Top–Quark Production and Flavor Physics—The Talk†

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Abstract
Because of the top quark’s very large mass, about 175 GeV, it now provides the best window into flavor physics. Thus, pair–production of top quarks at the Tevatron Collider is the most incisive probe of this physics until the Large Hadron Collider turns on in the next century. In this talk I discuss how moments of the $t\bar{t}$ invariant mass distribution can be used to distinguish among standard and alternative mechanisms of $t\bar{t}$ production.

1. Introduction
The CDF collaboration has reported evidence for top–quark production at the Tevatron Collider [1],[2]. According to these papers, the top mass is $m_t = 174 \pm 10^{+13}_{-12}$ GeV. The data in these papers are based on an integrated luminosity of $19.3 \pm 1$ pb. When combined with the detector’s efficiencies and acceptances, CDF reports the production cross section $\sigma(p\bar{p} \rightarrow t\bar{t}) = 13.9^{+6.3}_{-4.1}$ pb at $\sqrt{s} = 1800$ GeV. The predicted QCD cross section for $m_t = 174$ GeV, including next–to–leading–log corrections [3] and soft–gluon resummation [4] is $\sigma(t\bar{t}) = 5.10^{+0.73}_{-0.43}$ pb. This is 2.8 times smaller than the central value of the measured cross section. The uncertainty in $\alpha_S$ increases the theoretical error $\sigma(t\bar{t})$ to at most 30% [5].

The error on the CDF cross section is large, but so is the discrepancy with QCD. If it holds up, it heralds the long–awaited collapse of the standard model. In any event, it is clear that the top quark provides a wide–open window into the world of flavor physics. It is the heaviest elementary particle we know and, more to the point, the heaviest elementary fermion by a factor of 40! If the Higgs boson of the minimal one–doublet model exists, its coupling to the top quark, renormalized at $m_t = 174$ GeV, is $\Gamma_t = 2^{3/4} \sqrt{\frac{1}{m_t}} m_t = 1.00$. If charged scalars—members of Higgs–boson multiplets or technipions—exist, they couple to top quarks with $O(1)$ strength and they decay as $H^+ \rightarrow t\bar{b}$.

In this talk, we discuss how moments of the $t\bar{t}$ invariant–mass ($M_{t\bar{t}}$) distribution may be used to distinguish among competing models of top production. We point out that, in QCD, the mean and root–mean–square invariant masses are linear functions of the top–quark mass over the entire interesting range of $m_t$. Thus, the $M_{t\bar{t}}$ distribution can provide an independent determination of the top quark’s mass. We apply this to the existing data [1] and find good consistency with the reported mass. This analysis is made at the simplest theoretical level. The analysis needs to be carefully done by the CDF and DØ collaborations themselves.

The lowest two moments and their variance, $\Delta M_{t\bar{t}} = \sqrt{(M_{t\bar{t}}^2) - (M_{t\bar{t}})^2}$, can provide valuable discrimination among top–production models for limited statistics. Examples of this are given for three models of enhanced $t\bar{t}$ production. The first involves resonant production of a 400–600 GeV color–octet vector meson (“coloron”), $V_8$, which is associated with electroweak symmetry breaking via top–condensation [6] and which interferes with QCD production via the process $q\bar{q} \rightarrow V_8 \rightarrow t\bar{t}$ [7]. The second example invokes a color–octet pseudoscalar, $\eta_T$ [8]. In multiscale models

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of walking technicolor [1, 1], it is produced strongly in gluon–gluon fusion and decays mainly to $t\bar{t}$ [1, 12]. The third model has additional pair–production of an electroweak–isoscalar, color–triplet quark, $t_s$, which is approximately degenerate with the top quark and which, through mass–mixing, decays as $t_s \rightarrow W^+b$ [13]. The agreement between the directly measured top–mass and that extracted from the $M_2$ moments does not yet rule out these new mechanisms of top–quark production, but it may do so with data from the current Tevatron run.

For reasons of space, our discussions refer entirely to $t\bar{t}$ production at the Tevatron. The QCD process there is dominated by $q\bar{q}$ annihilation, as is top production in the $V_t$ model and the isoscalar quark model. As noted, production in the $η_T$ model is dominated by gluon fusion. If the energy of the Tevatron can be increased to 2 TeV, there will be a 35% increase in $σ(t\bar{t})$ if the new physics requires $q\bar{q}$ annihilation, but a 65% increase if the $η_T$ is involved1. Dramatic differences will occur when LHC energies are reached. The rate in the $V_t$ model is typically 10–20% higher than the standard QCD rate at the LHC (for $|η_t| < 1.5$). The isoscalar quark process remains a few times the standard top–quark rate. However, the rate in the $η_T$ model we consider is 10–15 times the standard one, reflecting the importance of gluon fusion for low–$x$ physics. Of course, if there is new physics involved in top–quark production, its origin should be determined at the Tevatron well before the LHC turns on.

A more complete version of the results summarized here was submitted to this conference in Ref. [14] and will appear in Ref. [15]. Also discussed there is the angular distribution of the top quark in $t\bar{t}$ production. Measurements of the angular distributions will require much larger data sets than will be available in the next year or two. Thus, to realize the full potential of the top–quark handle on flavor physics, it is essential that the Tevatron experiments be able to collect samples as large as 1–10 fb$^{-1}$. Such large data sets may even help our science avoid Mark Twain’s characterization of having “such wholesale returns of conjecture for such a trifling investment of fact” [16].

2. Invariant Mass Distributions

We calculated the $M_2$ distribution expected in QCD for the Tevatron Collider and top–quark masses in the interesting range 100–200 GeV and found that it is sharply peaked at $M_{\text{max}} \simeq 2.1 m_t + 10$ GeV. As a consequence, low moments of the mass distribution, the mean and RMS, are nearly linear functions of the top–quark mass (also see Ref. [18]). We found

\[ \langle M_1 \rangle = 50.0 \text{ GeV} + 2.24 m_t \]
\[ \langle M^2_1 \rangle / 2 = 58.4 \text{ GeV} + 2.23 m_t . \]

In the range $m_t \simeq 140–180$ GeV, the dispersion in $M_2$ expected for standard QCD production is $\Delta M_2 = 70–75$ GeV$^2$.

In Ref. [1], the top quark mass was determined from a sample of seven $W \rightarrow ℓν + 4$ jets events by making a constrained best fit to the hypothesis $p\bar{p} \rightarrow t\bar{t} + X$ followed by $t \rightarrow W^+b$ with one $W$ decaying leptonically and the other hadronically. The CDF paper provides the momentum 4–vectors of all particles in the event. From these, the central values of of the $M_2$ of seven events may be determined. These gave the following mean and RMS invariant masses and the corresponding top–masses:

\[ \langle M_2 \rangle = 439 \pm 11 \text{ GeV} \implies m_t = 173 \pm 5 \text{ GeV} \]
\[ \langle M^2_2 \rangle / 2 = 443 \pm 11 \text{ GeV} \implies m_t = 172 \pm 5 \text{ GeV} \]
\[ \Delta M_2 = 59.5 \text{ GeV} . \]

The errors in Eq. (2) are estimated by the “jacknife” method of computing the moments omitting one of the seven events. They are not to be interpreted as the true experimental errors. Only the CDF group can provide those.

The results in Eq. (2) give some confidence that the measured central value of the top–quark mass, 174 GeV, is accurate. For example, if $m_t = 160$ GeV (for which Ref. [1] predicts $σ(t\bar{t}) = 8.2^{+1.3}_{−0.8}$ pb), we would expect $\langle M_2 \rangle = 409$ GeV and $\langle M^2_2 \rangle / 2 = 415$ GeV, both well below the values determined above. Thus, if something is going to change in the CDF results from the next large data sample, we expect it will be the cross section— which would need to be 2–3 times smaller to agree with the standard model.

3. Distinguishing Models of Top–Quark Production

In this section we compute the first two moments and dispersion of $M_2$ for various input parameters to three

† Our calculations used lowest–order QCD subprocess cross sections and the EHLQ Set 1 parton distribution functions [12]. We believe that our general conclusions will remain true when higher–order corrections are included. Our $t\bar{t}$ cross sections have been multiplied by a factor of 1.6165. This makes our standard QCD rates as a function of $m_t$ agree to within a per cent with the central values quoted in Ref. [14] over the of top masses of interest. The results in Eq. (1) are accurate so long as the higher–order corrections are well–represented by a simple multiplicative factor. Our parton level calculations ignore transverse motion of the $\tau$ center–of–mass induced, e.g., by initial–state radiation. While this effect is not large, it can and should be taken into account in more detailed simulations.

† I thank S. Parke for emphasizing this point to me.
nonstandard models of top production \[1,2,3\]. The lowest order QCD subprocess cross sections at parton cm energy \(\sqrt{s}\) are

\[
\frac{d\hat{\sigma}(q\bar{q} \to t\bar{t})}{dz} = \frac{\pi\alpha_s^2\beta}{9s} (2 - \beta^2 + \beta^2 z^2),
\]

\[
\frac{d\hat{\sigma}(gg \to t\bar{t})}{dz} = \frac{\pi\alpha_s^2\beta}{6s} \left( 1 + \frac{1}{2}\beta^2 \right) \left[ 1 - \frac{1}{2}\beta^2 z^2 \left( 1 - \frac{(1 - \beta^2)^2}{1 - \beta^2 z^2} \right) \right]
+ \frac{1}{2}\beta^2 \left( 1 - \frac{1}{2}\beta^2 z^2 \left( 1 - \frac{(1 - \beta^2)^2}{1 - \beta^2 z^2} \right) \right)
- \frac{\alpha_s}{16}(1 + \beta^2 z^2). \tag{3}
\]

Here, \(z = \cos \theta\) and \(\beta = \sqrt{1 - 4m_t^2/s}\). For \(\hat{s} \gg 4m_t^2\), these cross sections—especially the gluon fusion one—are forward–backward peaked. But, at the modest \(\hat{s}\) at which QCD production is large, the cross sections are fairly isotropic.

For the “coloron” bosons of Ref. \[1\], we adopted a version of the model in which \(SU(3)_1 \otimes SU(3)_2\) breaks down to color \(SU(3)\), yielding eight massless gluons and equal-mass \(V_8\)’s. To study also the angular distributions in \(t\bar{t}\) production (discussed in \[14,15\]), we assumed that the \(V_8\) couples only to left–handed quarks with the amplitude

\[
A(V_8^q(p, \lambda) \to q(p_1) \bar{t}(p_2)) = g_s \xi_q \epsilon_\mu(p, \lambda) \bar{u}_q(p_1) \frac{\lambda_\mu}{2} \frac{1 - \gamma_5}{2} v_q(p_2). \tag{4}
\]

Here, \(g_s\) is the QCD coupling and, following Ref. \[1\], we took \(\xi_\ell = \xi_6 = \pm 1/\sqrt{3}\) \((q = u, d, c, s)\). For this chiral coupling, the \(q\bar{q} \to t\bar{t}\) angular distribution in Eq. (3) is modified by the addition of

\[
\frac{d\hat{\sigma}(q\bar{q} \to V_8 \to t\bar{t})}{dz} = \frac{\pi\alpha_s^2\beta}{36s} (1 + \beta z)^2 \times \left\{ 1 + \xi_q \xi_t \frac{\hat{s}}{\hat{s} - M_{V_8}^2 + i\sqrt{\hat{s}}\Gamma(V_8)} \right\}^2 - 1 \right\}. \tag{5}
\]

Ignoring all quark masses except \(m_t\), the \(V_8\) width is

\[
\Gamma(V_8) = \frac{\pi\alpha_s M_{V_8}}{12} \left\{ 4\xi_2^2 + \xi_2^2 (1 + \beta(1 - m_t^2/M_{V_8}^2)) \right\}, \tag{6}
\]

so that \(\Gamma(V_8) = 40\) (85) GeV for \(M_{V_8} = 450\) (475) GeV. The sign \(\xi_q\xi_t\) of the \(V_8\)-gluon interference strongly influences the shape of the \(t\bar{t}\) mass distribution.

If there exists a relatively narrow \(\eta_T\) decaying predominantly to \(t\bar{t}\), it modifies the gluon fusion cross section in Eq. (3) by the addition of the isotropic term \[14,15\]

\[
\frac{d\hat{\sigma}(gg \to \eta_T \to t\bar{t})}{dz} = \frac{\pi}{4} \Gamma(\eta_T \to gg) \Gamma(\eta_T \to \bar{t}t), \tag{7}
\]

Interference between the \(\eta_T\) and QCD gluon–fusion terms is a small effect and, so, is not displayed here.

So long as the \(\eta_T\) may be treated as a pseudo-Goldstone boson, its decay rates to gluons may be computed from the triangle anomaly \[3\]. We introduce a model–dependent dimensionless factor \(C_q\) in the Yukawa coupling of \(\eta_T\) to \(q\bar{q}\) \[12\]. We expect \(|C_q| = O(1)\). Then, the \(\eta_T\)’s main decay modes are to two gluons and \(t\bar{t}\) and they are given by

\[
\Gamma(\eta_T \to gg) = \frac{5\alpha_s^2}{384\pi^3} \frac{N_f^2 M_{\eta_T}^3}{F_Q^2}, \tag{8}
\]

\[
\Gamma(\eta_T \to t\bar{t}) = C^2 t_m^2 M_{\eta_T}^2 \beta_q \frac{M_{\eta_T}}{16\pi F_Q^2}. \tag{9}
\]
In these expressions, it is assumed that the $\eta_T$ is composed from a single doublet of techniquarks $Q = (U, D)$ in the $N_{TC}$ representation of $SU(N_{TC})$; $F_Q$ is the decay constant of technipions in the $\Omega\Omega$ sector. We took $N_{TC} = 5$, $F_Q = 30$ GeV, and $C_1 = -\frac{1}{4}$ in calculations. This value of $F_Q$ is typical of the small techniquark decay constant occurring in multiscale technicolor models $\mathfrak{T}$. Its smallness is crucial to obtaining a large $\eta_T$ contribution to $\Omega\Omega$ production. The $\eta_T$ width is then 32 GeV for $M_{\eta_T} = 450$ GeV, with branching ratios of $\frac{2}{3}$ and $\frac{1}{3}$ to $\Omega\Omega$ and $gg$, respectively.

The total $\Omega\Omega$ cross sections at the Tevatron and the characteristics extracted from the $M_{\eta_T}$ distributions are displayed in Table 1 for the CDF data (see Eq. (2)) and for the above input parameters to the three nonstandard production models. We stress the following features:

1.) The CDF data is narrower ($\Delta M_{\eta_T} = 60$ GeV) than the QCD expectation (77 GeV). While this $\Delta M_{\eta_T}$ is consistent with the resonant production models, the statistics are so low that we do not consider this significant. It is a feature worth watching for in future data samples.

2.) If $\xi_q\xi_t = -1$ corresponding to the notation $V_8^-$ in the table, the mass distribution is enhanced below the resonance and depressed above it, and vice-versa for $\xi_q\xi_t = +1$ ($V_8^+$). Thus, for a given $M_{\eta_T}$, the extracted value of $m_t$ is somewhat smaller than or significantly larger than the directly–measured one, depending on whether $\xi_q\xi_t = -1$ or +1.

3.) The $\eta_T$ does not interfere appreciably with the QCD gluon fusion process. Thus the value of the extracted top mass depends mainly on $M_{\eta_T}$. Resonance masses in the range 400–500 GeV return a top mass close to the directly–measured value.

4.) It is easy to double the QCD value of $\sigma(\Omega\Omega)$ in the isoscalar quark model: just choose $m_{\eta_T} = m_t$. But, as could be foreseen, it is difficult for the isoscalar quark model to give both a 13.9 pb cross section and an extracted mass close to the directly–measured one. To get a cross section $\sim 3$ times as large as QCD requires choosing one of the masses significantly lower than 174 GeV, leading to too small an extracted value. This model should be the easiest to eliminate with data from the current Tevatron run.

To sum up: It should be possible to extract valuable information on the mechanism of $\Omega\Omega$ production and, possibly, the physics of flavor, from even limited statistics on the $M_{\eta_T}$ distribution. We urge the CDF and DΦ experimenters to keep this possibility in mind. In the end, of course, nothing can make up for large data sets, of $O(1 - 10) fb^{-1}$. From these one can carry out incisive studies of the detailed shape of the mass distribution and of the $\Omega\Omega$ angular distribution. At the same time, one should study subsystem invariant masses to search for alternate mechanisms of top production—

and hints of flavor physics. This promises a very exciting physics program for the Tevatron Collider.

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