Physics 4213/5213
Lecture 5 (Part 1)

1 The J/ψ Meson

The discovery of the J/ψ meson led to the final acceptance of the quark model. First, it had been predicated to exist in order to explain why certain processes did not occur. Secondly, the spectrum of particles observed near the J/ψ mass, were consistent with $q\bar{q}$ bound states of different radial excitation, spin and orbital angular momentum. Finally, the longer than expected lifetime indicated something new was happening.

The lowest mass bound states are given by (note standard spectroscopic notation is used):

Particle	Mass (GeV)	S	ℓ	J
$\eta_c(1S)$	2.98	0	0	0
$\eta_c(2S)$	3.59	0	0	0
$J/\psi(1S)$	3.097	1	0	1
$J/\psi(2S)$	3.685	1	0	1
$\chi(1P)$	3.415	1	1	0
$\chi(1P)$	3.510	1	1	1
$\chi(1P)$	3.555	1	1	2

These states all have longer than expected lifetimes, states more massive than these have expected hadronic lifetimes and have masses greater than twice the D-meson (lightest meson having net charm)—its significance will be explained below.

2 Production of the J/ψ

The J/ψ can be produced both through the electromagnetic interaction or through the strong interaction. One of the original experiments that observed the production of J/ψ used the electron-positron annihilation ($e^+ + e^- \rightarrow J/\psi$) as shown in figure 1. The second experiment used the strong interaction process of pion proton scattering ($\pi^- + p \rightarrow J/\psi$). This process can produce the J/ψ through $q\bar{q}$ annihilation into a virtual photon and then to the J/ψ, but this is not the dominant process. Since quarks and gluons are available and have larger couplings, they will dominate in the production process. First note, $q\bar{q}$ to a single gluon will not work since the gluon has a net color while the J/ψ does not. This same argument holds for gluon-gluon fusing to form a third gluon ($g + g \rightarrow g^* \rightarrow J/\psi$) also doesn't work since this also produces a gluon with net color that has to form a colorless object. The only process that will work is the scattering of two gluons through the exchange of a charm quark (see fig. 2). This process requires that the gluons have anti-colors of each other to create a colorless $q\bar{q}$ pair to form the J/ψ.

3 Decay of the J/ψ

The J/ψ can decay into e^+e^-, $\mu^+\mu^-$ or into hadrons. The two leptonic decays, proceed through the annihilation of the two quarks into a virtual photon, that then decays into the lepton pair. The decay into hadrons is more complicated, even though in principle it can also go through a virtual photon, but it is going to be suppressed compared to possible strong processes.

The simplest process, is the decay into two charmed mesons through the diagram shown in figure 3. Even though this process proceeds through a single gluon, the final state does produce a colorless system. For the J/ψ, this process does not work due to the fact that the lowest mass charm mesons (D) have more than half the mass of the J/ψ. Since two need to be produced, energy would not be conserved—this process does work for higher excited states of the J/ψ.

The process that does produce hadrons in the final state is given in figure 4. Here the $c\bar{c}$ annihilate each other, but to produce a colorless final state, three gluons are required. This of course reduces the probability of decay (increases the lifetime) compared to the creation of a single gluon.

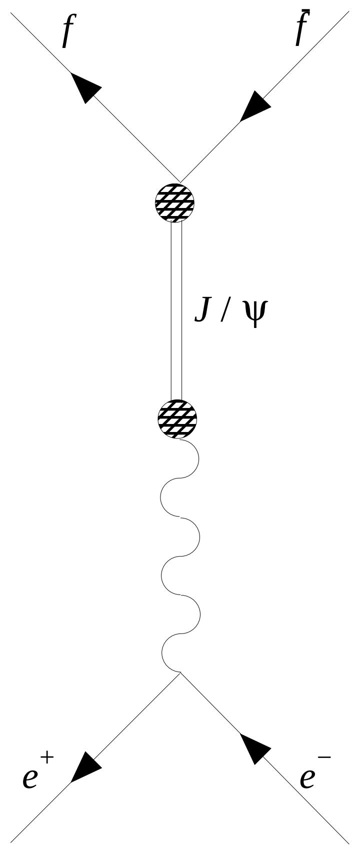

Figure 1: Production of J/ψ in e^+e^- collisions.

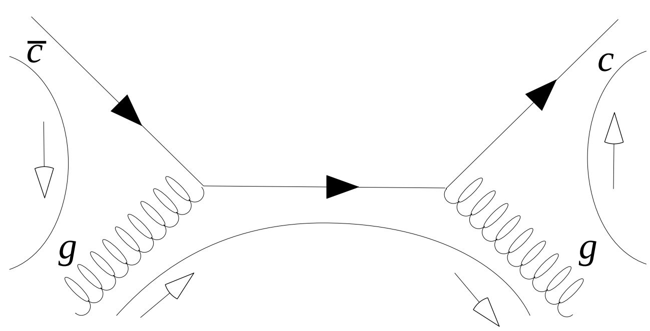

Figure 2: Production of J/ψ through gluon fusion. The open arrows show the direction of the color flow; recall arrows forward in time is color while those going backward in time are anti-color.

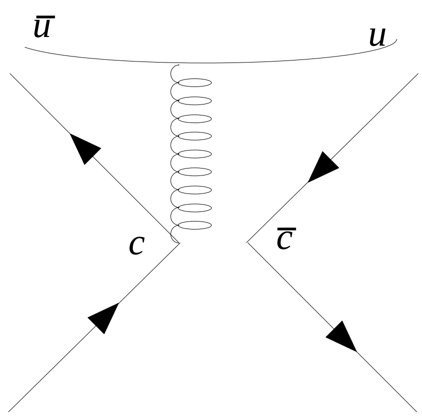

Figure 3: Direct decay of J/ψ into two D-mesons. This cannot occur for the J/ψ since the mass of the D-meson is more that half the mass of the J/ψ.

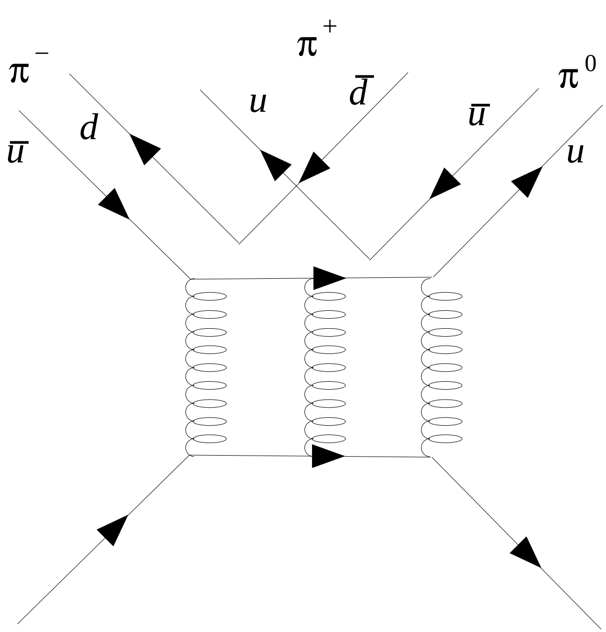

Figure 4: The preferred method for the strong decay of the J/ψ. Note that three gluons are involved, this being the lowest number necessary to conserve all quantum numbers—one does not work since the initial state is colorless and the gluon has a net color.