RMP Colloquia

Studying the top quark

S. Willenbrock

Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801

The top quark, discovered at the Fermilab Tevatron collider in 1995, is the heaviest known elementary particle. Its large mass suggests that it may play a special role in nature. It behaves differently from the other known quarks due to both its large mass and its short lifetime. Thus far we have only crude measurements of the properties of the top quark, such as its mass, weak interactions, strong interactions, and decay modes. These measurements will be made more precise when the Tevatron begins operation again in 2001. I review the present status of these measurements, and discuss their anticipated improvement.

CONTENTS

I. INTRODUCTION

There are six known quarks in nature, with the whimsical names up, down, strange, charm, bottom, and top. The quarks are arranged in three pairs or "generations," as shown in Fig. 1; each member of a pair may be transformed into its partner via the charged-current weak interaction. Together with the six known leptons (the electron, muon, tau, and their associated neutrinos; see Fig. 1), the six quarks constitute all of the matter[1] in the universe (with the possible exception of the mysterious "dark matter"). It is therefore essential that we understand the properties of the quarks and leptons in detail.

The most recently discovered of the quarks and leptons is the top quark, which was discovered in 1995 by the CDF (Abe *et al.*, 1995) and D0 (Abachi *et al.*, 1995) experiments at the Fermilab Tevatron, a proton-antiproton collider of center-of-mass energy[2] $\sqrt{S}$ $=1.8$ TeV located in the suburbs of Chicago. Due to its

relatively recent discovery, far less is known about the top quark than about the other quarks and leptons. In this article I review what has been learned about the top quark since its discovery [reviewed in this journal in Campagnari and Franklin (1997)],[3] and look forward to future experimental probes of the top quark at the Tevatron.[4]

Thus far, the properties of the quarks and leptons are successfully described by the so-called "standard model" of the strong and electroweak interactions. However, this theory does not account for the masses of these particles; it merely accommodates them. The top quark is by far the heaviest of the quarks and leptons, and it is tempting to speculate that it is special.[5] The goal of future experiments is therefore to measure the properties of the top quark, to compare them with the standard model, and to learn whether the top quark is indeed special.

What are the chances that a close inspection of the properties of the top quark will yield surprises? One way to address this question is to consider the top-quark's weak-interaction partner, the *b* quark. The *b* quark was discovered in 1977 (Herb *et al.*, 1977), and in 1983 it yielded its first surprise: its lifetime was found to be much longer than expected (Fernandez *et al.*, 1983; Lockyer *et al.*, 1983). The top quark has already yielded its first surprise: the large value of its mass, approximately 174 GeV. The next heaviest quark is the *b* quark, with a mass of only about 5 GeV. 15 years ago, there

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[1]The quarks and leptons are spin 1/2 fermions; it is customary to reserve the term "matter" for these particles. The other known particles are spin 1 gauge bosons, which mediate forces between the quarks and leptons; the photon (γ) mediates the electromagnetic interaction, the gluon (g) the strong interaction, W the charged-current weak interaction, and Z the neutral-current weak interaction.

[2]The upper-case "Mandelstam variable" S corresponds to the square of the total energy of the colliding proton and antiproton in the center-of-mass frame.

[3]For a nontechnical exposition on the discovery of the top quark, see Liss and Tipton (1997).

[4]In this article I restrict my attention to top-quark physics at the Tevatron. The Tevatron has a monopoly on the top quark until 2005, when the CERN Large Hadron Collider (a proton-proton collider of center-of-mass energy $\sqrt{S}=14$ TeV in Geneva, Switzerland) is scheduled to begin operation. Proposed high-energy lepton colliders would also contribute to top-quark physics.

[5]Speculations about the special role of the top quark in particle physics, and their experimental implications, are reviewed in Simmons (1999).

$$\text{Quarks:} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\text{Leptons:} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

FIG. 1. The six known quarks are arranged in three generations. Each quark is transformed into its partner via the charged-current weak interaction. The same is true of the six known leptons.

were few who would have guessed that the top quark would be so heavy. A detailed scrutiny of the top-quark's properties will reveal whether there are more surprises in top-quark physics.

Even if the top quark should prove to be a normal quark, the experimental consequences of this very heavy quark are interesting in their own right. Many of the measurements described in this article have no analogue for the lighter quarks. This is not just a consequence of the large mass of the top quark, but also of its very short lifetime. In contrast to the lighter quarks, which are permanently confined in bound states with other quarks and antiquarks,[6] the top quark decays so quickly that it does not have time to form bound states. There is also insufficient time to depolarize the spin of the top quark, in contrast to the lighter quarks, whose spin is depolarized by chromomagnetic interactions[7] within the bound states. Thus the top quark is free of many of the complications associated with the strong interaction. The top quark therefore presents novel experimental challenges and opportunities, which require innovative ideas and techniques.

II. OVERVIEW

The top quark was discovered during Run I of the Tevatron (Abe *et al.*, 1995; Abachi *et al.*, 1995) from 1992–1996, in which approximately 100 pb^{-1} of integrated luminosity[8] were collected. The top quark is believed to have a very short lifetime, about 0.5×10^{-24} s, so it can only be detected indirectly via its decay products, a W boson and a b quark ($t \to Wb$). A b quark is sufficiently long-lived (1.5 ps) that it travels a measurable distance before decaying (about 450 μm), leaving a secondary vertex which can be detected with a silicon vertex detector ("b tagging").[9] The W boson can decay either to a pair of leptons or a pair of quarks. The top

quark is produced via the strong interaction together with its antiparticle, the top antiquark (denoted $\bar{t}$).

Run II of the Tevatron is scheduled to begin in 2001, with an initial goal of 2 fb^{-1} of integrated luminosity, and an ultimate goal of up to 30 fb^{-1}. The machine energy in Run II will be $\sqrt{S} = 2$ TeV, an increase over the $\sqrt{S} = 1.8$ TeV energy of Run I. Both the CDF and D0 detectors will be upgraded such that they will have an increased acceptance for top-quark events (CDF II, 1996; D0 Upgrade, 1996).

These improvements in the accelerator and detectors translate into a large number of top quarks. For example, let us consider some of the cleanest top-quark events, $t\bar{t} \to WWb\bar{b}$, where one W boson is detected via its leptonic decay, the other W boson decays to a pair of quarks, and at least one of the b quarks is tagged. These events are fully reconstructable and have very little background. In the Run I data, each experiment had about 25 such events (Abe *et al.*, 1998a; Abachi *et al.*, 1997a).[10] There are expected to be about 1000 events per experiment in the initial stage of Run II (2 fb^{-1}), due mostly to the factor of 20 increase in integrated luminosity, but also due to the 37% increase in production cross section at $\sqrt{S} = 2$ TeV and the increased acceptance for top-quark events. The ultimate goal of 30 fb^{-1} corresponds to about 15 000 events per experiment. The large number of events produced in Run II will allow a detailed scrutiny of the properties of the top quark.

III. TOP MASS

The top-quark mass has been measured by the CDF (Abe *et al.*, 1999) and D0 (Abbott *et al.*, 1998a, 1998b, 1999) Collaborations to be

$$m_t = 176.0 \pm 6.5 \text{ GeV (CDF)} \tag{1}$$
$$= 172.1 \pm 7.1 \text{ GeV (D0).} \tag{2}$$

This yields a world-average mass of (Demortier *et al.*, 1999)[11]

$$m_t = 174.3 \pm 5.1 \text{ GeV (CDF+D0).} \tag{3}$$

To put this into context, I plot all the quark masses in Fig. 2, 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 [$m_b^{\overline{MS}}(m_b) = 4.25 \pm 0.15$ GeV] (Caso *et al.*, 1998). 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. Figure 3 sum-

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[6]These bound states, collectively called hadrons, come in two types: baryons (three quarks) and mesons (quark and antiquark). They are formed by the strong interaction.

[7]This is the strong-interaction analogue of magnetism.

[8]The integrated luminosity corresponds to the instantaneous luminosity integrated over time.

[9]A b quark can also be tagged via its semileptonic decay.

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[10]For example, CDF had 34 such events, of which about eight are thought to be background.

[11]This is the top-quark pole mass, which corresponds approximately to its physical mass (Smith and Willenbrock, 1997). The corresponding $\overline{MS}$ mass, which is an unphysical parameter useful for precision analyses, is $m_t^{\overline{MS}}(m_t^{\overline{MS}}) = 165.2 \pm 5.1$ GeV (Gray *et al.*, 1990).
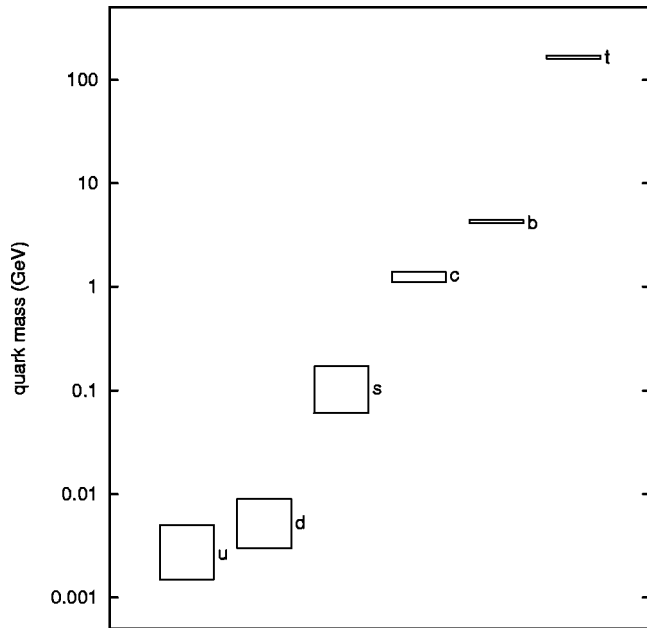
FIG. 2. The quark mass spectrum. The bands indicate the running $\overline{\text{MS}}$ mass, evaluated at the quark mass (for c,b,t) or at 2 GeV (for u,d,s), and the associated uncertainty.
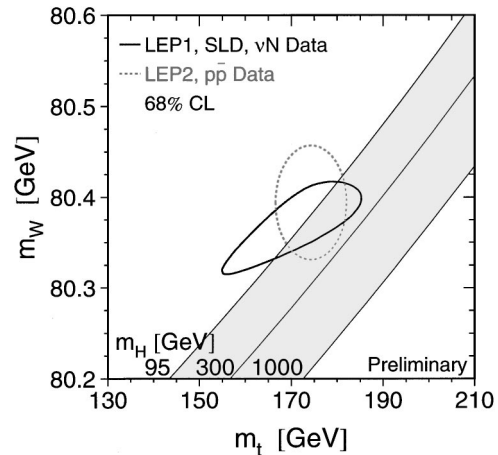

FIG. 3. W mass vs top-quark mass, with lines of constant Higgs mass. The solid ellipse is the 1σ (68% C.L.) contour from precision electroweak experiments. The dashed ellipse is the 1σ (68% C.L.) contour from direct measurements. Only the shaded region is allowed in the standard electroweak model. (Figure from LEP Electroweak Working Group, http://www.cern.ch/LEPEWWG/)

marizes 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 measured top-quark mass should lie within this contour. Since the contour spans about ± 8 GeV along the m_t axis, we conclude that the present uncertainty of 5 GeV in the top-quark mass is more than sufficient for the purpose of precision electroweak physics at this time.

There is one electroweak measurement, M_W, whose precision could increase significantly. An uncertainty of 20 MeV is a realistic goal for Run II (30 fb^{-1}) at the Tevatron (Amidei and Brock, 1996). Let us take this uncertainty and project it onto a line of constant Higgs mass in Fig. 3.[12] 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.

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 coupling of the top quark to the Higgs field ("Yukawa coupling") given by

$$y_t = \sqrt{2}\,\frac{m_t}{v} \approx 1, \tag{4}$$

where $v \approx 246$ 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.[13] The b-quark mass is currently known with an accuracy of 3.5%. Since the uncertainty is entirely theoretical, it is likely that it will be reduced in the future. If we assume that future work cuts the uncertainty in half, the corresponding uncertainty in the top-quark mass would be 3 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 3 GeV. This is well matched with future expectations. An uncertainty of 3 GeV per experiment is anticipated in the initial stage of Run II (2 fb^{-1}) (CDF II, 1996; D0 Upgrade, 1996), and additional running could reduce this uncertainty to 2 GeV (Amidei and Brock, 1996).

IV. TOP WEAK INTERACTION

The standard model dictates that the top quark has the same vector-minus-axial-vector $(V-A)$ charged-current weak interaction as all the other fermions, as shown in Fig. 4. It is easy to see that this implies that the W boson in top decay cannot be right handed, i.e., have

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[12]The hypothetical Higgs boson is discussed in Sec. VII.

[13]A particularly compelling model which relates the b and t masses is SO(10) grand unification (Georgi, 1974; Fritzsch and Minkowski, 1975). 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 (Gell-Mann et al., 1979) as $m_{\nu_\tau} \approx m_t^2/M_{\text{GUT}} \approx 10^{-2}$ eV (Wilczek, 1999).
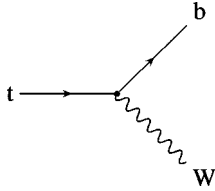
FIG. 4. Top-quark charged-current weak interaction.

positive helicity.[14] The argument is sketched in Fig. 5. In the idealized limit of a massless b quark, the $V-A$ current dictates that the b quark in top decay is always left handed.[15] If the W boson were right handed, then the component of total angular momentum along the decay axis would be $+3/2$ (there is no component of orbital angular momentum along this axis). But the initial top quark has spin angular momentum $\pm 1/2$ along this axis, so this decay is forbidden by conservation of angular momentum. CDF has measured

$$BR(t \to W_+ b) = 0.11 \pm 0.15, \qquad (5)$$

which is consistent with zero (Affolder *et al.*, 2000).

The top quark may decay to a left-handed (negative helicity) or a longitudinal (zero helicity) W boson. Its coupling to a longitudinal W boson is similar to its Yukawa coupling, Eq. (4), which is enhanced with respect to the weak coupling. Therefore the top quark prefers to decay to a longitudinal W boson, with a branching ratio

$$BR(t \to W_0 b) = \frac{m_t^2}{m_t^2 + 2M_W^2} \approx 70\%. \qquad (6)$$

CDF has made a first measurement of this branching ratio (Affolder *et al.*, 2000),

$$BR(t \to W_0 b) = 0.91 \pm 0.37 \pm 0.13, \qquad (7)$$

which is consistent with expectations. The anticipated fractional accuracy of this measurement in the initial stage of Run II (2 fb^{-1}) is 5.5% (CDF II, 1996; D0 Upgrade, 1996), with an ultimate accuracy (30 fb^{-1}) of less than 2% (Amidei and Brock, 1996).

Quarks are transformed into their partner via the charged-current weak interaction, but they are not completely loyal; there are also occasional transitions between different generations. This is described by the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) matrix. The matrix elements V_{tb}, V_{ts}, and V_{td} characterize the strength of the transition of a top quark into a bottom, strange, and down quark, respectively, ($|V_{ij}| \le 1$).

CDF has measured (Tollefson, 1999)

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[14]Helicity is the component of spin along the direction of motion of a particle.

[15]Being far from massless, the decaying top quark can be left or right handed.
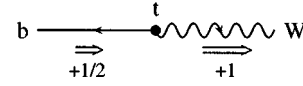
FIG. 5. Illustration that the top quark cannot decay to a right-handed (positive-helicity) W boson.

$$\frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99 \pm 0.29 \qquad (8)$$

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. (8) is unity, and we can immediately extract

$$|V_{tb}| = 0.99 \pm 0.15 \quad (>0.76 \; 95\% \; \text{C.L.})$$
$$(\text{three generations}). \qquad (9)$$

However, to put this into perspective, recall that three-generation unitarity also implies that $|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$, and since $|V_{ub}|$ and $|V_{cb}|$ have been measured to be small, one finds (Caso *et al.*, 1998)

$$|V_{tb}| = 0.9991 - 0.9994 \; (\text{three generations}), \qquad (10)$$

which is far more accurate than the present CDF result (as well as the anticipated accuracy from Run II).

If we assume more than three generations, then unitarity implies almost nothing about $|V_{tb}|$ (Caso *et al.*, 1998):

$$|V_{tb}| = 0.06 - 0.9994 \; (>\text{three generations}). \qquad (11)$$

At the same time, we also lose the constraint that the denominator of the middle expression in Eq. (8) is unity. All we can conclude from Eq. (8) is that $|V_{tb}| \gg |V_{ts}|, |V_{td}|$; we learn nothing about its absolute magnitude.

Fortunately, there is a direct way to measure $|V_{tb}|$ at the Tevatron, which makes no assumptions about the number of generations. One uses the weak interaction to produce the top quark; the two relevant processes are shown in Fig. 6. The cross sections for these two "single top" processes are proportional to $|V_{tb}|^2$. The first process involves an s-channel W boson (Cortese and
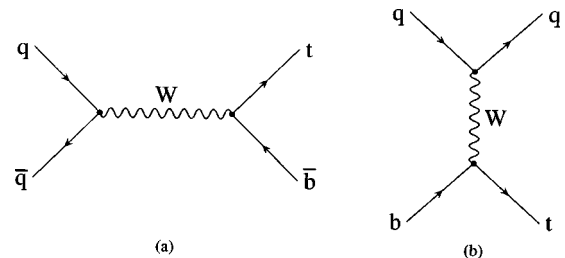
FIG. 6. Single-top-quark production via the weak interaction: (a) s-channel process; (b) t-channel process.
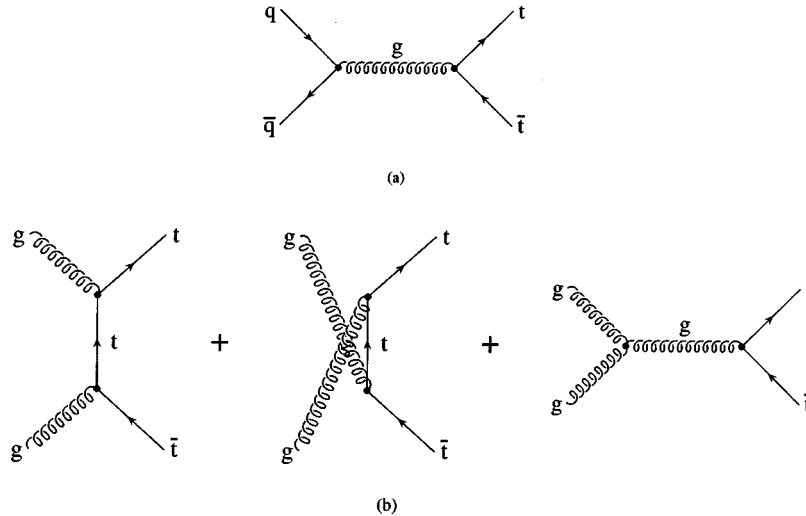
FIG. 7. Top-quark pair production via the strong interaction: (a) quark-antiquark annihilation; (b) gluon fusion. There are three Feynman diagrams which contribute to the latter process.

Petronzio, 1991; Stelzer and Willenbrock, 1996a; Smith and Willenbrock, 1996; Heinson *et al.*, 1997; Stelzer *et al.*, 1998; Belyaev *et al.*, 1999), while the second process involves a *t*-channel *W* boson[16] (and is often called *W*-gluon fusion, because the initial *b* quark actually comes from a gluon splitting to $b\bar{b}$) (Willenbrock and Dicus, 1986; Yuan, 1990; Ellis and Parke, 1992; Carlson and Yuan, 1993; Heinson *et al.*, 1997; Stelzer *et al.*, 1997, 1998; Belyaev *et al.*, 1999). The *t*-channel process has the advantage of greater statistics than the *s*-channel process, but the disadvantage of greater theoretical uncertainty. Thus far there is only a bound on single-top-quark production via the *t*-channel process from CDF (Tollefson, 1999),

$$\sigma(qb \to qt) < 15.4 \text{ pb} \quad (95\% \text{ C.L.}), \tag{12}$$

which is an order of magnitude away from the theoretical expectation of 1.70 ± 0.24 pb (Stelzer *et al.*, 1997, 1998). There is a similar bound on the *s*-channel process from CDF (Savard, 1999),

$$\sigma(q\bar{q} \to t\bar{b}) < 15.8 \text{ pb} \quad (95\% \text{ C.L.}), \tag{13}$$

which is even further from the theoretical expectation of 0.73 ± 0.10 pb (Smith and Willenbrock, 1996).

Both single-top processes should be observed in the initial stage of Run II (2 fb^{-1}); the *t*-channel process will yield a measurement of V_{tb} with an accuracy of about 13% (CDF II, 1996; D0 Upgrade, 1996). The ultimate accuracy (30 fb^{-1}) is anticipated to be about 5%, perhaps using the *s*-channel process owing to its small theoretical uncertainty (Amidei and Brock, 1996).

Single-top-quark production can also be used to test the $V-A$ structure of the top-quark charged-current weak interaction. This structure implies that the top-

quark spin is nearly 100% polarized along the direction (in the top-quark rest frame) of the *d* or $\bar{d}$ quark in the event, in both *W*-gluon fusion and the *s*-channel process (Mahlon and Parke, 1997a). This effect will be observable in Run II (Stelzer *et al.*, 1998).

V. TOP STRONG INTERACTION

The strong interaction of the top quark is best tested in its production. There are two subprocesses by which $t\bar{t}$ pairs are produced via the strong interaction at a hadron collider, shown in Fig. 7. At the Tevatron, the quark-antiquark annihilation process is dominant, accounting for 90% of the cross section at $\sqrt{S} = 1.8$ TeV. When the machine energy is increased to $\sqrt{S} = 2$ TeV in Run II, this fraction decreases to 85%. The cross section increases considerably, by about 37%, when the machine energy is increased from 1.8 to 2 TeV.

We show in Fig. 8 the $t\bar{t}$ cross section vs the top-quark mass. The dashed band is from a calculation at next-to-leading order (NLO) in the strong interaction (Nason *et al.*, 1988; Beenakker *et al.*, 1989). The uncertainty in this calculation is about 10%. The solid band includes the effect of soft gluon resummation at next-to-leading logarithm (NLL); this increases the cross section by only a few percent, but reduces the uncertainty by almost a factor of two (Laenen *et al.*, 1992; Berger and Contopanagos, 1995, 1996, 1998; Catani *et al.*, 1996a, 1996b; Bonciani *et al.*, 1998).[17] The measurements by CDF (Abe *et al.*, 1998b, Ptohas, 1999) and D0 (Abachi *et al.*, 1997b),

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[16]It is conventional to label the Feynman diagrams by the lower-case "Mandelstam variables" *s* and *t*, which correspond to the square of the four-momentum of the *W* boson in the diagrams.

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[17]These bands reflect the uncertainty in the cross section due to the variation of the renormalization and factorization scales. They do not include the uncertainty from $\alpha_s(M_Z)$ or the parton distribution functions. However, these additional uncertainties are relatively modest (Catani *et al.*, 1996a, 1996b).
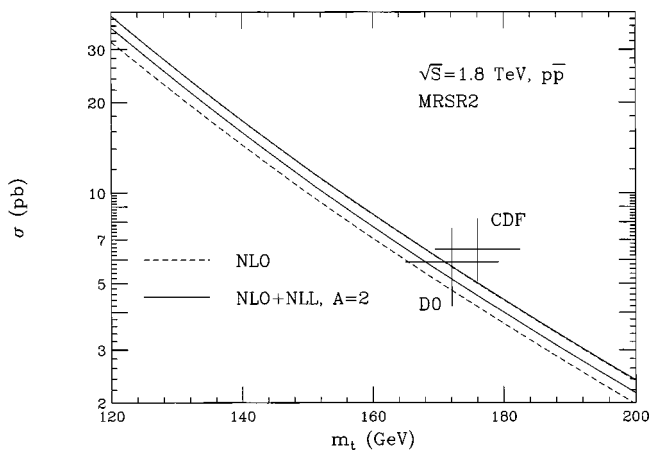
FIG. 8. Cross section for $t\bar{t}$ production at the Tevatron vs the top-quark mass. Dashed band is from next-to-leading-order (NLO) in the strong interaction (note that the upper solid and dashed lines are nearly coincident); solid band includes soft-gluon resummation at next-to-leading-logarithm (NLL). The calculation employs the MRSR2 parton distribution functions to describe the quark and gluon content of the proton (Martin *et al.*, 1996). Figure adapted from Bonciani *et al.* (1998).

$$\sigma = 6.5^{+1.7}_{-1.4} \text{ pb (CDF)}, \tag{14}$$

$$\sigma = 5.9 \pm 1.7 \text{ pb (D0)}, \tag{15}$$

are also shown in the figure, and are seen to agree with theory within one standard deviation. The anticipated accuracy of the measurement of the cross section in the initial stage of Run II (2 fb^{-1}) is 9% (CDF II, 1996; D0 Upgrade, 1996), with an ultimate accuracy (30 fb^{-1}) of 5% (Amidei and Brock, 1996).

An interesting aspect of the strong production of $t\bar{t}$ pairs is that the spins of the t and $\bar{t}$ are nearly 100% correlated (Kühn, 1984; Barger *et al.*, 1989; Hara, 1991; Arens and Sehgal, 1993; Mahlon and Parke, 1996; Stelzer and Willenbrock, 1996b; Brandenburg, 1996; Chang *et al.*, 1996; Mahlon and Parke, 1997b). The correct basis with which to measure the spins requires some consideration, however. At threshold ($\sqrt{s} \approx 2m_t$),[18] the cross section is entirely s wave, so the spins of the colliding quarks are transferred to the t and $\bar{t}$. Since the quark-antiquark annihilation takes place via a gauge interaction, the quark and antiquark must have opposite helicities, so the spins of the t and $\bar{t}$ are aligned along the beamline as shown in Fig. 9(a). At the other extreme, far above threshold ($\sqrt{s} \gg 2m_t$), the t and $\bar{t}$ behave like massless quarks, and therefore must have opposite helicities, as shown in Fig. 9(b). The question is whether there is a basis which interpolates between the beamline basis near threshold and the helicity basis far above threshold, and the answer is affirmative—it has been dubbed the "off-diagonal" basis (Park and Shadmi,

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[18]The lower-case "Mandelstam variable" s corresponds to the square of the total energy of the colliding quarks in the center-of-mass frame.
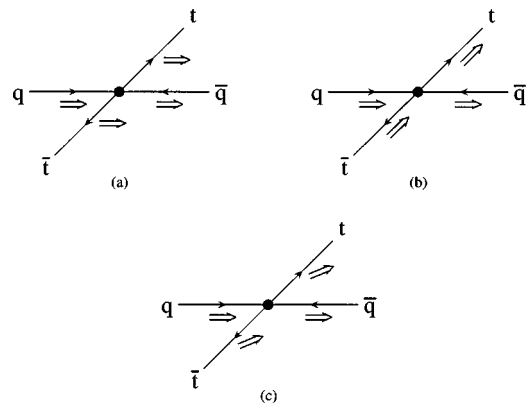

FIG. 9. Top-quark and light-quark spins in $q\bar{q} \rightarrow t\bar{t}$: (a) near threshold; (b) far above threshold; (c) intermediate energies.

1996; Mahlon and Parke, 1997b). The t and $\bar{t}$ spins are 100% correlated in this basis, as shown in Fig. 9(c). Since the quark-antiquark annihilation process accounts for most of the cross section at the Tevatron, the spin correlation is nearly 100%. A first attempt to observe this effect has been made by D0, based on six dilepton events (Abbott *et al.*, 2000). This effect should be observable in Run II (Snyder, 1999).

Another interesting aspect of the strong production of $t\bar{t}$ pairs is an asymmetry in the distribution of the t and $\bar{t}$ quarks (Kühn and Rodrigo, 1998, 1999). This effect arises at next-to-leading order, and leads to a forward-backward asymmetry of about 5% in $t\bar{t}$ production at the Tevatron.

VI. RARE DECAYS

Rare top decays in the standard model tend to be very rare, outside the range of the Tevatron. Thus far CDF has placed limits on the rare decays (Abe *et al.*, 1998c):

$$BR(t \rightarrow Zq) < 33\% \quad (95\% \text{ C.L.}), \tag{16}$$

$$BR(t \rightarrow \gamma q) < 3.2\% \quad (95\% \text{ C.L.}), \tag{17}$$

which have tiny branching ratios in the standard model (Eilam *et al.*, 1991).

The least rare of the rare decays within the standard model are the CKM suppressed decays $t \rightarrow Ws$ and $t \rightarrow Wd$, shown in Fig. 10. These decays are interesting because they allow a direct measurement of the CKM matrix elements V_{ts} and V_{td}. Assuming three generations, the branching ratios are predicted to be

$$BR(t \rightarrow Ws) \approx 0.1\%, \tag{18}$$

$$BR(t \rightarrow Wd) \approx 0.01\%, \tag{19}$$

which are small, but not tiny. Since there will be about 10 000 raw $t\bar{t}$ pairs produced in the initial stage of Run II (2 fb^{-1}), and about 150 000 ultimately (30 fb^{-1}), events of these types will be present in the data. However, there is no generally accepted strategy for identifying these events.
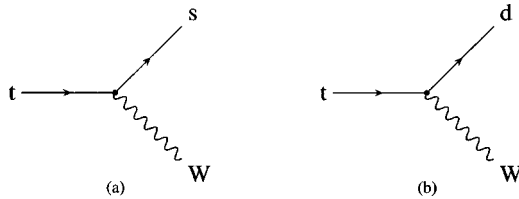
FIG. 10. Rare top decays: (a) $t \rightarrow Ws$; (b) $t \rightarrow Wd$.

VII. OUTLOOK

Top-quark physics is in its infancy. Since its discovery in 1995, we have only had a crude look at the top quark's properties. Run II of the Fermilab Tevatron, scheduled to begin in 2001, will allow a careful study of the top quark; its strong and weak interactions, as well as its mass, will be accurately measured. The goal of these studies is to determine if the top quark, which is so much heavier than the other quarks and leptons, is special. Even if the top quark should prove to be normal, the study of this very massive quark will be intriguing, since many of these studies have no analogue for the lighter quarks.

The CERN Large Hadron Collider, scheduled to begin operation in 2005, will allow an even closer look at the top quark (ATLAS, 1999; Beneke *et al.*, 2000). Proposed lepton colliders would provide a complementary view of the top quark, especially if they are designed to operate near the $t\bar{t}$ threshold (Murayama and Peskin, 1996).

It is not known if the study of the top quark will bring us closer to an understanding of the mechanism which endows the top quark, as well as the other quarks and leptons, with mass. In the standard Higgs model, it is the coupling of the quarks and leptons to the Higgs field which is responsible for the generation of mass. [19] The discovery of the Higgs boson would be compelling evidence that this model is correct in its essence. The search for the Higgs boson, or whatever else nature has provided, is a central focus of particle physics. If we are fortunate, the Higgs boson could be discovered in Run II of the Tevatron (Stange *et al.*, 1994a, 1994b; Amidei and Brock, 1996; Han and Zhang, 1999; Han *et al.*, 1999; Carena *et al.*, 1999). The Higgs boson cannot elude the Large Hadron Collider (ATLAS, 1999), so we are certain to glean important information about the generation of mass in the coming decade.

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[19]This coupling also yields the Cabbibo-Kobayashi-Maskawa matrix.

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