REPORT OF THE SUBGROUP ON THE TOP QUARK

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and

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\textbf{ABSTRACT}

The top group studied discovery issues as well as measurements to be made at the Tevatron, the LHC and the SSC.

1. Introduction

The top physics section was a subgroup of the heavy flavors group. The results compiled in this report are based on a review talk given by C.–P. Yuan\textsuperscript{[1]}, and reports presented at both the SSC Physics Symposium held in Madison, Wisconsin on 29–31 March 1993 and the Workshop on Physics at Current Accelerators and the Supercollider held in Argonne, Illinois on 2–5 June 1993. To make this report more informative, we also include some recent results in the literature.

2. Why Study the Top Quark?

The top quark is a crucial element of the Standard Model (SM). The top quark has been found to be heavier than 45 GeV from the SLAC and LEP experiments and 108 (103) GeV from CDF (D0) data assuming different top production cross sections\textsuperscript{[2,3]}. The first limit is model independent while the second limits are for the Standard Model top quark. A model independent limit derived from $W$ and $Z$ cross sections at CDF of 62 GeV was also presented\textsuperscript{[2]}. Upper bounds on $m_t$ can be obtained from examining the radiative corrections to low energy observables, such as the $\rho$ parameter, which are proportional to $m_t^2$ at the one loop level and thus sensitive to $m_t$. The consistency of all the low energy experimental data requires

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$m_t$ to be less than about 200 GeV. Overall fits, dominated by LEP data, give a top mass of about 160 GeV with a statistical error of about 20 GeV and a systematic variation with the Higgs mass of another $\pm 20$ GeV [4].

Since the top quark is heavy, of the same order of magnitude as the $W$–boson mass, any physical observable related to the top quark may be sensitive to new physics. The top quarks will therefore allow many new tests of the SM and new probes of physics at the 100 GeV scale [3]. The most important consequence of a heavy top quark is that to a good approximation it decays as a free quark, since its lifetime is short and it does not have time to bind with light quarks before it decays [6]. Thus, we can use the polarization properties of the top quark as an additional tool, testing the SM and probing for new physics [5]. Furthermore, because the heavy top quark has the weak two–body decay $t \to bW^+$, it will analyze its own polarization.

First, we discuss the production mechanism for top quarks at hadron colliders, then we discuss the decay modes and branching ratios for top quarks. We also report on how well the mass and width of the top quark can be measured, and how to detect CP violation effects in top quarks studies.

3. How to Produce Top Quarks

At the Tevatron, the dominant production mechanisms for a SM top quark are the QCD processes $q\bar{q}$, $gg \to t\bar{t}$. For a heavy top quark, $m_t > 100$ GeV, the $q\bar{q}$ process becomes most important. The full next-to-leading-order calculation for these QCD processes was completed several of years ago [7]. The electroweak radiative corrections to these processes were also calculated in Refs. [8] and [9]. Therefore, the production rates for top quark pairs at hadron colliders are well predicted.

If the top quark is as heavy as 140 GeV, then another production mechanism known as the $W$–gluon fusion process becomes important [10,11]. The production mechanism of the latter process involves the electroweak interaction, therefore it can probe the electroweak sector of the theory. This is in contrast to the usual QCD production mechanism which only probes the QCD interaction when counting the top quark event rates.

At the SSC/LHC, the dominant production mechanism for a SM top quark is the QCD process $gg \to t\bar{t}$. The subprocess $q\bar{q} \to t\bar{t}$ is always small compared with the gluon–gluon fusion process, even into the TeV region. In one year there will be about $10^8 t\bar{t}$ pairs produced at the SSC from the QCD processes. The $W$–gluon fusion process is also important. For a 140 GeV top quark, about $10^7$ top quarks per year are produced via this mechanism at the SSC. The production rates of the top quark at the LHC, given ten times higher luminosity, are about equal to those at the SSC.
4. Polarization of Top Quarks

In the SM, the heavy top quarks produced from the Born level QCD processes are unpolarized. At the one loop level, the top quarks are transversely (perpendicular to the scattering plane) polarized at the level of a couple of percent \[12, 13\]. Top quarks will have longitudinal polarization if weak effects are present in their production. The polarization of the top quark produced from the usual QCD process after including the electroweak radiative corrections was discussed in Ref. \[9\]. In the SM, the heavy top quark produced via the $W$–gluon fusion process is left–handed polarized. If new interactions occur, they may manifest themselves in an enhancement of the polarization effects in the production of the top quark via the $W$–gluon fusion process \[9\].

5. How Top Quarks Decay

For a SM top quark heavier than the $W$–boson, the dominant decay mode of the top quark is the weak two–body decay $t \rightarrow bW^+$. In this mode, the top quark will analyze its own polarization \[3\].

QCD and SM electroweak radiative corrections to the decay width of $t \rightarrow bW^+$ were found to be $\sim -10\%$ and $\sim 1\%$, respectively \[14\]. The corrections to $\Gamma(t \rightarrow bW^+)$, from models such as a two Higgs doublet model and the Minimal Supersymmetric Standard Model (MSSM), can reach the level of 1% in favorable cases \[15\].

An extension of the standard Higgs sector with two Higgs doublets has both charged and neutral Higgs bosons. If the charged Higgs boson is lighter than the top quark, the branching ratio for the decay $t \rightarrow bH^+$ could be comparable to that for $t \rightarrow bW^+$ \[14\]. The QCD corrections could reduce the $t \rightarrow bH^+$ decay rate by more than 10% \[17\]. The electroweak radiative corrections to $t \rightarrow bH^+$ were calculated and found to reduce the partial width by a few to 10 percent, depending strongly on the parameter $\tan \beta$ and the top quark mass \[15\]. The supersymmetric non-standard decay mode, $t \rightarrow \tilde{t}_1 \tilde{Z}_1$, has been examined in Ref. \[19\].

Another interesting channel for the decay of the top quark is the Flavor Changing Neutral Current (FCNC) decay mode. In the SM, the branching ratios for the FCNC decay modes were found to be too small to be detected: $Br(t \rightarrow cH) \sim 10^{-7}$, $Br(t \rightarrow cg) \sim 10^{-10}$, $Br(t \rightarrow cZ) \sim 10^{-12}$, $Br(t \rightarrow c\gamma) \sim 10^{-12}$ \[21\]. The branching ratios of these modes in two Higgs doublet models or the MSSM could be enhanced by $3$–$4$ orders of magnitudes if one pushes the parameters far enough \[21, 22\]. It is thus a prediction of the SM and the MSSM that no large FCNC decays exist for top quarks, so if any is detected it is beyond these approaches. In some models, the branching ratio of the FCNC ($t \rightarrow cH$) decays may be significantly enhanced, of the order 1%, due to large Yukawa couplings \[23\].
6. How to Detect Top Quarks

The strategies in detecting SM top quark via the QCD processes at the Tevatron, LHC and SSC have been studied in detail. We refer the readers to the Proceedings of the 1990 Summer Study on High Energy Physics [24], the SDC Technical Design Report [25], the GEM Technical Design Report [26], and the Proceedings of the Large Hadron Collider Workshop [27]. Other results on top pair signatures can be found, for instance, in Refs. [28,29], [30,29] and [31] for the dilepton, the single lepton and the all–jet modes, respectively.

In this Workshop, H. Baer, C. Chen and M. Reno presented their study on the jet activity associated with pair production of top quarks at hadron colliders [32]. Their approach is based upon a merger of $2 \rightarrow 3$ matrix elements with initial and final state parton showers, thus yielding a calculation of $t\bar{t}$ plus multi-gluon production, where the hardest gluon radiation is constrained to agree with tree-level matrix element results. It is found that the merged calculation yields more jet activity in the forward region than pure matrix element estimates, but also more jet activity in the central region.

The strategies for observing a top quark from the $W$–gluon fusion process at the Tevatron are extensively discussed in Ref. [10]. With proper kinematic cuts, with mass of 140 GeV and including the branching ratio $W \rightarrow e, \mu$, there should be about 10 $t$ or $\bar{t}$ signal events from this process produced at the Tevatron with a 100 pb$^{-1}$ at $\sqrt{s} = 1.8$ TeV. The major background is from $W + jets$ production which is of the same order as the signal rate with $b$-tagging using a vertex detector. The $b$-quark tagging efficiency is assumed to be 50% with no misidentification.

A preliminary study shows that it should be possible to study top quarks produced via this process at the SSC and the LHC if a $b$-vertex detector is used [33]. There are about 20,000 signal events and 700 background events for a 140 GeV top quark produced via the $W$–gluon fusion process at the SSC, where the branching ratios for $W^\pm \rightarrow e^\pm$ or $\mu^\pm$ are included. This result is obtained by assuming that it is possible to detect a jet within rapidity 4.0 and with a minimum transverse momentum of 40 GeV. This result of a large signal-to-background ratio is mainly due to the characteristic features of the transverse momentum and rapidity distributions of the spectator quark which emitted the virtual $W$ in the $W$-gluon fusion process. However, if the rapidity coverage of the SSC/LHC detector is smaller, then the efficiency of keeping signal events is lower and the background event rate becomes larger [27].

In models such as the MSSM and the two Higgs doublet models, top quarks can also decay into a charged Higgs boson. A. Pomarol and C. Schmidt showed in this workshop that the differences in the lepton energy spectra from top quark decay to $H^+$ and $W^+$ may be useful in enhancing the charged Higgs signal and for detecting the top quark when the branching ratio of $t \rightarrow bH^+ \rightarrow bl^+\nu$ is large [34]. Further analysis is required in order to optimize the use of lepton energy information, especially in conjunction with other techniques for enhancing the $H^+$.
signal, such as $\tau$ polarization [35] or $b$-tagging [36].

7. Measuring the Top Quark Mass

Based on the studies performed in Refs. [25], [26] and [27], the top quark mass can be measured to within about 1.6%. The first method is to study the $e\mu$ mode of the $t\bar{t}$ pair [28]. After measuring the branching ratio of $t \to bW^+(\to l^+\nu)$, one can deduce the mass of the top quark from the calculated event rate predicted by the SM. The second method is to measure the invariant mass of the top quark via $t \to bW^+(\to q_1\bar{q}_2)$ [30]. The third method, which gives the best measurement of $m_t$, is to measure the invariant mass $M_{e\mu}$ of $e^+$ and $\mu^-$ from the decay of $t \to b(\to \mu^-)W^+(\to e^+\nu)$.

It has been shown that $M_{e\mu}$ is not sensitive to the QCD corrections [9]. The distribution of $M_{e\mu}$ depends on the polarization of the top quark [37]. Without any kinematical cuts on the decay products of the top quark, $M_{e\mu}$ should be the same for either a left-handed or a right-handed top. When kinematical cuts needed to suppress the backgrounds are applied, the mean value of $M_{e\mu}$ can be different for a left-handed or a right-handed top [38]. As discussed in section 4, the top quarks produced from the QCD processes are almost unpolarized. However, in the $W$–gluon fusion process, they are almost one hundred percent longitudinally polarized. Therefore, the effects of the polarization of the top quark should be carefully included when measuring the mass of the top quarks produced by the $W$–gluon fusion process. According to the studies done by G.A. Ladinsky in this workshop, 100% polarization would affect the mass measurement of the top quark by a few percent.

8. Measuring the Top Quark Width

Reference [37] shows that the intrinsic width of a SM top quark cannot be measured at the SSC and the LHC through the usual QCD processes. For instance, the intrinsic width of a 140 GeV SM top quark is about 0.6 GeV and the full width at half maximum of the reconstructed top quark invariant mass will be about 11 GeV including the detector resolution effects which smear the final state parton momenta. A similar conclusion was also given from a hadron level analysis presented in the SDC Technical Design Report; the top quark reconstructed invariant mass has a width of 9 GeV for a 150 GeV top quark mass [25]. Can the top quark width $\Gamma(t \to bW^+)$ be measured better than the factor $11/0.6 \sim 20$ mentioned above? The answer is yes. As pointed out in Ref. [37], the width $\Gamma(t \to bW^+)$ can be measured by counting the production rate of top quarks from the $W$–$b$ fusion process. This is equivalent to the $W$–gluon fusion process with the proper treatment of the bottom quark and the $W$ boson as partons inside the hadron. The $W$–boson which interacts with the $b$–quark to produce the top quark can be treated as an on–shell boson in the leading log approximation. The moral is that even with the approximations considered, a factor of 2 in the uncertainty for the production rate for this process
gives a factor of 2 in the uncertainty for the measurement of $\Gamma(t \rightarrow bW^+)$. This is still much more accurate than what can be done at the SSC and the LHC through the usual QCD processes. Therefore, this is an extremely important measurement to make at the Tevatron because it directly tests the SM coupling of $t$-$b$-$W$. Similarly, this production mechanism is also useful at the SSC/LHC for detectors covering a large enough rapidity region, as discussed in section 6.

After the top quark is found, one can measure the branching ratio of $t \rightarrow bW^+(\rightarrow l^+\nu)$ by the ratio of $(2l + jets)$ and $(1l + jets)$ event rates from $t\bar{t}$ production. Then, a model independent measurement of the decay width $\Gamma(t \rightarrow bW^+)$ can be made by counting the production rate of $t$ in the $W$–gluon fusion process. Should the top quark be found to be different from the SM expectations, we would then look for non-standard decay modes of the top quark \[39\]. It is still important to measure at least one partial width $\Gamma(t \rightarrow bW^+)$ precisely, in order to discriminate between different models of new physics.

9. CP Violation in Top Quarks

If CP is violated in the production of top quarks at the Tevatron, the production rate of $t$ from $\bar{p}p(W^+g) \rightarrow \bar{t}bX$ would be different from that of $\bar{t}$ from $\bar{p}p(W^-g) \rightarrow \bar{t}bX$. Therefore, one can detect large CP violation effects by observing the difference in the production rates of $t$ and $\bar{t}$. Large CP violating effects are required to have the cosmological baryon asymmetry produced at the weak phase transition \[40\].

In the $W$–gluon fusion process, the top quark is almost one hundred percent longitudinally polarized. This allows us to probe CP violation in the decay process $t \rightarrow W^+b \rightarrow l^+\nu b$. The most obvious observable for this purpose is the expectation value of the time–reversal quantity $\vec{\sigma}_t \cdot \vec{\hat{p}}_b \times \vec{\hat{p}}_l$, where $\vec{\sigma}_t$ is the polarization vector of $t$, and $\vec{\hat{p}}_b$ ($\vec{\hat{p}}_l$) is the unit vector of the $b$ ($l^+$) momentum in the rest frame of the top quark \[41\]. This was suggested in Ref. \[5\] and further studied in Ref. \[42\].

Furthermore, it was shown in Ref. \[43\] that it is possible to study CP violation effects, via the usual QCD processes, by observing the asymmetry in the energies of the two leptons from the decay of the $t\bar{t}$ pairs produced at the SSC/LHC. A detailed study, including all the possible interactions for top quarks, on how to measure the CP violation effects at the SSC and LHC colliders is given in Ref. \[44\] by C. Im and G.L. Kane.

10. Top Quark Couplings

Recently, there has been a lot of interesting work studying the effects of large Yukawa couplings due to heavy top quarks in the Supersymmetric Grand Unified Theories (SUSY–GUT). Some of these effects, such as the unification of the gauge couplings, the evolution of the Yukawa couplings, and the evolution of the CKM matrix, etc., were discussed by V. Barger in this Workshop \[45\].

In the SM, the top quark gains mass through the Yukawa coupling to the
Higgs boson $H$. To test the dynamics of the generation of the fermion mass, we should also measure the coupling of the $Ht\bar{t}$. The direct measurement of this coupling can be done by studying the production of top quarks in $gg, q\bar{q} \rightarrow t\bar{t}H$ and $qq, q\bar{q} \rightarrow t\bar{b}H$ [10,17]. Since the signal rate is not large at the SSC/LHC, it might be difficult to get a precise measurement from these processes. If the luminosity of the collider is high enough to produce a large number of $qg, q\bar{g} \rightarrow t\bar{b}H$ events, one can test the relative sign of the $Ht\bar{t}$ and $HW^+W^-$ couplings which depend on the underlying dynamics of symmetry breaking. Another place to look for the coupling of $Ht\bar{t}$ is in the production of the Higgs boson from the gluon fusion process through a top quark triangle loop. The QCD next-to-leading-order calculation of this cross section was performed a several years ago [48]. To get a precise measurement of the $Ht\bar{t}$ coupling through radiative corrections to Higgs boson production, we have to know the kinematics of the Higgs boson after including the multiple gluon emission effects from initial state radiation. This calculation of the QCD-gluon resummation was performed in Ref. [49].

11. Top Quark Decays as Backgrounds

Up to now, we have only discussed the top quark as a signal; it is also one of the most important backgrounds in probing new physics at high energy colliders. For example, Refs. [50] and [51] show how to suppress the backgrounds associated with the top quark in order to study the strongly interacting longitudinal $W$-boson system in the TeV region to probe the mechanism of the electroweak symmetry breaking. These top quark background estimates depend on a forward jet tagging requirement. This is precisely the region where multiple gluon emission effects can be large. Ref. [32] estimates these effects, and finds the multiple gluon effects lead to larger $t\bar{t}$ backgrounds if only forward jet tagging is required. However, a combination of forward jet tag and central jet veto yields results perhaps coincidentally close to $2 \rightarrow 3$ calculations, due to extra gluon radiation in the central region as well. Top quarks as backgrounds for some other processes were discussed in Ref. [52].

In conclusion, we have to study the top quark and its production in detail to test the SM, to probe directly for new physics and to allow other probes for new physics. Most of these goals can be accomplished at the Tevatron and SSC/LHC colliders.

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