FUTURE OF TOP-QUARK PHYSICS AT FERMILAB

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I discuss some of the physics of the top quark which will be explored in the near and more-distant future at the Tevatron.

1 Introduction

Now that the existence of the top quark is firmly established, we should begin to explore the opportunities for top-quark physics. This is an enormous topic, as evidenced by the two-day workshop devoted to top-quark physics following this Symposium. In this talk, I restrict myself to top-quark physics at Fermilab, both in the immediate and the more-distant future. My emphasis is on top-quark physics in the next ten years or so, during which Fermilab will have a monopoly on the top quark. In a final section I speculate on the role of Fermilab during the LHC era.

The talk is divided into several subsections:

- Top-quark yields
- Mass
- Decay
- Production
- Not-so-rare decays
- Speculations

The top-quark mass from combining the measured CDF and D0 values is 179 ± 12 GeV. For definiteness, I use $m_t = 175$ GeV throughout this talk.

2 Top-quark yields

The machine parameters and running schedule of the Fermilab Tevatron are given in Table 1. Run I is now coming to a close, and each experiment will have accumulated an integrated luminosity in excess of 100 $pb^{-1}$ by the end of the run. The peak luminosity achieved thus far is about $\mathcal{L} = 2 \times 10^{31}/cm^2/s$, impressive for a machine that was designed for $\mathcal{L} = 10^{30}/cm^2/s$.

Run II will begin in late 1998/early 1999, with a machine energy of 2 TeV. The increase in energy is made possible by cooling the magnets to a lower temperature, thereby allowing a higher field strength. This increases the top-quark production cross section by about 35%.

The most important change that will occur in Run II is a ten-fold increase in luminosity, to $\mathcal{L} = 2 \times 10^{32}/cm^2/s$. This will be achieved by two additions to the existing accelerator complex:

- Main Injector: The original Main Ring in the Tevatron collider tunnel is a bottleneck to higher luminosity. It will be replaced by the Main Injector, a 120 GeV synchrotron housed in a separate tunnel, now under construction. The Main Injector will enable the production of many more antiprotons, yielding a five-fold increase in luminosity.

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Table 1: Schedule and machine parameters for Run I and II at Fermilab.

| Run I              | Run II            |
|--------------------|-------------------|
| 1992-1995          | 1999              |
| $\sqrt{s} = 1.8\ TeV$ | $\sqrt{s} = 2\ TeV$ |
| $\mathcal{L} = 2 \times 10^{31}/cm^2/s$ | $\mathcal{L} = 2 \times 10^{32}/cm^2/s$ |
| $\int \mathcal{L} dt > 100\ pb^{-1}$    | $\int \mathcal{L} dt > 1\ fb^{-1}$ |

- **Recycler:** A new development within the past year is the addition of another element to the Main Injector project, the Recycler ring. It is an 8 GeV, low-field, permanent-magnet ring which will be installed in the Main Injector tunnel. The primary function of the Recycler is to allow more efficient accumulation of antiprotons. Its secondary role, from which it takes its name, is to allow the reuse of antiprotons left over from the previous store. The Recycler will yield a two-fold increase in luminosity.

There will also be a variety of detector upgrades for Run II. One of the most significant is an improved silicon vertex detector (SVX), used to detect secondary vertices from $b$ quarks. This is of obvious importance for top physics, since the top quark decays via $t \rightarrow Wb$. Both CDF and D0 will have an SVX in Run II, and they will be longer than the existing CDF SVX, allowing for nearly 100% acceptance of $b$ quarks from top decays. The silicon detector will also be more sophisticated, providing a stereo view of the events. This will increase the SVX tagging efficiency of fiducial $b$ jets ($p_T > 20\ GeV$ and within the SVX) from the present value of about 40% up to nearly 60%. As a result of these improvements, the fraction of top events with at least one $b$ tag will increase from 50% to 85%. The fraction with two $b$ tags will increase dramatically, from 13% to 40%.

Taken together, the improvements in the accelerator and the detectors will result in a dramatic increase in the potential for top-quark physics in Run II. In $t\bar{t}$ events, the final state with the most kinematic information is $W + 4j$, where the $W$ is detected via its leptonic decay. These events are fully reconstructable. To reduce backgrounds, it is best to demand at least one $b$ tag. The number of such events is about $500/fb^{-1}$. The number of events with two $b$ tags, which have very small background, is about $250/fb^{-1}$. Depending on the length of Run II, the integrated luminosity delivered to each detector will be between 1 and a few $fb^{-1}$. Thus there will be on the order of 1000 tagged, fully reconstructed top-quark events in Run II, to be compared with the approximately 20 $W + 4j$ single-tagged top events in Run I.

3 Mass

Due in part to their SVX, CDF has the best measurement of the top-quark mass, $m_t = 176 \pm 8 \pm 10\ GeV$. It is anticipated that the errors will be reduced to $\pm 6 \pm 8\ GeV$ at the end of Run I. If one assumes that the error scales like the inverse of the square root of the number of events, the error will be reduced to $\pm 3\ GeV$ in Run II. It may be optimistic to assume that all the systematic errors scale like the statistical error, so $\Delta m_t \sim 3 - 5\ GeV$ is a more conservative prognosis.

There will also be an improved measurement of the $W$ mass in Run II, as well as a measurement at LEP II. An error of $\pm 50\ MeV$ is anticipated from each experiment, to be compared with the current error of $\pm 180\ MeV$. Figure 1 shows the well-known plot of $M_W$ vs. $m_t$, with bands of constant Higgs mass. The contours show the one- and two-sigma fits to data from LEP and SLC. The large cross indicates the present direct measurement of $M_W$ from CDF and UA2, and $m_t$ from CDF and D0. The small cross indicates the errors expected in Run II; $\Delta M_W = 50\ MeV$, $\Delta m_t = 5\ GeV$, placed arbitrarily on the plot. Note that the length of the Run II $\Delta M_W$ and $\Delta m_t$ error bars are similar. Since the lines of constant $m_H$ are sloped towards the horizontal, a reduction of the
uncertainty in $M_W$ yields more sensitivity to the Higgs mass than a reduction of the uncertainty in $m_t$, a point I will return to in the last section.

![Global Fit to 1994 Z^0 Data](image_url)

**Figure 1:** $W$ mass vs. top-quark mass, with bands of constant Higgs mass. The contours are the one- and two-sigma regions from precision LEP and SLC data. The large cross is the direct measurement of $M_W$ and $m_t$. The small cross, placed arbitrarily on the figure, is the anticipated uncertainty in $M_W$ and $m_t$ in Run II. Adapted from Ref. 5.

There is another perspective on the top-quark mass that is interesting to consider. Ultimately we want to find a theory of fermion masses, and we can ask how well we want to know the top-quark mass to help pin down this theory. It is reasonable to strive for a measurement of $m_t$ which is as good (fractionally) as the best-known quark mass. This is the $b$ mass, which is $m_b(\overline{m_b}) = 4.0 \pm 0.1$ GeV extracted from the Upsilon spectrum calculated with lattice QCD. The top-quark mass is already the second best-known quark mass. Since the uncertainty in $m_b$ is entirely theoretical, one can anticipate that it will be reduced by perhaps a factor of two, corresponding to an uncertainty of $\pm 1.3\%$. This is comparable to a 3 GeV uncertainty in the top-quark mass. So $\Delta m_t \sim 3$ GeV is a good benchmark.

### 4 Decay

This section and the next are devoted to studying the decay and production of the top quark. To gain some perspective, I will first ask:

**Is the Top Quark Exotic?**

There are two extreme viewpoints on this question:

- Yes. The top quark is much heavier than the other known fermions, and its mass is close to the electroweak scale (e.g., the Higgs-field vacuum-expectation value). It seems likely that the top quark is related to electroweak symmetry breaking. This point of view is embodied, for example, by top-quark-condensate models.

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2. This is the running $\overline{MS}$ mass evaluated at the quark mass.
No. The top-quark Yukawa coupling to the Higgs field is close to unity, a natural value. The other known fermions have Yukawa couplings $<< 1$, which must be explained. This point of view is embodied, for example, by grand-unified Yukawa-matrix models.

The way to decide this issue is to study the properties of the top quark. If the top quark is exotic, a study of its properties may reveal that fact. One can imagine that non-standard interactions of fermions are proportional to the fermion mass, in which case the top quark is the best hope to discover such effects.

With 1000 fully-reconstructed $t\bar{t}$ events, the statistical accuracy on the measurement of top-quark properties should be around 3%. Including a comparable systematic error, we anticipate a knowledge of the properties of the top quark at about the 5% level at the end of Run II.

![Diagram](image)

Figure 2: The matrix element of the top-quark charged current, probed via top-quark decay.

The weak decay of the top quark is pictured in Fig. 2. The decay involves the matrix element of the top-quark charged current. Using only Lorentz invariance, we can write down the structure of this current in terms of four form factors

$$\bar{u}(b)\Gamma^\nu u(t) = \frac{g}{2\sqrt{2}} V_{tb} \bar{u}(b) \left[ F_1^L \gamma^\nu (1 - \gamma_5) + F_1^R \gamma^\nu (1 + \gamma_5) \right] - \frac{i}{2m_t} F_2^L \sigma^{\mu\nu} q_\nu (1 - \gamma_5) - \frac{i}{2m_t} F_2^R \sigma^{\mu\nu} q_\nu (1 + \gamma_5) u(t)$$

where the form factors $F_{1,2}^{L,R}(q^2)$ are evaluated at $q^2 = M_W^2$. These form factors are calculable in the standard model, and are given by

$$F_1^L = 1 + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s)$$
$$F_1^R = F_2^L = F_2^R = 0 + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s)$$

An example of a measurement which provides information on the form factors is the fraction of top decays in which the $W$ boson is longitudinal (helicity zero) in the top-quark rest frame.

Consider the case where we set $F_1^R = F_2^L = 0$, as is true in the standard model in the limit $m_b = 0$. The ratio of the longitudinal and transverse partial widths is given by

$$\frac{\Gamma_L}{\Gamma_T} = \frac{m_t^2}{2M_W^2} \left| 1 + \frac{M_b^2}{2m_t^2} F_2^L \right|^2$$

$^c$There are two additional form factors,

$$\bar{u}(b) \left[ \frac{i}{2m_t} F_3^L \sigma^{\mu\nu} P_\nu (1 - \gamma_5) + \frac{i}{2m_t} F_3^R \sigma^{\mu\nu} P_\nu (1 + \gamma_5) \right] u(t)$$

where $P = p_t - p_b$. However, these terms do not contribute to the top-quark decay amplitude if the $W$ boson decays to massless fermions.

$^d$The form factors $F_1^R$ and $F_2^L$ are zero to all orders in the standard model in the limit $m_b = 0$. 
which grows quadratically with the top-quark mass. However, the quantity that is measured is the branching ratio of the top quark to longitudinal $W$ bosons,

$$B(t \rightarrow W_L b) = \Gamma_L/ (\Gamma_L + \Gamma_T)$$

which is much less sensitive to the top-quark mass. At leading order in the standard model, $B(t \rightarrow W_L b) = 0.70$. A measurement of this quantity to 5% corresponds to an uncertainty in the top-quark mass of 15 GeV, much greater than the uncertainty in a direct measurement. Our ability to predict this branching ratio is therefore not limited by the uncertainty in the top-quark mass.

The form factor $F_R^2$ is non-zero in the standard model, arising dominantly from gluon loops. QCD decreases the ratio $\Gamma_L/ \Gamma_T$ by about 6%, which decreases the longitudinal branching ratio by about 2%, to $B(t \rightarrow W_L b) = 0.69$. A measurement of $B(t \rightarrow W_L b)$ to 5% is sensitive to a non-standard value of $|F_R^2/F_L^1| > 0.2$.

5 Production

The QCD production of top-quark pairs occurs via the quark-antiquark annihilation and gluon-fusion processes. The quark-antiquark annihilation process accounts for about 80% of the cross section at the Tevatron. This process is sensitive to the gluon coupling to top quarks and to resonances which might occur in this channel. The gluon-fusion process, although suppressed, could be greatly enhanced if there is a resonance, such as a techni-eta. The measured cross section is within one sigma of the band of theoretical predictions, so there is no indication of new physics in the production of top-quark pairs at this time.

There are two processes which produce a single top quark, rather than a $t\bar{t}$ pair: the $W$-gluon-fusion process, depicted in Fig. 3(a), and $q\bar{q} \rightarrow t\bar{b}$, shown in Fig. 3(b). Both involve the weak interaction, so they are suppressed relative to the QCD production of $t\bar{t}$; however, this suppression is partially compensated by the presence of only one heavy particle in the final state. Both processes probe the charged-current weak interaction of the top quark. The single-top-quark production cross sections are proportional to the square of the Cabbibo-Kobayashi-Maskawa matrix element $V_{tb}$, which cannot be measured in top quark decays since the top quark is so short-lived.

![Figure 3: Single-top-quark production at hadron colliders: (a) W-gluon fusion; (b) quark-antiquark annihilation.](image)

The single-top-quark processes lead to a final state of $Wb\bar{b}$ (plus an additional jet, for $W$-gluon fusion). The backgrounds are more serious for the single-top-quark processes than for $t\bar{t}$, but they are manageable. The dominant background is $Wb\bar{b}$ from ordinary QCD/weak interactions. Fig. 4 shows a recent study of the signal and backgrounds for $Wjj$ events with a single $b$ tag. The distribution of the reconstructed top-quark mass is plotted for $Wjj$ events with a single $b$ tag. Both processes should be observed in Run II. The process $q\bar{q} \rightarrow t\bar{b}$ will yield a measurement of $|V_{tb}|$ which is limited mostly by statistics; a 10% measurement may be possible in Run II.

*This also includes the effect of real gluon emission.

$^f$Most of the events in the signal contain one $b$ jet plus the spectator jet from the radiation of the virtual $W$ boson.
6 Not-so-rare decays

The top quark can also provide a window into new physics via its decay to new particles. In this section I discuss several decays which could occur at the few to tens of percent level. These decays could be accessible even in Run I.

The decay of the top quark to a charged Higgs boson is a well-known decay mode, and has been sought for several years. The charged Higgs is sought via its decay to $\bar{\tau}\nu$ or $c\bar{s}$. These are the dominant decay modes in a multi-Higgs doublet model with natural flavor conservation. However, it is conceivable that the Higgs coupling to fermions are generation-changing, in which case the decay $H^+ \rightarrow cb$ could dominate. If the other top quark decays conventionally, this would give rise to events with three $b$ quarks, which could be distinguished by tagging all three $b$ jets.

Continuing along this line of thought, one can also imagine tree-level flavor-changing neutral-current decays of the top quark, such as $t \rightarrow c h^0$. Flavor-changing neutral currents are severely restricted in the first two generations of fermions, but could be large in the third generation. The dominant decay of the neutral Higgs would likely be $h^0 \rightarrow b\bar{b}$. If the other top quark decays conventionally, the events would again have three $b$ quarks in the final state.

If the top squark is light, it could potentially be discovered in top-quark decays. The decay mode $t \rightarrow \tilde{t}_1 \chi^0_1$ could have a significant branching ratio ($\chi^0_1$ is the lightest neutralino). If it is kinematically allowed, the top squark will decay via $\tilde{t}_1 \rightarrow \chi^0_1 b$; otherwise, the loop-induced decay $\tilde{t}_1 \rightarrow \chi^0_1 c$ would dominate. The extraction of these signals from backgrounds is challenging.

7 Speculations

As discussed in the section on top-quark yields, the Main Injector and the Recycler will allow the Tevatron to achieve a luminosity of $2 \times 10^{32} \, cm^{-2} s^{-1}$ in Run II. One can ask if even higher luminosity can be achieved. The answer seems to be yes. A design exists which would achieve a luminosity of at least $10^{33} \, cm^{-2} s^{-1}$. The main requirement to achieve this luminosity is to increase the rate
of antiproton production. This can be attained by directing more bunches from the Main Injector onto the antiproton-production target, a technique called “multibatch targeting.” The cost of this scheme is modest in comparison with the Main Injector, and could be in place for Run II.

A luminosity of $10^{33}/\text{cm}^2/\text{s}$ would produce about 5,000 tagged and fully-reconstructed top-quark pairs per year. One can imagine pushing the uncertainty on the top-quark mass down to 2 GeV, and the accuracy on the measurement of the top-quark properties down to 2 – 3%. There are other physics opportunities which become available as well. The error on the $W$ mass could potentially be pushed down to 20 MeV. This may be even more interesting than improving the accuracy on the top-quark mass, as remarked in section 3. The production of the Higgs boson in association with a $W$ boson, followed by $H \rightarrow b\bar{b}$, may also become accessible, in the mass range $m_H = 80 - 120$ GeV.

Given the physics opportunities afforded by $\mathcal{L} = 10^{33}/\text{cm}^2/\text{s}$, why don’t we do it? The stumbling block is not the accelerator, but the detectors, which cannot operate at such a high luminosity. Significant detector upgrades, or perhaps a new detector, are needed to take advantage of this luminosity. One can even imagine this occuring during the LHC era, especially if some of the physics objectives of such a machine are complementary to the LHC.

Can one contemplate a luminosity for a $pp$ collider as high as $\mathcal{L} = 10^{34}/\text{cm}^2/\text{s}$, the LHC design luminosity? There doesn’t seem to be any reason why not. If such a luminosity can be attained, it might remove the advantage of $pp$ colliders over that of $p\bar{p}$. A $pp$ collider requires only a single ring of magnets, so it can potentially be built more economically than a $pp$ collider, which requires either two rings, or a 2-in-1 magnet such as for the LHC. Magnets are a significant fraction of the cost of an accelerator; they account for roughly two thirds of the cost of the LHC, for example. The next hadron collider after the LHC might be a return to $pp$. 

Figure 5: Signal and backgrounds for single-top-quark production via $q\bar{q} \rightarrow t\bar{b}$ at the Tevatron, via $Wjj$ with a double $b$ tag. From Ref. 24.
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