Soft Jets and Top Mass Measurement at the Tevatron

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Abstract

Extra soft jets in top events in $p\bar{p}$ collisions may arise not only from gluons radiated off initial state partons or final state $b$ quarks, but may also be radiated from the $t$ quarks themselves. We discuss predictions for distributions of soft gluons in $tt$ production at the Tevatron and the implications for attempts to measure the top mass by reconstructing the invariant mass of its decay products.

1. Introduction

In $tt$ production at the Tevatron, the final state particles may be accompanied by additional soft jets due to gluon radiation. These soft jets must be accounted for somehow in attempts to measure the top mass $m_t$ by momentum reconstruction. In particular, one would like to know whether soft jets should be combined with the top’s daughter $W$’s and $b$’s in such reconstructions. It is obvious that if the gluon has been radiated off the final $b$ or $\bar{b}$, the gluon should be included, but if it was radiated off an initial state quark, then it should not. Our intuition tells us that final-state radiation, as in the former case, corresponds to jets near the $b$ or $\bar{b}$ direction, and that initial-state radiation, as in the latter case, corresponds to jets near the beam axis.

This intuitive picture is incomplete, however, because we must also consider radiation off the top quarks themselves. Do such gluons belong to the initial state or the final state? That this question cannot be answered indicates that the the initial/final state picture of gluon radiation is too naive in the case of the top quark. Top production and decay must be considered simultaneously in a treatment of gluon radiation.

In this talk we report results of a study of soft gluon radiation in top production and decay in which all diagrams are correctly taken into account. Our aims are (i) to determine where the gluons come from and where they go, in a way that is relevant to $m_t$ measurement, and (ii) to compare the correct results which those of simple, intuitive models that are in the spirit of what might be easily implemented in Monte Carlo Simulations.

2. Soft gluons: formalism and features

We work in the soft approximation (i.e., we assume that the gluons are less energetic than other particle in the event); for a discussion of the soft gluon formalism in top physics see [4]. We consider the process $q\bar{q} \to t\bar{t} \to bW^+\bar{b}W^-$ with emission of a soft gluon. The matrix element and phase space factorize so that we can write
the gluon distribution as
\[
\frac{1}{d\sigma_0} \frac{d\sigma}{dE_g d\cos \theta_g d\phi_g} = \frac{\alpha_s}{4\pi^2} E_g (F_{\text{PROD}} + F_{\text{DEC}} + F_{\text{INT}}),
\]
(1)
where \(d\sigma_0\) is the differential cross section for the lowest-order process (with no gluon). \(F_{\text{PROD}}\) corresponds to gluons radiated in association with \(t\bar{t}\) production, \textit{i.e.}, radiated before the \(t\) or \(\bar{t}\) quark goes on shell. Similarly, \(F_{\text{DEC}}\) corresponds to gluons radiated in the decay of the \(t\) or \(\bar{t}\). \(F_{\text{INT}}\) represents the interferences between the two and depends on the top width \(\Gamma_t\). Expressions for \(F_{\text{PROD}}, F_{\text{DEC}},\) and \(F_{\text{INT}}\) can be found in \cite{3}.

The important point is that this production–decay–interference decomposition provides a gauge–invariant substitute for the initial/final state picture discussed above. It determines for us whether the gluon’s momentum should be combined with those of the initial \(q\) and \(\bar{q}\) and the \(t\) and \(\bar{t}\), as well as that of the gluon itself. Similarly, \(F_{\text{DEC}}\) knows nothing about the initial state and depends only on the momenta of the \(t, \bar{t}, b, \bar{b},\) and gluon. Both \(F_{\text{PROD}}\) and \(F_{\text{DEC}}\) can be written as sums of “color antennae” which can be interpreted in terms of a pair of quarks connected by a color string. These antennae exhibit color coherence, or the string effect: more radiation appears between such paired quarks than outside of them.

3. Gluon distributions at the Tevatron

Let us examine soft gluon distributions for \(t\bar{t}\) production in \(p\bar{p}\) collisions at 1.8 TeV center-of-mass energy at the Tevatron. The results shown are from \cite{1}, where a more complete discussion can be found. We take \(m_t = 174\) GeV and work at the parton level, considering only the \(q\bar{q}\) initial state (which dominates) and using minimal kinematic cuts, which are:

\[
\begin{align*}
|\eta_b|, |\eta_{\bar{b}}| & \leq 1.5 , \\
|\eta_g| & \leq 3.5 , \\
10 \text{ GeV}/c & \leq p_T^b \leq 25 \text{ GeV}/c , \\
E_g & \leq 100 \text{ GeV} , \\
\Delta R_{bg}, \Delta R_{\bar{b}g} & \geq 0.5 .
\end{align*}
\]
(2)

3.1. Angular distributions and top momentum reconstruction

We focus on angular distributions since we are interested in where soft jets will appear in detectors. Figure 1(a) shows the gluon pseudorapidity distribution. The total (solid line) is shown along with its decomposition.
Figure 2. Distribution in the cosine of the angle between the gluon and the $b$-quark, (a) with cuts described in the text and (b) with the additional cut $|\eta_g| \leq 1.5$.

according to Eq. 1 into production (dotted line) and decay (dashed line) contributions. The production piece is peaked in the forward direction and centrally suppressed. This reflects the color antennae connecting the initial-state quarks with the top quarks. The decay contribution is peaked in the central region, which is where the radiating top and bottom quarks tend to be produced. The net distribution is only slightly peaked in the center. Note that, while gluons at larger rapidities are almost exclusively associated with production (and hence should be ignored in top momentum reconstruction), central gluons are nearly as likely to have come from production as from decay.

In Figure 2 we test the second part of our guess (see introduction) by examining to what extent proximity of gluons to the $b$-quark correlates with having come from the decay contribution. Fig. 2(a) shows the distribution in cosine of the angle between the $b$ quark and the gluon with the same cuts and decomposition as in Fig. 1(a). The contribution from production is flat, as expected since it contains no explicit dependence on the $b$ quark's momentum. The decay contribution does increase as the gluon approaches the $b$, leading to an excess above the production contribution close to the $b$. The excess is only a slight one, though, and the result is very sensitive to the cut on $\Delta R$. Furthermore, no hadronization effects have been taken into account. We can improve the situation by recalling that forward gluons tend to come from production. If we tighten the gluon pseudorapidity cut to $|\eta_g| < 1.5$, we see more of an excess in decay gluons near the $b$, as shown in Fig. 2(b). Sensitivity to the $\Delta R$ cut and fragmentation effects remain a problem, however.

We now return to the pseudorapidity distribution to compare the correct distribution in Fig. 1(a) to those in Fig. 1(b), obtained from some simpler models that are intuitively appealing and easily implemented in Monte Carlo simulations. The ISR model (dotted line) includes radiation off the initial $q\bar{q}$ state only, as if the $q$ and $\bar{q}$ formed a color singlet. We might expect this to correspond to the contribution associated with production, but we see by comparing to the dotted line in Fig. 1(a) that the ISR model overestimates radiation in the central region. In the ISR/FSR model (dashed line) we add to the ISR model radiation from the final $b\bar{b}$ pair as if they too formed a color singlet. This model corresponds roughly to the naïve expectation mentioned in the introductory paragraph. Figure 1(b) shows that this model overestimates the total radiation and gets the shape wrong. In the BB model (dot-dashed line) we use the correct color structure but ignore radiation off the top quark. This model approximately reproduces the correct pseudorapidity distribution. However, it does not give the correct azimuthal distribution, and, more important for $m_t$ reconstruction, does not permit a production–decay decomposition.

3.2. Color structure and forward-backward asymmetry

Finally, we discuss briefly a forward-backward asymmetry in the radiation pattern (for appropriately chosen final states) that arises from the color structure of gluon emission in hadronic $t\bar{t}$ production. While not directly relevant to measurement of the top mass, the asymmetry is interesting because it is a result of the fact that the top quarks themselves can radiate before decaying. It also reveals major differences between the correct distribution and the simpler models.

This asymmetry arises from the string effect mentioned above. For example, in $q\bar{q} \rightarrow t\bar{t}$ the $q$–$t$
antenna produces more radiation in the region between the $t$ and $q$ than, say, between the $t$ and $\bar{q}$, resulting in a forward–backward asymmetry in the gluon radiation. To avoid cancellation of the effect by an equal and opposite asymmetry due to the $\bar{q}$ and $\bar{t}$, we try to preferentially select gluons that are more likely to be in the $t$ than the $\bar{t}$ hemisphere, with the additional cuts $\Delta \phi_{b\bar{b}} > 135^\circ$ and $\Delta \phi_{bg} < 90^\circ$.

The resulting distribution is shown in Figure 3(a). A forward–backward asymmetry is evident, and we see from the decomposition that it comes entirely from the production piece; the decay knows nothing about the initial quarks’ direction. In Fig. 3(b) we show the same distribution for the three simpler models. There is no asymmetry for the ISR and ISR/FSR models because there is no connection between radiation in the initial and final states. In contrast, the BB model shows a more marked asymmetry than the correct distribution because without radiation from the intermediate top quarks there is a more direct color connection between the initial and final states.

4. Summary

We have shown that the subject of gluon radiation in $t\bar{t}$ production and decay is a complicated one due to the rich color structure of the process. For purposes of top mass reconstruction, we saw that there is no simple prescription for dealing with additional soft jets in $t\bar{t}$ events, but that the production–decay decomposition provides some guidance. A comparison to simpler, intuitively appealing models such as one might easily implement in Monte Carlo simulations showed that they do not reproduce the correct distributions and/or do not allow for the production–decay decomposition. Finally, we discussed a forward–backward asymmetry in soft gluon radiation that illustrates the color structure, including in particular radiation off the top quarks themselves.

References

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