INFRARED CORRECTIONS TO THE TOP QUARK WIDTH

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ABSTRACT

We present a nonperturbative analysis of the top quark propagator using the Schwinger Dyson equation in the ladder approximation including both the electroweak as well as the infrared QCD effects. We find that the infrared effects are negligible only for top mass larger than about 250 GeV.

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1. Introduction

The success of perturbative QCD is based on the fact that the QCD coupling gets smaller at large momentum. Therefore for any process for which the dominant contribution comes from the high momentum region, perturbative QCD should yield quantitatively reliable predictions. However for several interesting cases, perturbation theory fails to give reasonable results. For example, for the calculation of bound state masses the perturbative gluon propagator does not give correct results even for quark masses much larger then the typical scale of nonperturbative QCD. Presumably the infrared region gives a significant contribution in this case. Another important example is quark confinement. The fact that quarks are never observed as free particles suggests that the quark propagator is considerably different from the perturbative propagator and might receive significant contributions from the infrared region. This is supported by nonperturbative calculations, performed by choosing phenomenologically and theoretically motivated models for gluon propagator, which suggest that, independently of the mass of the quark, the dressed quark propagator is very different from the free propagator and in particular admits no mass pole, presumably a signal of confinement. Intuitively we can argue that, because of the large coupling, a quark has a large amplitude to exchange a soft gluon with itself which can in principle modify its singularity structure. This argument may not hold for the top quark because of its large decay rate into a W boson and a bottom quark. This suggests the possibility that the top quark might decay before exchanging a soft gluon with itself. If this were the case then the infrared region will be completely ignorable and perturbation theory becomes quantitatively reliable.

To get a rough idea of the mass of the top at which the infrared effects become negligible we compare the width of the top with the typical hadronic scale. If the width is much smaller than the scale of confinement then the top will have sufficient time to exchange a soft gluon. For a top quark of mass 150 GeV, its purely electroweak width at tree level is about 800 MeV. This is clearly comparable to the hadronic scale and we cannot rule out the possibility of significant infrared corrections. For the top quark of mass 250 GeV, however, the top width is larger than 4 GeV and the infrared effects should be completely negligible.

The top propagator can be calculated nonperturbatively by solving the Schwinger-Dyson (SD) equation [1],

\[ S^{-1}(q) = S_0^{-1}(q) - i \int \frac{d^4k}{(2\pi)^4} \gamma_\mu S(k) \gamma_\nu G_{\mu\nu}(k - q) \]  \hspace{1cm} (1)

We employ the ladder approximation for our calculation and choose phenomenologically and theoretically motivated models for the gluon propagator. We choose the Landau gauge for our calculation, in which case the gluon propagator has the form, \( G_{\mu\nu}(k) = (g_{\mu\nu} - k_\mu k_\nu/k^2)G(k^2) \). We are interested in calculating the corrections to the top width due to the low momentum region and therefore need a model for \( G(k^2) \) which might be qualitatively reliable in this region. There is some theoretical and phenomenological evidence that the gluon propagator has a \( 1/k^4 \) behavior at small momentum. We therefore choose the following two models for \( G(k^2) \), which
represent a regularized form of the $1/k^4$ behavior.

\[ G^a(k) = i \frac{4}{3} (2\pi)^4 \eta^2 \delta^4(k) \]  

\[ G^b(k) = \frac{8\pi a}{(k^2 - \epsilon^2)^2}. \]  

The second model $G^b(k)$ leads to a linear potential, $V(r) = ar$, in the nonrelativistic limit as long as $\epsilon$ is small compared to the scale of confinement. We calculate the parameters in these potentials by fitting the light and heavy meson spectrum and decay constants [1], which give a range of values for these parameters.

2. Results and discussion

In this section we present the results for the top width obtained by choosing the two gluon propagator model given in Eqns. 2 and 3. Since we are only interested in getting a qualitative idea, the parameters in these potentials will be chosen within their range such that they give the smallest correction to the tree level calculation of width. For the potential $G^a$, this implies that $\eta = 450$ MeV and for $G^b$, we get $a = (450 \text{ MeV})^2$, $\epsilon = 150$ MeV. The numerical results are given in Table 1.

### Table 1: Results for the top quark width $\Gamma$ including infrared QCD corrections for the gluon propagator models given in Eqns. 2 and 3.

| $m_t$ (GeV) | $\Gamma_0$ (GeV) | $\Gamma$ (GeV) | $\Gamma$ (GeV) |
|-------------|-----------------|----------------|----------------|
|             |                 | (model $G^a$)  | (model $G^b$)  |
| 100         | 0.0922          | 0.0461         | 0.0713         |
| 150         | 0.80            | 0.40           | 0.61           |
| 190         | 2.0             | 1.44           | 1.85           |
| 234         | 4.0             | 3.79           | 3.91           |

Our results show that the low momentum region gives a negligible correction to the top width only if its mass is larger than about 250 GeV. For a top quark of mass 150 GeV, the infrared region can give a significant correction. These results follow the trend, as anticipated in the introduction, that as the width of the top gets much larger than the scale of confinement the infrared region becomes negligible. For comparison, perturbative QCD calculations gives about a 10% correction [2].

In conclusion, we have shown here that infrared effects can give significant contribution to the top width if the mass of the top quark is less than about 150 GeV. However once the mass gets larger than about 250 GeV, the infrared corrections are completely negligible. The magnitude of the corrections is dependent on the width of the top. The corrections get negligible only if the width is much larger than the scale of confinement.

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4. References

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