Precision Top-Quark Physics

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I consider the measurement of the top-quark mass, the CKM matrix element $V_{tb}$, and the top-quark Yukawa coupling to the Higgs boson at the Tevatron, the LHC, and a Linear Collider. The theoretical motivations for these measurements, as well as the experimental possibilities, are discussed.

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1 Introduction

The top quark was discovered in 1995 by the CDF \[1\] and D0 \[2\] experiments at Fermilab, during Run I of the Tevatron $p\bar{p}$ collider ($\sqrt{S} = 1.8$ TeV, $\int \mathcal{L} dt \approx 100$ pb$^{-1}$). In Table 1 I briefly summarize the top-quark measurements made in Run I and compare them with the expectations from the standard model. The standard model does not predict the top-quark mass, but it can be inferred indirectly from precision electroweak experiments \[3\], and this indirect mass is in good agreement with the measured mass. The strong interaction of the top quark is probed by measuring the top-quark cross section, which proceeds via the strong processes $q\bar{q}, gg \to t\bar{t}$; this cross section is in good agreement with next-to-leading-order QCD. The weak interaction of the top quark is probed in a variety of ways. In the three-generation standard model, top decays almost exclusively to bottom, as confirmed by experiment. The branching ratios of top to longitudinal (zero-helicity) $W$ bosons and to right-handed (positive-helicity) $W$ bosons are predicted to be approximately 0.7 and zero, respectively, in agreement with experiment. The weak interaction of the top quark is also probed indirectly by precision electroweak experiments and $b$-quark physics, as illustrated in Figs. 1 and 2. All of these experiments are consistent with the three-generation standard model. Thus, although the properties of the top quark have thus far been measured only crudely, there is no evidence for physics beyond the standard model in top-quark physics.

Table 1: Comparison of theory and experiment for top-quark physics from Run I of the Fermilab Tevatron. [$W_{0,+}$ denote a longitudinal (zero-helicity) and right-handed (positive-helicity) $W$ boson.] For discussion and references, see Refs. \[1\][3].

|          | Experiment | Theory       |
|----------|------------|--------------|
| $m_t$    | 174.3 ± 5.1 GeV | 168.2$^{+9.6}_{-7.4}$ GeV |
| $\sigma(t\bar{t})$ | 6.2 ± 1.7 pb | 4.75 ± 0.5 pb |
| $BR(t \to Wb)/BR(t \to Wq)$ | 0.94$^{+0.31}_{-0.24}$ | ≈ 1 |
| $BR(t \to W_0b)$ | 0.91 ± 0.39 | ≈ 0.7 |
| $BR(t \to W_+b)$ | 0.11 ± 0.15 | ≈ 0 |

Let us assume that the top quark is indeed a standard quark. What parameters of the top quark do we want to measure? There are only a few standard-model parameters associated with the top quark; its mass ($m_t$), its Cabibbo-Kobayashi-Maskawa matrix elements ($V_{tb}, V_{ts}, V_{td}$), and its Yukawa coupling to the Higgs field ($y_t$). This last parameter is not truly independent, as it is related to the top-quark mass (at leading order) via $y_t = \sqrt{2m_t}/v$, where $v \approx 246$ GeV is the vacuum-expectation value of the Higgs field. However, this parameter is especially interesting, as it is related
Figure 1: The weak interaction of the top quark is probed indirectly by the vector-boson self energies.

Figure 2: The weak interaction of the top quark is also probed indirectly by $b$ physics.

to the electroweak-symmetry-breaking sector, which has yet to be directly probed experimentally. A measurement of the top-quark Yukawa coupling therefore probes the mechanism that generates the top-quark mass.

In this talk I discuss the measurement of the parameters $m_t$, $V_{tb}$, and $y_t$. I first ask how accurately we desire these parameters. I then ask how accurately we can measure them with present and future colliders. I consider the upgraded Fermilab Tevatron ($\sqrt{s} = 2$ TeV), with an integrated luminosity of 2 fb$^{-1}$ (Run IIa) and 15 fb$^{-1}$ (Run IIb), the CERN Large Hadron Collider (LHC, $\sqrt{s} = 14$ TeV pp collider), and the Linear Collider, an $e^+e^-$ collider running at the $t\bar{t}$ threshold [as well as at the $W^+W^-$ threshold and at the $Z$ mass (Giga Z)].

The standard-model parameters of the top quark are interesting in their own right. Furthermore, any discrepancies between theory and experiment would indicate new physics. Thus top-quark physics could serve to further solidify the standard model, or to indicate physics beyond the standard model.
Figure 3: The quark mass spectrum. The bands indicate the running $\overline{\text{MS}}$ mass, evaluated at the quark mass (for $c, b, t$) or at 2 GeV (for $u, d, s$), and the associated uncertainty.

2 Top-quark mass

The top-quark mass has been measured by the CDF and D0 collaborations to be

$$m_t = 174.3 \pm 5.1 \text{ GeV (CDF + D0)}.$$  \hspace{1cm} (1)

To put this into context, I plot all the quark masses in Fig. 3 on a logarithmic scale. The width of each band is proportional to the fractional uncertainty in the quark mass. We see that, at present, the top-quark mass is the best-known quark mass, with the $b$-quark mass a close second ($m_{b,\overline{\text{MS}}}(m_b) = 4.25 \pm 0.15 \text{ GeV}$). \hspace{1cm} (2)

An important question for the future is what precision we desire for the top-quark mass. There are at least two avenues along which to address this question. One is in the context of precision electroweak data. Fig. 4 summarizes the world’s precision electroweak data on a plot of $M_W$ vs. $m_t$. The solid ellipse is the 1σ contour. If the standard electroweak model is correct, the predicted top-quark mass from precision electroweak data is

$$m_t = 168.2^{+9.6}_{-7.4} \text{ GeV}.$$ \hspace{1cm} (3)

We conclude that the present uncertainty of 5 GeV in the top-quark mass is sufficient for the purpose of precision electroweak physics at this time.

There is one electroweak measurement, $M_W$, whose precision will increase significantly. An uncertainty of 20 MeV is a realistic goal for Run IIb at the Tevatron and the LHC \hspace{1cm} (4, 5, 6). Let us take this uncertainty and project it onto a line of

\hspace{1cm} (4)This is the top-quark pole mass, which is defined to order $\Lambda_{QCD} \approx 200 \text{ MeV}$ \hspace{1cm} (4). The corresponding $\overline{\text{MS}}$ mass is $m_{t,\overline{\text{MS}}}(m_t^{\overline{\text{MS}}}) = 165.2 \pm 5.1 \text{ GeV}$ \hspace{1cm} (8).
Figure 4: $W$ mass vs. top-quark mass, with lines of constant Higgs mass. The solid ellipse is the $1\sigma$ (68% CL) contour from precision electroweak experiments. The dashed ellipse is the $1\sigma$ (68% CL) contour from direct measurements. Only the shaded region is allowed in the standard electroweak model. Figure from LEP Electroweak Working Group, [http://www.cern.ch/LEPEWWG/].

constant Higgs mass in Fig. 4. This is appropriate, because once a Higgs boson is discovered, even a crude knowledge of its mass will define a narrow line in Fig. 3, since precision electroweak measurements are sensitive only to the logarithm of the Higgs mass. An uncertainty in $M_W$ of 20 MeV projected onto a line of constant Higgs mass corresponds to an uncertainty of 3 GeV in the top-quark mass. Thus we desire a measurement of $m_t$ to 3 GeV in order to make maximal use of the precision measurement of $M_W$ at the Tevatron and the LHC.

Looking further ahead, a high-luminosity Linear Collider running at the $WW$ threshold could measure the $W$ mass with an accuracy of 6 MeV [12]. This would require a measurement of $m_t$ to 1 GeV. The same machine running at the $Z$ mass (Giga $Z$) could make a measurement of $\sin^2 \theta_W$ with an accuracy of $1 \times 10^{-5}$ [12]. This would also require a measurement of $m_t$ with an uncertainty of order 1 GeV [13].

Another avenue along which to address the desired accuracy of the top-quark mass is to recall that the top-quark mass is a fundamental parameter of the standard model. Actually, the fundamental parameter is the Yukawa coupling of the top quark
to the Higgs field, given at leading order by

\[ y_t = \sqrt{2} \frac{m_t}{v} \approx 1 \]  

(2)

where \( v \approx 246 \text{ GeV} \) is the vacuum-expectation value of the Higgs field. The fact that this coupling is of order unity suggests that it may be a truly fundamental parameter. We hope someday to have a theory that relates the top-quark Yukawa coupling to that of its weak-interaction partner, the \( b \) quark. The \( b \)-quark mass is currently known with an accuracy of 3.5% [3]. Since the uncertainty is entirely theoretical, it is likely that it will be reduced in the future. If we assume that future work reduces the uncertainty to 1%, the corresponding uncertainty in the top-quark mass would be 2 GeV.

We conclude that both precision electroweak experiments and \( m_t \) as a fundamental parameter lead us to the desire to measure the top-quark mass with an accuracy of 1–3 GeV. This is well matched with future expectations. An uncertainty of 3 GeV per experiment is anticipated in Run IIa [15][19], and 2 GeV per experiment in Run IIb [4]. The LHC could potentially reduce the uncertainty to 1 GeV, although that has not been established [10].

Recall that the need to reduce the uncertainty in the top-quark mass to 1 GeV is driven by the precision measurement of \( M_W \) and \( \sin^2 \theta_W \) at the Linear Collider. Such a machine, operating at the \( t\bar{t} \) threshold, could make a much more accurate determination of the top-quark mass. It is interesting to ask if there is any motivation to go beyond 1 GeV in the accuracy of the measurement of \( m_t \).

No such motivation appears to exist solely within the context of the standard model, but it is plausible that physics beyond the standard model could lead us to desire \( m_t \) with an accuracy much less than 1 GeV. I offer two examples. Imagine that nature is supersymmetric, and the Higgs sector consists of two Higgs doublets, as in the minimal supersymmetric standard model. There is an upper bound on the mass of the lightest Higgs scalar, and this bound is saturated in the limit that the pseudoscalar Higgs mass and the ratio of vacuum-expectation values, \( \tan \beta \), are large. The mass of the lightest Higgs scalar is predicted to be [20][21][22]

\[ m_h^2 = M_Z^2 \frac{3 G_F}{\pi^2} \sqrt{2} m_t^4 \ln \frac{M_{\text{S}}^2}{m_t^2} \]  

(3)

where \( M_Z^2 \) is the average of the two top-squark squared masses and I have assumed no top-squark mixing, for simplicity. The second term is from loops of top quarks and top squarks, as shown in Fig. [3], and since it depends on the top-quark mass.

\footnote{A particularly compelling model that relates the \( b \) and \( t \) masses is SO(10) grand unification [14][15]. This model may be able to account for the masses of all the third-generation fermions, including the tau neutrino, whose mass is given by the “see-saw” mechanism [16] as \( m_{\nu_\tau} \approx m_t^2/M_{\text{GUT}} \approx 10^{-2} \text{ eV} [17] \).}
to the fourth power, an uncertainty in the top-quark mass implies an uncertainty in the predicted Higgs mass. The Higgs mass will be measured with an accuracy of about 0.1% at the LHC [10]; this requires a measurement of $m_t$ to about 100 MeV (where I have taken $M_S \approx 1$ TeV). However, there is an uncertainty in the predicted Higgs mass due to the unknown three-loop contributions to Eq. (3), which has been estimated to be about 3 GeV [23,24]. This corresponds to an uncertainty in the top-quark mass of about 2 GeV. Thus the motivation to go beyond 1 GeV accuracy hinges on the knowledge of higher-order terms in Eq. (3).

A second motivation for going beyond 1 GeV in the accuracy of the top-quark mass measurement is a more model-independent one. The generation of mass is related to the breaking of the electroweak symmetry. The electroweak interaction has been measured with an accuracy of about 0.07% (the accuracy in our present knowledge of $\sin^2 \theta_W$). If the mechanism that breaks the weak interaction is related to the weak interaction itself, then a measurement of $m_t$ to 0.07%, i.e., 100 MeV, may be warranted.

Both of these arguments, although speculative, lead to a goal of about 100 MeV for the accuracy of the top-quark mass measurement. Such an accuracy may be within the reach of a Linear Collider operating at the $t\bar{t}$ threshold. Recent next-to-next-to-leading-order (NNLO) calculations of the $t\bar{t}$ threshold in a nonrelativistic expansion yield a line shape with sufficient accuracy to extract the mass within 100 MeV [25]. It is essential to use a short-distance “threshold mass” in such calculations [26,27]. The threshold mass has recently been related to the more commonly-used MS mass to $O(\alpha_s^3)$ [28,29], so the theoretical work required for a NNLO extraction of the top-quark mass from the $t\bar{t}$ threshold is complete. However, at the time of this symposium, there remained a mystery in the normalization of the line shape. Work performed after this symposium has resolved that mystery via renormalization-group improvement, as shown in Fig. 6, so the normalization is now also known with good accuracy [30].
Figure 6: Renormalization-group-improved NNLO calculation of the $t\bar{t}$ threshold at a Linear Collider. The curves are leading log (dotted), next-to-leading log (dashed), and next-to-next-to-leading log (solid), for three different renormalization scales. From Ref. [30].

3 $V_{tb}$

It is remarkable that, although it has not yet been directly measured, $V_{tb}$ is the best-known Cabibbo-Kobayashi-Maskawa (CKM) matrix element (as a percentage of its value), if we assume three generations: $V_{tb} = 0.9990 - 0.9993$ [3]. This is due to the small measured values of $V_{ub}$ and $V_{cb}$ and the three-generation unitarity constraint $|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$. Thus, if there are three generations, we desire a measurement of $V_{tb}$ with an accuracy of 0.0002. Unfortunately, there is no known way to achieve such an accuracy.

If there are more than three generations, $V_{tb}$ is almost completely unknown: $V_{tb} = 0.07 - 0.993$ [3]. In this case, a measurement of $V_{tb}$ with any accuracy is worthwhile. The existence of a fourth generation is disfavored by precision electroweak data at the 97% C.L., however [3]. If there are only three generations, then a measurement of $V_{tb}$ may be considered as a probe of physics beyond the standard model [31,32].

CDF has measured [33]

$$\frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}$$

(4)

and it is interesting to ask what this tells us about $V_{tb}$. If we assume that there are just three generations of quarks, then unitarity of the CKM matrix implies that the denominator of Eq. (4) is unity, and we can immediately extract

$$|V_{tb}| = 0.97^{+0.16}_{-0.12} (> 0.75 \text{ 95\% CL}) \text{ (3 generations).}$$

(5)
Figure 7: Single-top-quark production via (a) $t$-channel $W$ exchange, (b) $s$-channel $W$ exchange, and (c) associated production with a $W$.

However, we already know that $V_{tb} = 0.9990 - 0.9993$ if we assume three generations, which is far more accurate than the above measurement. If we assume more than three generations, then we lose the constraint that the denominator of Eq. (4) is unity. All we can conclude from Eq. (4) is that $|V_{tb}| > |V_{ts}|$, $|V_{td}|$; we learn nothing about its absolute magnitude.

Fortunately, there is a direct way to measure $|V_{tb}|$ at the Tevatron and the LHC, which makes no assumptions about the number of generations. One uses the weak interaction to produce the top quark; the three relevant processes are shown in Fig. 4.

The cross sections for these “single top” processes are proportional to $|V_{tb}|^2$. The first process involves a $t$-channel $W$ boson [34,35,36], the second process involves an $s$-channel $W$ boson [37,38], and the third process is associated production of a single top quark with a real $W$ boson [39,40]. The cross sections for these processes are given in Table 2, along with the cross section for $t\bar{t}$ pair production. The largest single-top cross section comes from the $t$-channel process, which is about 1/3 of the cross section for $t\bar{t}$ pair production. The $s$-channel process is relatively larger at the Tevatron than the LHC, since it is a quark-antiquark initiated process. It has the advantage of small theoretical uncertainty. The cross section for associated production is only significant at the LHC.

Thus far there are only upper bounds on the cross sections from CDF and D0. The upper bounds on the $t$-channel cross sections are [11,12]

\[
\sigma(qb \rightarrow qt) < 13.5 \text{ pb (95\% CL)} \quad \text{(CDF)}
\]

\[
\sigma(qb \rightarrow qt) < 58 \text{ pb (95\% CL)} \quad \text{(D0)}
\]

which is an order of magnitude away from the theoretical expectation. There is a similar bound on the $s$-channel process [11,12]

\[
\sigma(q\bar{q} \rightarrow t\bar{b}) < 12.9 \text{ pb (95\% CL)} \quad \text{(CDF)}
\]

\[
\sigma(q\bar{q} \rightarrow t\bar{b}) < 39 \text{ pb (95\% CL)} \quad \text{(D0)}
\]
Table 2: Total cross sections (pb) for single-top-quark production and top-quark pair production at the Tevatron and LHC, for $m_t = 175$ GeV. The NLO $t$-channel cross section is from Ref. [45]. The NNLO $s$-channel cross section is from Refs. [46,47]. The cross section for the $Wt$ process is from Ref. [40]; it is leading order, with a subset of the NLO corrections included. The uncertainties are due to variation of the factorization and renormalization scales; uncertainty in the parton distribution functions; and uncertainty in the top-quark mass (2 GeV).

|                 | Tevatron   | LHC        |
|-----------------|------------|------------|
| $t$-channel     | 2.12 ± 0.24| 238 ± 27   |
| $s$-channel     | 0.88 ± 0.06| 10.2 ± 0.7 |
| $Wt$            | 0.088 ± 0.023| 51 ± 9   |
| $t\bar{t}$     | ≈ 6.5      | ≈ 770      |

which is even further from the theoretical expectation. The $t$- and $s$-channel processes will be first observed in Run II [9,43,44], while the associated-production process must await the LHC [10,11,40].

The most accurate measurements of $V_{tb}$ will come from the $t$- and $s$-channel processes. Both the $t$-channel [45] and the $s$-channel [46] total cross sections have been calculated at next-to-leading order (NLO) in QCD, with an uncertainty of about 5% from varying the factorization and renormalization scales. After this symposium, a calculation of the leading (in the large $N_c$ limit) next-to-next-to-leading-order (NNLO) QCD correction to the $s$-channel process appeared [47]; this essentially eliminates the uncertainty from varying the factorization and renormalization scales. It is also desirable to have a calculation of the differential cross section at NLO; this work is in progress [48]. Taking all uncertainties into account, it seems possible that $V_{tb}$ can be measured at the Tevatron and the LHC with an uncertainty of 5% [11,43].

At a Linear Collider, $V_{tb}$ can be extracted by measuring the top-quark width from a scan of the $t\bar{t}$ threshold. The anticipated uncertainty in $V_{tb}$ from such a measurement is about 10% [49]. The width is known with very good theoretical precision, thanks to recent calculations at NNLO in QCD [50,51]. The recent renormalization-group-improved calculation of the $t\bar{t}$ threshold (Fig. 6), mentioned in the previous section, removes any theoretical uncertainty in the normalization of the cross section that would impede the extraction of the width [30].
As mentioned in the introduction, the top-quark Yukawa coupling is related to the top-quark mass (at leading order) via $y_t = \sqrt{2} m_t / v$, where $v$ is the vacuum-expectation value of the Higgs field. However, it is the Yukawa coupling, not the mass, which is the truly fundamental parameter. The Yukawa coupling transmits the information that the Higgs field has acquired a vacuum expectation value to the top quark, thereby generating its mass. Since the Yukawa coupling is associated both with electroweak symmetry breaking and with fermion mass generation, it may be the most interesting parameter in top-quark physics.

How accurately do we desire to measure the top-quark Yukawa coupling? Since it is linearly related to the top quark mass, it would be desirable to measure it with the same fractional precision as the top-quark mass. A measurement of the top-quark mass with an accuracy of 1–2 GeV would correspond to a measurement of the Yukawa coupling to about 1%. Unfortunately, there is no known way to make a measurement with this accuracy.

The most direct way to measure the top-quark Yukawa coupling at a hadron collider is via the associated production of the Higgs boson with a top-quark pair, as shown in Fig. 8. If the Higgs boson decays to $b\bar{b}$, there are four $b$ quarks in the final state, and tagging three or more of them reduces the background to an acceptable level. It has recently been argued that this process can be used to discover the Higgs boson in Run II of the Tevatron, given 15 fb$^{-1}$ of integrated luminosity [52]. This process would yield only a crude measurement of the Yukawa coupling, however, due to the limited statistics. Even at the LHC, the anticipated accuracy is only about 16% via this process [10][11]. A next-to-leading-order calculation of the production cross section is still needed. This calculation has thus far been performed only in the limit $m_h \ll m_t$ [53].

A less direct way to measure the top-quark Yukawa coupling at a hadron collider is to produce the Higgs boson via gluon fusion, as shown in Fig. 9 [54]. In the standard model this process is dominated by a top-quark loop, but if there are other heavy colored particles that couple to the Higgs boson (such as squarks), they too
contribute to the amplitude, complicating the extraction of the top-quark Yukawa coupling. Assuming only the top quark contributes substantially to this process, the Yukawa coupling can be measured with an accuracy of about 10%. The next-to-leading order calculation of this cross section is already in hand, but the remaining scale dependence is significant, about 15% \cite{55}. The gluon luminosity contributes another 10% to the uncertainty in the cross section \cite{56}.

The top-quark Yukawa coupling can also be measured at a Linear Collider, using the analogue of Fig. 8 with the initial quark-antiquark replaced by electron-positron and the intermediate gluon replaced by $\gamma, Z$. The measurement is limited by statistics, and depends on the machine energy. In Table 3 I list the accuracy of the measurement of the Yukawa coupling at a 500 GeV and a 1 TeV Linear Collider for two Higgs masses \cite{57}. At the 500 GeV machine one is limited by phase space. One does much better at the 1 TeV machine, but cannot achieve the desired 1% accuracy. The next-to-leading-order calculation of this cross section is already available \cite{58,59}.

Table 3: Accuracy of the measurement of the top-quark Yukawa coupling from $e^+e^- \rightarrow t\bar{t}h$ at a Linear Collider of energy 500 GeV and 1 TeV. From Ref. \cite{57}.

| $m_h$ (GeV) | 500 GeV | 1 TeV |
|------------|---------|--------|
| 110 | 12% | 6% |
| 130 | 44% | 8% |

Figure 9: Higgs-boson production from gluon fusion via a top-quark loop.
5 Conclusions

Thus far the properties of the top quark have been tested only crudely. This decade will witness measurements of the top quark with increasing precision at the Tevatron and the LHC, and perhaps eventually at a Linear Collider. These measurements will either confirm that the top quark is an ordinary standard-model quark, or will indicate the presence of new physics. In either case, the study of the top quark will be rewarding.

In this talk I concentrated on the measurement of the fundamental parameters associated with the top quark. I argued that the desire to measure the top-quark mass to an accuracy of 1–3 GeV, the goal of the Tevatron and LHC, is well motivated by precision electroweak analyses, and by comparison with the anticipated accuracy in the $b$-quark mass. Although the Linear Collider can measure the mass with an accuracy of 100 MeV, there is no compelling motivation within the standard model to pursue such an accuracy. I considered two speculative motivations for pursuing this accuracy from physics beyond the standard model.

The CKM matrix element $V_{tb}$ will be measured with an accuracy of about 5% at the Tevatron and the LHC via single-top-quark production. If there are only three generations, this measurement is not nearly accurate enough to help determine the CKM matrix. A Linear Collider cannot make a more accurate measurement.

The top-quark Yukawa coupling to the Higgs boson is perhaps the most interesting parameter, since it is associated with electroweak symmetry breaking and fermion mass generation. Since the Yukawa coupling is proportional to the top-quark mass, it would be desirable to measure them both with the same percentage accuracy. Unfortunately, this is well out of reach. Only a crude measurement of the top-quark Yukawa coupling can be made at the LHC. A Linear Collider with energy significantly above 500 GeV can measure the Yukawa coupling with an accuracy below 10%, but cannot achieve the desired 1% accuracy.

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