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Hard Gluon Radiation and the Top Mass Value from CDF

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Abstract

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The effect of hard gluon radiation on the top quark mass determination at Tevatron energies is studied. An expectation value $\langle \Delta m \rangle$ for the correction implied on m_{top} is defined, and it is shown that the hard gluon effect is of the order of GeV. Quantitative numerical results are obtained on the basis of the complete higher order matrix elements for production and decay of the top quark.

Recently, evidence has been found for the production of top quarks at the Fermilab Tevatron collider at $\sqrt{S} = 1.8 \text{ TeV}$ using the Collider Detector at Fermilab (CDF) [1]. Under the hypothesis that the CDF events are due to top quark production the top quark mass was determined to be $m_t = 174 \pm 10^{+13}_{-12} \text{ GeV}$. This value was obtained on the basis of the leading standard model processes for top quark production and decay. At the Tevatron the dominant production mechanism for top quarks is $q\bar{q} \rightarrow t\bar{t}$ whereas gluon initiated processes like $gg \rightarrow t\bar{t}$ can be neglected [2]. The main decay mode of the top quark is $t \rightarrow bW^+$ (BR > 99.9%) with the W decaying either to two quarks (jets) $q_1 + q_2$ or leptonically, $W^+ \rightarrow \ell^+ + \nu_\ell$. The complete production and decay process is depicted in fig. 1. Events like fig. 1 where just one of the top quarks decays semileptonically are well suited for the m_t determination. This is because a very hard lepton in conjunction with a tagged b-quark is a rather unambiguous signal for top, and the top mass can be inferred from the invariant mass of three of the four jets in the event, $(b + q_1 + q_2)^2 = m_t^2$. The quantity m_t which is determined this way is the so called pole mass of the top quark. The relation to the running mass is well known [3].

In general it is not possible to distinguish a b from a $\bar{b}$ jet. Therefore there is an ambiguity in the assignment of the jets. This can usually be resolved by the requirement that the two jets from the W^+ should fulfil $(q_1 + q_2)^2 = m_W^2$ and that $(b + q_1 + q_2)^2$ should be in some range around 170 GeV, say $170 \pm 30 \text{ GeV}$.

In this letter I want to discuss in detail to what extent hard gluon radiation can modify the value obtained for m_t . Hard gluons enter the problem both on the production and on the decay side, namely through the processes $q\bar{q} \rightarrow t\bar{t}g$, $t \rightarrow bgW$ and, to less extend, $W \rightarrow q_1q_2g$. The matrix elements for these oneloop QCD processes are known [4, 5] and will be the basis of the following discussions. It should be noted that interference contributions of diagrams where the gluon is emitted on the production side (before the top quark goes on shell) and on the decay side (after it goes on shell) are not known (except in the infrared limit [6]). However, these contributions are suppressed by powers of Γ_t/m_t as compared to the ordinary QCD corrections. Therefore they will not be considered in the following although their effect on the m_t determination might be somewhat larger than suggested by this suppression factor.

It is well known that both the production cross section and the decay width of the top quark get significant corrections from perturbative QCD ($\geq 10\%$) [5, 7]. Therefore, a priori, a large modification of the m_t value by QCD effects is conceivable. However,

those corrections come to a large extent from soft gluons. Soft gluon radiation that is not detected will certainly affect the jet energy determination and this way induce an error on m_t . This error was estimated by the CDF collaboration to be about 4% . Recently, Orr and Stirling have examined the effect of soft gluons in the central region of the detector [8].

Using the HERWIG shower Monte Carlo CDF has also examined the effect of hard gluon radiation and found it to be insignificant. The main aim of this letter is to criticize their qualitative statement on a quantitative level. We do this by using the full QCD results for production and decay.

Hard gluons can falsify the m_t determination in a number of ways. Depending whether it comes from the decay or the production part of the process its momentum must or must not be included in the invariant mass that gives m_t . The problem is that in a given event one cannot distinguish at what point the gluon was emitted. Furthermore, gluons from the decay side may disappear in the beam pipe and gluons from the production side may form a jet together with one of the final state partons. It is true that the matrix elements give no particular enhancement for these configurations. But the phase space regions in question are not so small, and we shall see that shifts in the value for m_t of up to 5 GeV can arise. The shift depends on the details of the procedure and on the cuts. I will first review the details of the CDF procedure before I include gluons and my own results.

CDF has found an excess of b-tagged 4 jet events with an additional hard lepton which can be attributed to the process $t_1 t_2 \rightarrow \ell \nu b_1 + q_1 q_2 b_2$. Each of these events allows to determine m_t from the invariant mass $(q_1 + \bar{q}_2 + b_2)^2 = m_t^2$. The four momenta $q_1, \bar{q}_2, b_1$ and b_2 of the primary partons were inferred from the measured energy and angle of the four jets. Then a kinematic fitting program was used to reconstruct the whole event, assuming the vertex structure of fig. 1. The neutrino momentum could be determined only up to the sign of its longitudinal component. Given that one b is tagged there are 12 combinatoric possibilities to attribute the four jets to t_1 and t_2 . Among the 12 possibilities the one with the best overall kinematic fit was chosen and the corresponding Wb invariant mass gave the top quark mass for the event.

This procedure is superior to other methods discussed in the literature, like the “half plane procedure” suggested by Baer et al. [9, 10] The idea of the “half plane procedure” is that the decay products of top and antitop quark should be distributed

in opposite hemispheres. Therefore Baer et al [9] suggested to collect in a given event all particles going to the hemisphere opposite to the lepton direction and to determine their invariant mass. They argued that the corresponding invariant mass distribution should peak at m_t . However, this is a reasonable approach only if t and $\bar{t}$ are produced at high energies whereas in practice many $t\bar{t}$ events are near threshold events.

To reduce the background CDF checked the W mass conditions $(\ell + \nu)^2 = m_W^2$ and $(q_1 + q_2)^2 = m_W^2$ and used the following cuts

- a rapidity cut $|\eta| < 2$ for all observed particles and jets (i.e. not being along the beam direction)
- a transverse energy cut $E_T^\ell > 20\text{GeV}$ for leptons and $E_T^q > 10\text{GeV}$ for jets.

Finally, the hadronization corrections and detector acceptance effects were included by using the HERWIG shower Monte Carlo and the CDF detector simulation program.

Let me now come to my own analysis: I have used a simplified model to study the effect of hard gluons. My main simplification as compared to the CDF analysis is that I do not care about tree level ambiguities. That is, I assume that without gluons the top quark mass can be unambiguously determined to be m_t , from the invariant mass $(q_1 + q_2 + b)^2$ of the quark momenta defined in fig. 1. Furthermore, I neglect final state hadronization and detector acceptance effects. This way I was able to get a clear and separate view on the ambiguities which arise from hard gluon emission.

The first step in my study was to write a Monte Carlo program for the process fig. 1 and for the analogous processes with gluons. For each event the phase space factors (PS with and PS_0 without gluons) and the matrixelements ($|M|^2$ with and $|M_0|^2$ without gluons) were determined, as well as an invariant mass m_{inv} defined as follows. m_{inv}^2 was chosen to be either $(q_1 + q_2 + b + g)^2$ or $(q_1 + q_2 + b)^2$ depending whether the gluon was collinear to one of the decay products q_1, q_2, b or not. Then I calculated

$$\langle \Delta m \rangle := \frac{\int (m_{\text{inv}} - m_t) \cdot |M|^2 \cdot PS}{\int |M_0|^2 \cdot PS_0} \quad (1)$$

$\langle \Delta m \rangle$ is a measure of the modification which hard collinear gluons induce on the value determined for the top quark mass. Virtual and extremely soft gluons do not contribute because for soft and virtual gluons $m_{\text{inv}} \approx m_t$. Therefore $\langle \Delta m \rangle$ does not have the infrared divergence difficulty which often arises in higher order quantities. Note that the denominator of eq. (1) is given to a good approximation by the lowest order term. To improve on eq. 1 one would need twoloop corrections in the numerator and oneloop corrections in the denominator.

Collinearity of quarks and gluons is defined by means of an angle cut α , i.e. the gluon is counted in m_{inv} , if $\nexists (q_1, g) < \alpha$, $\nexists (q_2, g) < \alpha$ or $\nexists (b, g) < \alpha$, otherwise not. This way $\langle \Delta m \rangle$ depends on the choice of α . There is also a dependence on the rapidity and the transverse energy cuts which I choose identical to the CDF values given above.

For the gluon I have included a rapidity cut but no transverse energy cut. I did not use a gluon energy cut so that in principle soft gluons are included, but do not contribute very much because low energy gluons give an invariant mass m_{inv} close to m_t . The gluon rapidity cut is very useful to avoid the initial state singularities of the process $q\bar{q} \rightarrow t\bar{t}g$. Whenever a gluon from this process goes along the beam pipe the top quark mass is correctly assigned to be m_t so that this event does not contribute in eq. 1 and need not be considered further. Of course, this is different for the process $t \rightarrow bWg$. Whenever a gluon from the process $t \rightarrow bWg$ vanishes in the beam pipe the invariant mass m_{inv} comes out $(q_1 + q_2 + b)^2 < m_t^2$ and contributes negative to $\langle \Delta m \rangle$.

It is generally clear that m_{inv} determined in the case of decay gluons will be $\leq m_t$ (so that $\langle \Delta m \rangle_{\text{decay}} < 0$) whereas the m_{inv} determined from the process $p\bar{p} \rightarrow t\bar{t}g$ will always be $\geq m_t$ (so that $\langle \Delta m \rangle_{\text{production}} > 0$). The histogram fig. 2 shows the distribution in m_{inv} , in arbitrary units. It proves that these expectations are indeed fulfilled because the decay contribution is to the left and the production to the right of m_t . In fig. 2 a top quark mass of $m_t = 174$ GeV is assumed and the same η and E_T cuts as in the CDF experiment. Furthermore, we have taken the gluon collinearity cut $\alpha = 10^\circ$ and demanded that $m_{\text{inv}} \in [140, 200]$ GeV. The bins below 170 GeV get contributions only from decay gluons whereas the bins above 175 GeV get contributions only from production gluons. Fig. 2 shows that the effect of decay gluons ($t \rightarrow bWg$) is much larger than that of production gluons.

The central bin around $m_t = 174$ GeV gets singular contributions, for example from

soft gluons. These infinite contributions drop out if one includes virtual gluon exchange. They do not enter out quantity $\langle \Delta m \rangle$ because they fulfil the condition $m_{\text{inv}} = m_t$.

In fig. 3 $\langle \Delta m \rangle$ is shown as a function of α , both for $t \rightarrow bWg$ and $q\bar{q} \rightarrow t\bar{t}g$. The increase of $\langle \Delta m \rangle$ with increasing α can be understood easily because with increasing α more gluons fulfil the collinearity condition. It is interesting to note that the decay gluons give a rather large effect (a few GeV) which may become important once CDF has found more events. I have checked that this result is maintained if one switches to other procedures of top mass determination [9] or to other collinearity conditions (like invariant mass cut).

The contribution from the production process $q\bar{q} \rightarrow t\bar{t}g$ is generally quite small. It would be interesting to see whether this feature survives if one goes to LHC energies and includes the process $gg \rightarrow t\bar{t}g$. I have also examined the dependence of $\langle \Delta m \rangle$ on the rapidity and transverse energy cut. This dependence is not so interesting and rather moderate so that I shall not give it here.

Let me now come to the conclusions. We have seen that hard gluons can affect the determination of m_t at CDF in an appreciable way. Our main point was about collinearity of gluons whereas soft gluons do not play an important role in this discussion. We have defined a measure $\langle \Delta m \rangle$ which reflects the effects of hard gluons on m_t in a very nice way and have determined $\langle \Delta m \rangle$ for a number of cases. Admittedly, the whole analysis needs further study. It should be brought nearer to the real experimental situation by including hadronization effects, tree level ambiguities and more CDF characteristics. Even the hard gluon analysis is incomplete because I did not include the effects of gluon emission in the decays of $\bar{t}$, W , b and c quark but concentrated on the processes $q\bar{q} \rightarrow t\bar{t}g$ and $t \rightarrow bWg$. I conjecture that the secondary gluons from $\bar{t}$, W , b and c decay play only a minor role in the modification of the top mass value. For example, consider the process $W \rightarrow q_1 q_2 g$. One can extremely reduce the effect of hard gluons from this process by taking notice of the fact that the jets from W decay should fulfil the W mass condition.

Note added: After starting this work I noticed the paper by Orr and Stirling [8] who have computed soft gluon angular distributions and discussed their implications for top quark mass measurements. They wanted to know where soft jets are expected to appear in the detector and found out that in the central region soft gluons can-

not be unambiguously assigned to either production or decay. Contrary to naive expectation a large part of central soft gluons comes from the production side, even if cuts are tightened.

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Fig. 1

Fig. 2

Fig. 3