GLUON RADIATION IN TOP MASS RECONSTRUCTION:
EFFECT OF HADRONIC W DECAYS

L.H. ORR

Department of Physics and Astronomy, University of Rochester, Rochester NY 14627-0171, USA
E-mail: orr@pas.rochester.edu

T. ANDRE

Department of Physics and Astronomy, University of Rochester, Rochester NY 14627-0171, USA and
Department of Physics, University of Chicago, Chicago IL 60637, USA
E-mail: troy@hep.uchicago.edu

T. STELZER

Department of Physics, University of Illinois, Urbana, IL 61801, USA
E-mail: stelzer@pobox.hep.uiuc.edu

Top quark events in hadron collisions often contain additional hadronic jets from gluon bremsstrahlung off the quarks and gluons in the hard subProcesses. Such extra jets must be taken into account in attempts to reconstruct the momentum of the top quark from those of its decay products. We have performed a complete calculation of gluon radiation in top production and decay at the Fermilab Tevatron including hadronically decaying W bosons. In this talk we discuss the effect of gluon radiation on the reconstructed mass of the top quark, using various top mass reconstruction scenarios. Implications for the LHC are briefly discussed.

Presented by LHO at the XXIX International Conference on High Energy Physics, Vancouver, B.C., July 23-29, 1998.

1 Introduction

Measuring the top quark mass at hadron colliders requires reconstructing its momentum from its decay products. Radiated gluons in top events can complicate the reconstruction process, because for example the jets from gluons can be indistinguishable from the jets in top decays. It is important to account correctly for these gluons because future top mass measurements will be dominated by systematic effects due to gluon radiation.

Given a top event with an extra jet from a radiated gluon, what should we do with the extra jet? In particular, should the extra jet be combined with the W and b quark to reconstruct \( m_t \)? The answer depends on where the gluon originated. If it was radiated from an initial state quark, then it is a correction to the production process that is not part of the top decay, and it should be ignored. If the gluon was radiated from one of the b quarks from the t or \( \bar{t} \) decay, then it is itself part of the decay and should be included in the reconstruction. Suppose the gluon was radiated by the top quark itself — is it associated with top production or decay? In fact it can be either, depending on when the top quark went on shell.

The point is that in a given event we cannot usually distinguish between the possibilities (even apart from the fact that they interfere), so we must consider top production and decay together in our treatment of gluon radiation. This has been done for top production and decay at the Tevatron \(^{1}\) and LHC \(^{2}\) without radiation from hadronic decays of the W bosons. But in the detection modes in which at least one of the top quarks can be fully reconstructed from its decay products — the lepton + jets and all-jets modes — one or both of the W bosons decays to quarks, which can themselves radiate. Radiation from hadronically decaying W’s in top events was treated in the soft gluon approximation in \(^{3}\). The soft approximation serves as a useful guide to the distribution of gluons and the relative importance of the various contributions, but it does not incorporate exact kinematics and cannot be used to study mass reconstruction.

In this talk we present the results for an exact calculation of gluon radiation in top production and decay at the Tevatron with hadronic W decays fully taken into account.

2 Gluon Distributions

We have calculated the cross section for \( pp \rightarrow b\bar{b}q\bar{q}l\nu j \) and \( pp \rightarrow b\bar{b}q\bar{q}q\bar{q}j \) where \( j \) is an extra radiated jet. This tree-level calculation is exact at \( O(\alpha_s^3) \) and contains all spin correlations, top width effects, and interferences. The center of mass energy is 1.8 TeV, and top and bottom masses are 175 and 5 GeV, respectively.
licity amplitudes are computed with the assistance of the MADGRAPH package. The results shown below are for the $q\bar{q}$ initial state that dominates in top production at the Tevatron; we have done the calculation for the $gg$ and $qg$ initial states but do not show those results here.

We apply the following kinematic cuts to all final-state jets (which in this parton-level calculation are quarks and gluons) and to the charged lepton:

$$E_{Tj}, E_{Tl} \geq 15 \text{ GeV} ,$$
$$|\eta_j|, |\eta_l| \leq 2.5 ,$$
$$\Delta R_{jj}, \Delta R_{jl} \geq 0.4 .$$

These are meant to mimic experimental cuts, so that the partons are likely to appear in the detectors with enough angular separation to be distinguishable as separate particles. They also protect the theoretical cross section from the soft and collinear singularities that appear at tree level.

In the distributions we present below we will decompose the cross section into contributions from radiation associated with various parts of the process. These contributions are:

1. **Production-stage radiation**, which comes from the initial quarks or internal gluon line, or from the top (or antitop) quark before it goes on shell.
2. **Decay-stage radiation** that is part of the $t$ or $\bar{t}$ decay; this is further subdivided into:
   a. **Decay-tb radiation** from either of the $b$'s or from either of the $t$'s after they go on shell.
   b. **Decay-W radiation** from the decay products of hadronically decaying $W$ bosons.

We make these distinctions in the parton-level calculation based on kinematics to see how the various contributions behave; this cannot of course be done for a given event in the experiments. In principle the production-stage and decay-stage contributions can interfere with each other (with the exception of the decay-$W$ radiation, which cannot interfere with the other processes because the $W$ is a color singlet). And although we do include all interferences in our calculation, in practice the production-decay interference is very small for gluon energy thresholds large compared to the top width $\Gamma_t = 1.5 \text{ GeV}$, as in the present case.

Figure 1 shows the distribution in pseudorapidity of the extra jet at the Tevatron for the lepton + jets case, i.e. for a single hadronically decaying $W$. The production-stage radiation, shown as a dashed histogram, has the broadest distribution, populating most of the accessible rapidity range. The two decay-stage contributions are more centrally peaked. The decay-$tb$ contribution (dotted histogram) is slightly larger, as it accounts for radiation from both the $t$ and $\bar{t}$, but the decay-$W$ contribution (dot-dashed histogram) from a single $W$ is similar in size and shape to the decay-$tb$, as was found in the soft approximation. The central region of the detector is populated by all three contributions, which means that distinguishing them will be challenging at best.

Results for the all-hadronic mode, where both $W$ bosons decay to quarks, are similar, the main difference being that the decay-$W$ contribution approximately doubles in size.

The transverse energy distributions of the radiated jet are shown in Figure 2 for the lepton + jets (top) and all-hadronic modes. The spectra look quite similar for the various contributions, and extend to large values of transverse energy.

### 3 Top Mass Reconstruction

Given the difficulty of distinguishing extra jets radiated in the production stage from those from decay, we can ask what effect the extra jet has on mass reconstruction. First, however, we have to ask which jet is the extra one. It seems reasonable to assume that the gluon jet is the
one with the lowest $E_T$, given the infrared singularity that characterizes emitted radiation. While it is true that of the final state jets, the gluon has the softest $E_T$ spectrum, the gluon has the lowest $E_T$ only just over half the time (just under half for the all-jets mode). Still, there is no method that is obviously better for identifying the extra jet.

We reconstruct the top mass from the final state partons without assuming we know which jet is which, but we omit the jet with the lowest $E_T$. For the lepton + jets mode we do the following.

1. Drop the lowest $E_T$ jet. This leaves four jets.
2. Find the jet pair with invariant mass closest to $m_W$.
3. Solve for the neutrino four-momentum using the charged lepton momentum and $W$ mass constraint.
4. Combine each of the $W$’s with each of the remaining jets to give $m_t$ and $m\bar{t}$. Choose the combination that minimizes the $t-\bar{t}$ mass difference.

The $m_t$ distributions obtained from this procedure are shown in Figure 3. The top plot shows the distribution for the top with the hadronically decaying $W$, and the bottom corresponds to leptonic $W$ decay. In both cases we see a peak at the correct central value, where the procedure resulted in the correct mass. We also see smooth, reasonably flat high and low tails from wrong combinations, in addition to bumps in the low tails corresponding to the omission of jets that were part of the decays. Note that these bumps appear in the contributions from decay-stage radiation, when all of the jets should be included in the mass reconstruction. Finally, the leptonically decaying $W$ gives a sharper top mass distribution because with no radiation from the $W$ decay, there are fewer wrong combinations.

The results shown in Figure 3 are meant to be illustrative and should not be taken as a direct representation of distributions measured in experiment. In particular, this calculation is at the parton level; we have not included backgrounds; and these distributions only include events with a radiated gluon. The effects of hadronization, energy resolution and detector effects, and background will certainly make things worse. However there are certainly ways to improve on this simplistic analysis as well. For example, although we minimized mass differences we did not cut on them explicitly. Figure 4 shows the magnitude of the $t-\bar{t}$ mass difference on an event-by-event basis for the case shown above. It suggests that an absolute cut on the mass difference could reduce the tails in the mass distributions. Interestingly, $b$-tagging, i.e. assuming we can identify $b$ jets, does not improve the mass distributions much. This is because we do not include backgrounds.

The results for the all-jets mode are similar, except that with both $W$’s decaying to quarks there are two more jets in each event, leading to more possible wrong
Figure 3: The reconstructed top mass distributions (solid histograms) in the lepton + jets mode for the hadronically decaying $W$ (top plot) and the leptonically decaying $W$, and their decomposition in terms of production, decay-$tb$ and decay-$W$ emission contributions.
combinations and a corresponding increase in the tails.

4 Conclusions

In top quark physics, as statistics improve, systematic effects associated with gluon radiation will dominate measurements of the top mass. We have added hadronic $W$ decays to analyses of gluon radiation in top production and decay and presented some initial results here. We find that the contribution from radiation from a single hadronically decaying $W$ is nearly as large as and comparable in shape to the remaining decay-stage radiation from both the $t$ and $\bar{t}$. The presence of radiation from both the top production and decay stages complicates the reconstruction of the top momentum from its decay products and hence complicates the measurement of the top mass. Further analysis is in progress for the Tevatron and LHC.

Acknowledgements

Work supported in part by the U.S. Department of Energy, under grant DE-FG02-91ER40685 and by the U.S. National Science Foundation, under grant PHY-9600155.

References

1. L.H. Orr, T. Stelzer, and W.J. Stirling, Phys. Rev. D 52, 124 (1995); Phys. Lett. B354 (1995) 442.
2. L.H. Orr, T. Stelzer, and W.J. Stirling, Phys. Rev. D 56, 446 (1997).
3. B. Masuda, L.H. Orr, and W. J. Stirling, Phys. Rev. D 54 (1996) 4453.
4. T. Stelzer and W.F. Long, Comp. Phys. Commun. 81 (1994) 357.
5. T. Andre, L.H. Orr, and T. Stelzer, in preparation.