least one jet,** such that the event contains at least two jets.
- We will come back to the jet phenomenon in Module 5, when we treat strong interactions.

$$\sigma(e^+e^- \to \text{hadrons}) \simeq \sum_i \sigma(e^+e^- \to q_i\bar{q}_i)$$

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq 3 \sum_{i,4m_i^2<s} Q_i^2$$

$R = 3[(\frac{2}{3})^2 + 2(\frac{1}{3})^2] = 2$	u, d, s	$\sqrt{s} < 2m_c \simeq 3.7$ GeV
$R = 2 + 3(\frac{2}{3})^2 = \frac{10}{3}$	u, d, s, c	$3.7 < \sqrt{s} < 2m_b \simeq 10$ GeV
$R = \frac{10}{3} + 3(\frac{1}{3})^2 = \frac{11}{3}$	u, d, s, c, b	$10 < \sqrt{s} < 2m_t \simeq 350$ GeV
$R = \frac{13}{3} + 3(\frac{2}{3})^2 = 5$	u, d, s, c, b, t	$350 < \sqrt{s}$

- Because of the conversion of quarks into hadrons, we cannot necessarily differentiate their flavor either. We consider therefore the **inclusive hadron cross section** , *σ(*e+ e- ➔ hadrons*)*, which to first order is given by the **sum of the individual cross sections**. This again because, in principle, flavor allows to distinguish them.
- You may wonder if the conversion of quarks into hadron jets does not change the cross section. This is not the case because - as far as we know - this **conversion is always happening**, with probability 1. In other words, the quarks are always and without residues converted into hadrons, the cross section does not change.
- To compensate for the important reduction with the square of the energy, *~1/s*, of all electron-positron cross sections, we often form the **ratio *R*** of the hadronic cross section to that of our reference process $e^+e^- \to \mu^+\mu^-$,
- The sum **includes all flavors** that can be produced at a given energy in the center of mass frame. At first order, in the different energy regions we obtain simple ratios of whole numbers. At each threshold there is a **step** in the cross section, because a new channel opens up.



http://pdg.lbl.gov/2016/reviews/rpp2016-rev-cross-section-plots.pdf

- This figure compares this rough calculation to a **compilation of experimental results** by the Particle Data Group. The data come from experiments at various $e^+ e^-$ colliders at different energies.
- We see the **gross features** of the cross section as predicted, including the small **steps at the quark thresholds.** But the measured cross sections are **significantly larger** than the simple fractions we calculated.
- This is again due to higher order contributions. We will see in the next module that **final states with additional gluons** add some 10 percent to the total inclusive hadron cross section.
- At high energies above a few tens of GeV we see the influence of the weak neutral interactions. The exchange of its intermediate boson, the **Z boson**, dominates the total cross section at these energies. We will see much more of this in Module 6.

- In the next module we discuss strong interactions and hadronic structure.