Fermi National Accelerator Laboratory

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TOP QUARK PRODUCTION DYNAMICS[1]

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I review standard top quark production at the Fermilab Tevatron. The current theoretical understanding of the total cross section and many partial differential cross sections is presented. Studies on the effects of extra gluon radiation on the top quark mass determination are reviewed. The possibility of new mechanisms for $t\bar{t}$ production are also discussed.

INTRODUCTION

Top quark production at the Fermilab Tevatron probes very high mass scales, $\mathcal{O}(500\ GeV)$, and therefore is sensitive to new physics at this scale. Hence, it is important that we studied this process with high precision and compare the results with the standard model predictions. Also the top quark mass along with the W-boson mass can be used as an indirect measurement of the Higgs boson mass or even demonstrate the failure of the standard model. Therefore we must measure the top quark mass with the greatest precision possible with the events available to us.

Here I review the status of the cross section calculations for top quark production not only for the total cross section but also for the shape of the various distributions associated with the production. For the kinematic measurement of the top quark mass the effects of extra gluon radiation are important for precision measurements. I will discuss the status of our understanding of this extra radiation. Finally, I will present a few of the possibilities for new physics that can dramatically change top quark production not only in total rate but also in the shape of the kinematic distributions.

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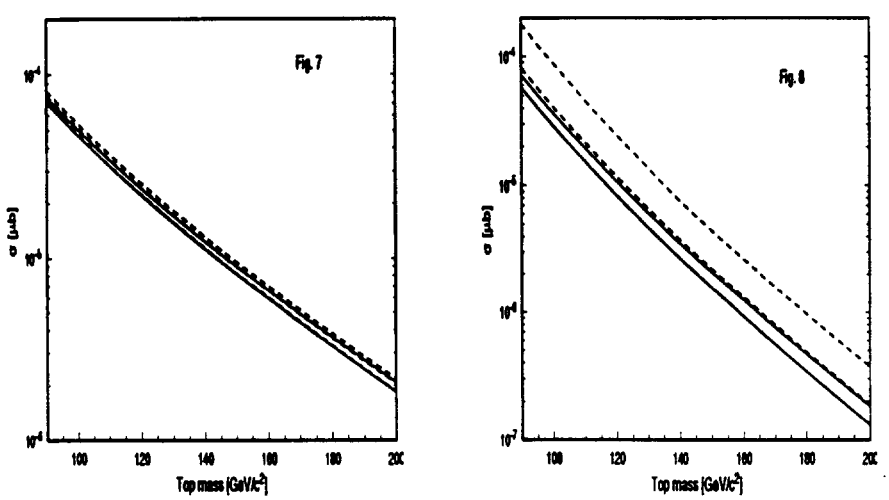
CROSS SECTION

Total

In hadron colliders the dominant mode of top quark production is via quark-antiquark annihilation or gluon-gluon fusion,

$$q\,\bar{q} \rightarrow t\,\bar{t}$$
$$g\,g \rightarrow t\,\bar{t}.$$

Currently, the most accurate determination of the QCD top cross section is the Resummed Next to Leading Order (Re$\sum$ NLO) calculation of Laenen, Smith and van Neerven (1). Fig. 1 is a comparison of this Re$\sum$ NLO calculation and the exact NLO calculation of Ellis (2) for both the $q\bar{q}$ channel and the gg channel at the Fermilab Tevatron. Clearly, the gg channel has larger corrections from these resummed soft gluons. However, for large top quark mass at the Tevatron, this channel is only a small part of the total cross section.



(a) (b)

FIG. 1. Range of cross sections for the exact NLO calculation (solid) and the Resummed NLO calculation (dashed): (a) for the $q\bar{q}$ channel only, (b) for the gg channel only.

Fig. 2 is a similar comparison for the total cross section. At large top quark masses the difference between the Re$\sum$ NLO calculation and the NLO calculation is at the 20% level. At the LHC where the gg channel will be the dominant production mode these resummed corrections will be a much larger correction to the total cross section.

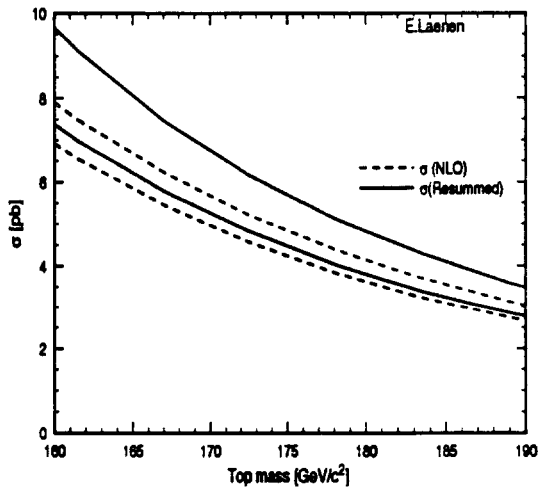
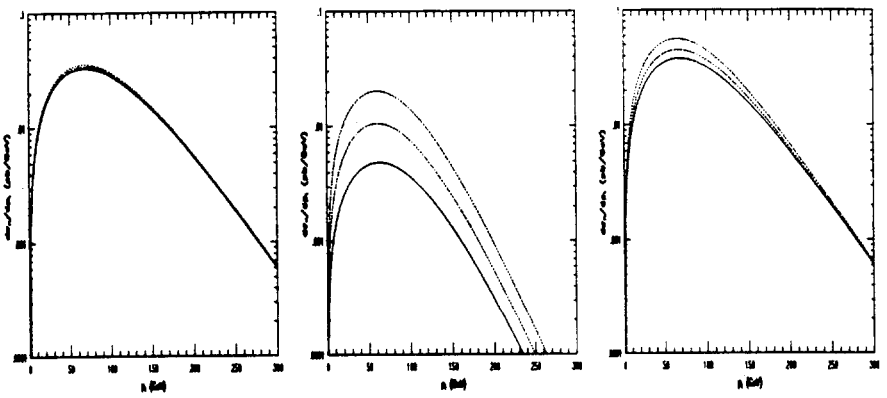


FIG. 2. The total QCD Top Quark Production Cross Section at the Tevatron. The solid curves give the range of values using the resummed next to leading order calculations and the dashed curves are the range for the next to leading order calculations. The same structure functions were used.

The resummation technique of Laenen, Smith and van Neerven involves a infra-red cutoff which is set appropriately. Contopanagos and Sterman (3) have pioneered a resummation technique, principal value resummation, which does not involve such an arbitrary cutoff. This method has been applied to top production at the Tevatron by Berger and Contopanagos (4). At the time of this conference they had completed the $q\bar{q}$ channel but were still working on the gg channel. The results using the principal value resummation for the less sensitive $q\bar{q}$ channel are in close agreement with the infra-red cutoff resummation. The completion of this calculation for the total cross section is important for determining how well we know the total top quark cross section.

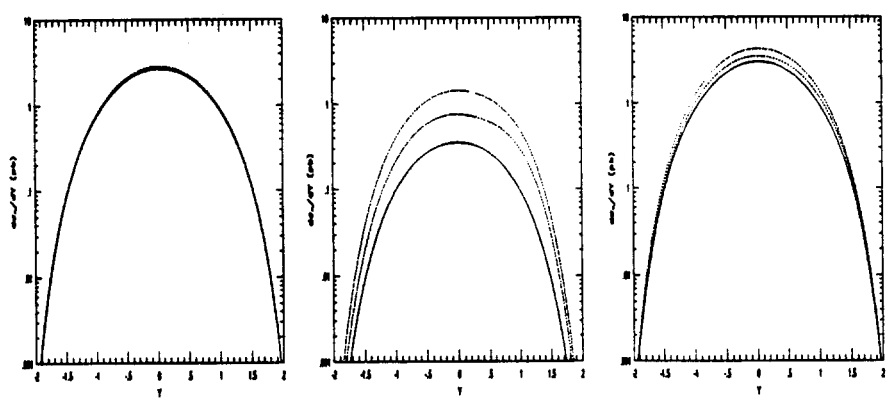
Shapes

Kidonakis and Smith (5) have calculated the inclusive transverse momentum and rapidity distributions for top quark production at the Fermilab Tevatron using the infra-red cutoff resummation technique. A comparison of these results to the next leading order calculation for the transverse momentum of the top quark is shown in Fig. 3 and for the rapidity in Fig. 4.



(a) (b) (c)

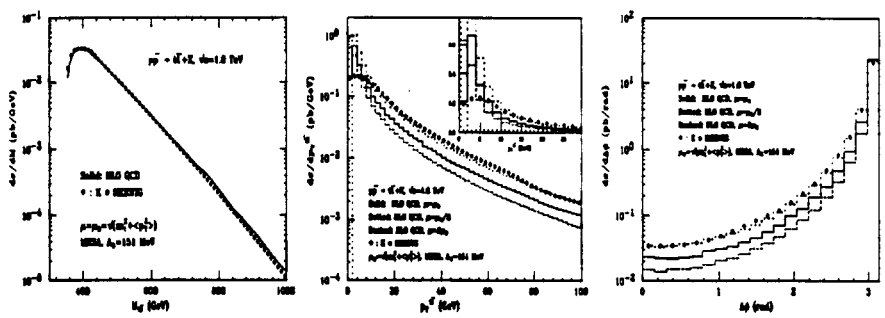
FIG. 3. The top quark p_t distribution for 175 GeV top quark mass. Solid line is NLO and the dashed lines are the range of values for the Re$\sum$ NLO calculation. For (a) $q\bar{q}$ channel, (b) gg channel, (c) Sum.



(a) (b) (c)

FIG. 4. The top quark rapidity distribution for 175 GeV top quark mass. Solid line is NLO and the dashed lines are the range of values for the Re$\sum$ NLO calculation. For (a) $q\bar{q}$ channel, (b) gg channel, (c) Sum.

Frixione, Mangano, Nason and Ridolfi (6) have calculated a number of distributions for top quark production in NLO and made comparisons with the HERWIG monte carlo. In Fig. 5, I show from their paper the invariant mass distribution of the $t\bar{t}$ pair, the transverse momentum distribution of the $t\bar{t}$ pair and the azimuthal distribution of the $t\bar{t}$ pair. These last two distributions are trivial at lowest order so it is satisfying to see that the two calculations are comparable in the region where we expect approximate agreement.



(a) (b) (c)

FIG. 5. For a top quark mass of 174 GeV at NLO verses HERWIG for (a) the invariant mass distribution of the $t\bar{t}$ pair, (b) the transverse momentum distribution of the $t\bar{t}$ pair and (c) the azimuthal distribution of the $t\bar{t}$ pair.

EXTRA GLUON RADIATION

For precision measurements of the top quark mass, we need to understand the effects of extra gluon radiation in top quark production. This has been studied by Lampe (7), Orr and Stirling (8) and most recently by Orr, Stelzer and Stirling (9). In Fig. 6, I show the results of Orr, Stelzer and Stirling, for the invariant mass of the W-boson and b-quark jet without and with an extra gluon jet. Clearly the results of the mass fitting are sensitive to how this extra jet is treated. Therefore it is important that we understand this process very well for precision top quark mass measurements.

Orr, Stelzer and Stirling have also compared their exact tree-level calculation with the HERWIG monte carlo, see Fig. 7. The difference between these two calculation, I believe, is dependent upon how the top quark mass is included in the monte carlo. This discrepancy is still to be resolved. Further discussion on this problem can be found in Orr, Stelzer and Stirling (10) which addresses this issue in the simpler environment of an e+e- collider.

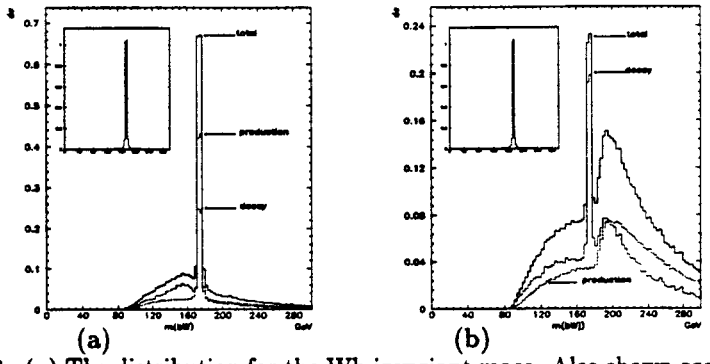


FIG. 6. (a) The distribution for the Wb invariant mass. Also shown are the distributions corresponding to the production (dot-dashed) and decay (dotted) emission contributions. (b) The distribution for the Wb+jet invariant mass. Also shown are the distributions corresponding to the production (dot-dashed) and decay (dotted) emission contributions.

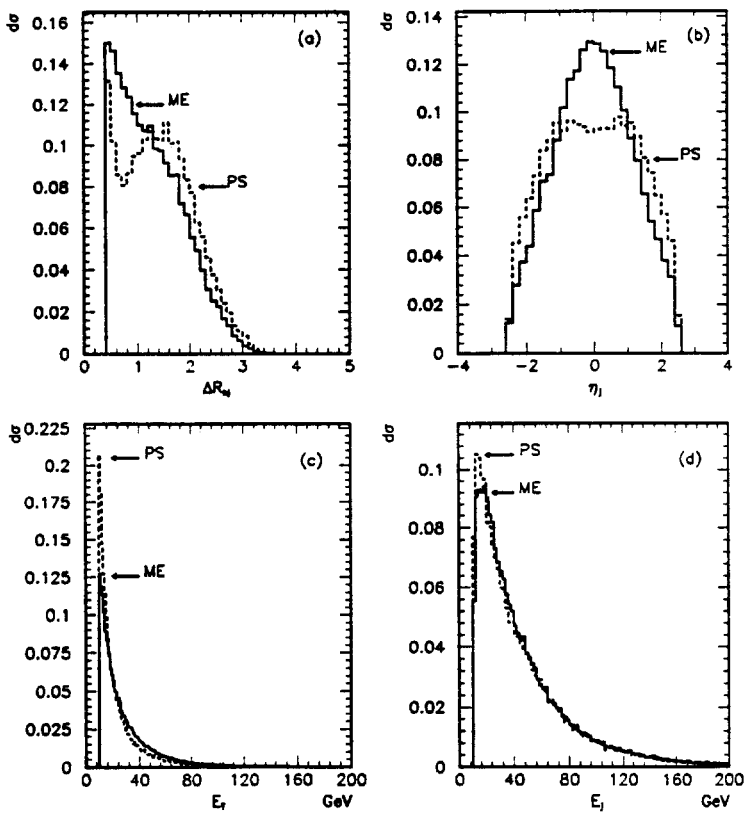


FIG. 7. Distributions in (a) the jet-b separation ΔR_{bj}, (b) the jet pseudorapidity η_j, (c) the jet E_T, and (d) the jet energy E_j in the subprocess center-of-mass frame, for the exact calculation (solid, labeled ME) and as obtained using the HERWIG parton-shower monte carlo program (dashed, labeled PS).

NEW DYNAMICS

Since the top quark mass is close to the electro-weak symmetry breaking scale it is possible that top quark production will provide an exciting window on new physics.

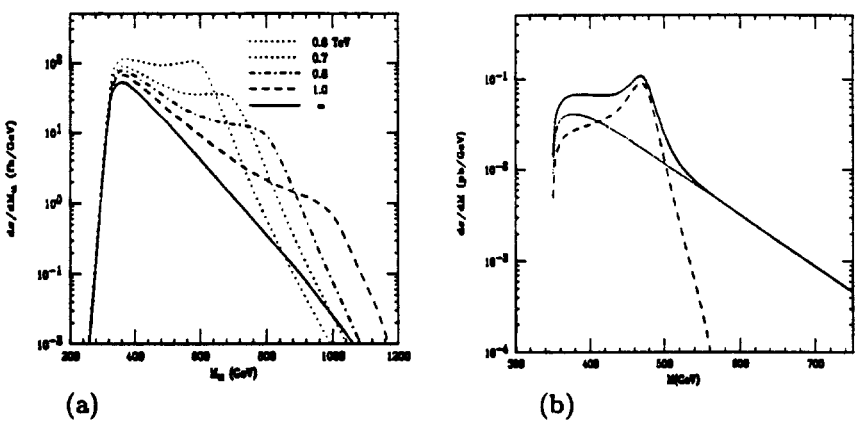


FIG. 8. The invariant mass of the $t\bar{t}$ pair for (a) topcolor octet model and (b) the two scale technicolor model.

Hill and Parke (11) have shown the effects of new physics on top production in the $q\bar{q}$ channel using both a general effective Lagrangian approach as well as in a specific top color model. Fig. 8(a) gives the distortions in the $t\bar{t}$ invariant mass in the color octet top color model for various masses of the top color boson.

Later Eichten and Lane (12) discussed the effects on top quark product in a multi-scalar technicolor model. Here the enhanced production is in the gg channel. Fig. 8(b) is their invariant mass plot.

CONCLUSIONS

The total cross section for $t\bar{t}$ production is in good shape for the Fermilab Tevatron. New calculations which include higher order effects give small contributions. Therefore the uncertainties in this cross section are well under control. Many differential cross section have also been calculated, some simple ones using the Re$\sum$ NLO techniques while others which are trivial at tree level have been calculated at NLO.

The effects of extra gluon radiation in the determination of the top quark mass is still under study. I expect that the discrepancy between the tree level

matrix element calculation and the HERWIG monte carlo will be resolved in the near future.

The possibility of finding new physics in $t\bar{t}$ production is very exciting. Kinematic distributions for top production and decay are eagerly waited. Watch out for surprises!

I wish to thank all the authors of the references who help me in the preparation of this presentation.

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