Top Quark Physics: Summary

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Abstract. This talk summarizes recent progress in top quark physics studies for high energy linear electron-positron colliders as presented at the LCWS2000 Workshop at Fermilab. New results were presented for top pair production at threshold and in the continuum, as well as for top production at $\gamma\gamma$ colliders.

INTRODUCTION

Top quark production promises to provide an excellent system in which to study the physics of the Standard Model and beyond, and a linear e^+e^- collider provides an excellent environment in which to do so. The top quark's mass of 174 GeV gives it a number of unique features. Its decay width $\Gamma_t = 1.4$ GeV is so large that top decays before hadronizing [1], unlike the lighter quarks. This rapid decay causes the top quark's spin information to be passed to its decay products. Top also has the largest coupling to the Higgs sector of all the fermions; indeed the fact that its Yukawa coupling is very close to unity suggests that the top quark may play a special, fundamental role in Electroweak Symmetry Breaking. The importance of the top quark to new physics studies is indicated by the fact that the top quark was featured in talks at this conference not only in the present session but also in the Higgs, Electroweak, New Phenomena, and Supersymmetry sessions. This underscores the point that in order to get at physics beyond the SM, we must understand the physics of the top quark in detail.

Here we summarize the work that was presented in the Top Quark session. Significant progress has been made in a number of areas since LCWS99 at Sitges (see [2] and [3] for summaries of theoretical and experimental aspects of top physics at LCWS99), including top production at threshold, at high energies, and in $\gamma\gamma$ collisions. Threshold studies by the European Working Group were not presented here but will be included in the TESLA TDR to be released in Spring 2001 [4].

TOP AT THRESHOLD

A linear e^+e^- collider operating in the threshold region for top pair production (around 350 GeV in the center of mass) allows us to make precise measurements of the top quark mass and the strong coupling constant α_s. The top width and couplings can be measured to a lesser extent. Top-antitop pairs cannot form toponium because they decay too fast, but there is still a Coulomb-like QCD interaction between the t and $\bar{t}$ which results in notrivial structure in the top production cross section at threshold. Experimental simulations indicate that a threshold scan could give a top mass measurement with an experimental uncertainty as low as 40 or 50 MeV [3]. This would be an improvement over the LHC, where we can expect to measure the top mass to a GeV or two at best. This presents a challenge to theorists to achieve comparable precision in threshold cross section predictions.

Theoretical Issues

NNLO calculations of the top threshold cross section were presented at Sitges, and the results did not at first bode well for the prospect of achieving the desired theoretical precision [2]. There were several problems: the NNLO corrections to the normalization were unexpectedly large, the $1S$ peak position (used to determine m_t) shifted with respect to NLO by large amounts (600–800 MeV), and the renormalization scale dependence was no better at NNLO than at NLO.

The situation was already improving around the time of the Sitges meeting, and it has been further clarified since then. The resolution of the peak position–mass problem was discussed in talks here by Sumino [5] and Yakovlev [6], and a summary of the situation can be found in [7]. The problem arose from the top mass definition used in the calculations. Specifically, if one calculates in terms of the familiar pole mass — the position of the pole in the top quark propagator and the mass measured in top quark reconstruction (for example by CDF and D$\emptyset$) — one is sensitive to effects associated with long distance/low energy phenomena such as hadronization. This so-called renormalon ambiguity gives rise to uncertainties of order Λ_{QCD} and results in a shift in the NNLO peak position.

The solution is to switch to a mass definition that is appropriate for short distances, such as the $1S$ mass; see [7] for a discussion of the various possibilities. The renormalon contribution to the relation between the pole mass and the short distance mass is exactly canceled by a corresponding contribution in the relation between pole mass and the binding energy of the $t\bar{t}$ state. The resulting NNLO peak shift is well under control, and one can realistically expect much-improved theoretical precision.

Just what it would take to achieve 50 MeV theoretical precision was the subject of the talk by Sumino [5]. It requires higher-order calculations in which the renormalons continue to cancel. There was some confusion at Sitges about order counting in the cancellation, but this has since been clarified: the cancellation takes place at *different* orders in α_s in the binding energy and the m_{pole}–$m_{\bar{M}S}$ relation; one has to go one order higher in $E_{binding}$. For the desired theoretical precision, one needs $\mathcal{O}(\alpha_s^4)$ in the mass and $\mathcal{O}(\alpha_s^5)$ in $E_{binding}$. Sumino reported results for $E_{binding}$ to $\mathcal{O}(\alpha_s^5)$ in the large-β_0 approximation, which is sufficient to demonstrate the renormalon cancellation. He obtained the following masses for the "toponium" $1S$ state (keeping the contributions from individual orders in α_s separate):

$$M_{1S} = 2 \times (174.79 - 0.46 - 0.39 - 0.28 - 0.19) \text{ GeV} \quad (1)$$
$$= 2 \times (165.00 + 7.21 + 1.24 + 0.22 + 0.052) \text{ GeV} \quad (2)$$

where the first result is for the pole-mass scheme and the second is for the $\bar{M}S$-mass scheme; the improvement in convergence in the latter scheme is clear. The last number in each line is a new result reported here at LCWS2000. This represents significant progress; still needed for the desired theoretical precision are the $\mathcal{O}(\alpha_s^4 m)$ relation between m_{pole} and $m_{\bar{M}S}$ (a four-loop calculation), inclusion of final-state interactions and electroweak corrections, and a determination of the effect of initial state radiation on the position of the $1S$ peak.

Yakovlev also discussed top production at the threshold [6]. He introduced a new short-distance mass definition, the $\bar{PS}$ mass, which is a modification of the PS (potential-subtracted) mass defined in [8]. The $\bar{PS}$ mass includes recoil corrections of order $1/m$ and further improves the behavior of the cross section. Yakovlev also reported that nonfactorizable corrections to the threshold cross section cancel at NNLO.

The peak position problems with the top threshold are therefore now solved, paving the way for a precise threshold mass measurement. The problems associated with the overall normalization and renormalization scale dependence must also be resolved if we wish to measure top couplings at the threshold. Fortunately, there was some good news on this front about the time of this workshop. Although it was not presented here, a new threshold calculation appeared recently which involves resumming logarithms of the top velocity. The calculation results in a vast reduction of the theoretical uncertainty to the few percent level. Details can be found in [9].

Experimental Issues

Ikematsu discussed experimental aspects of top momentum reconstruction near threshold [10]. Previous studies have focused on threshold scans (see [3] for a status report) which measure the total top production cross section. But as Ikematsu pointed out, we can extract additional information by examining threshold top events in more detail. For example, anomalous CP-violating gluon EDM couplings are enhanced at the threshold. To study these, we need to measure the momentum of the top quark. Ikematsu presented results of an experimental simulation at $\sqrt{s} = 2m_t + 2$ GeV including ISR, beamstrahlung, and QCD threshold corrections for lepton plus jets events. He compared a traditional direct momentum reconstruction algorithm to a kinematic fitting technique that incorporated a likelihood function. The kinematic fit significantly improves energy resolution and resolution in the direction of the top momentum. Extension of the study to energies below threshold and incorporation of an improved jet clustering algorithm are in progress.

CONTINUUM TOP PRODUCTION

Anomalous Couplings

At center of mass energies well above threshold, a linear collider allows us to probe the couplings associated with the top production and decay vertices. The production vertex involves the couplings of top to the photon and Z^0, which are difficult-to-impossible to measure at the LHC. The decays are sensitive to the coupling of top to the W boson and b quark. In both of these processes we can look for CP-violating couplings in electric and weak dipole moments. The work reported here [11,13] focused on the top production vertex.

Kiyo [11] discussed the effects of anomalous γ and Z^0 couplings in spin correlations in top production and decay. Using the off-diagonal spin basis of Parke and Shadmi [12], Kiyo showed that the azimuthal angle dependence of final-state leptons can be very sensitive to CP-violating effects. Let the coupling at the top production vertex be given by

$$g_{tt\gamma,Z} = g_V\{Q_L^{\gamma,Z}\gamma_\mu L + Q_R^{\gamma,Z}\gamma_\mu R + \frac{(p_t - p_{\bar{t}})_\mu}{2m_t}[G_L^{\gamma,Z}L + G_R^{\gamma,Z}R]\} \tag{3}$$

with anomalous couplings $G_{L,R}$. With $if_3 = G_R - G_L$, $|f_3| = 1$ corresponds to an electric dipole moment of $10^{-16}e$ cm. One can define a leptonic azimuthal asymmetry as a function of the top quark scattering angle. This asymmetry vanishes in the SM but can be as large as 5 or 10% for $|f_3|$ of the order of 0.2. In addition, one can distinguish between the various couplings (γ vs. Z and positive vs. negative) by adjusting the polarization of the initial electrons and positrons.

This method does require reconstruction of the top quark direction. Being able to distinguish the up- vs. down-type decay products of the W boson is also helpful; in leptonic W decays this information is given by the lepton charge.

M. Iwasaki addressed these experimental issues associated with measuring the couplings at the top production vertex [13]. The particular questions of interest were how well we can reconstruct the t and $\bar{t}$ quarks (and identify which is which), whether we can identify I_z of the W decay products, and to what extent we can use this information to constrain couplings. She presented results from an LCD fast simulation using Pandora-Pythia, with ISR, beamstrahlung, and QCD radiation included.

The presence of two neutrinos in dilepton events makes it difficult to obtain the t and $\bar{t}$ momenta, so this mode was not included in Iwasaki's studies. For lepton plus jets events, jet energies were obtained with a combination of tracking (for charged particles) and calorimetry (for neutrals) rather than straight calorimetry. b-tagging was performed by requiring that the p_T-corrected mass at the vertex be greater than 1.8 GeV, and by cutting on the number of significant tracks in the jet. The resulting flavor tag dramatically improved W and top mass reconstruction. The lepton charge provided I_z information.

Flavor tagging played an even more important role in the all-jets mode, with six jets and no leptons. Here Iwasaki used the mass tag for b tagging and added a measurement of vertex charge to distinguish b from $\bar{b}$. A charm tag — using a combination of p_T corrected mass and vertex momentum — was also shown to be reasonably effective (28% efficiency and 69% purity) in obtaining detailed information about the W decays. Note that such a charm tag would be very difficult at the LHC.

The result of the lepton plus jets analysis is that we can expect measurements to about 2–4 $\times 10^{-2}$ in the axial couplings $F_{1A}^{\gamma,Z}$. Vector coupling studies are in progress, as studies of the top decay vertex. An analysis for the all-jets mode is also on the way.

QCD

Precision measurements require precision predictions that include QCD corrections. Progress was reported here on fixed-order QCD corrections to top production and decay [14] and improvements in parton shower Monte Carlos to take the top mass into account [15,16].

QCD corrections to top processes have previously been performed for the production and decay processes separately or combined in the on-shell approximation. As of the Sitges meeting [2], real gluon corrections to the full top production and decay process with off-shell top quarks were calculated. Macesanu discussed the calculation of virtual corrections to top production and decay for off-shell top quarks [14] with all interferences, including so-called nonfactorizable corrections that contain diagrams with gluons connecting different parts of the process (t production and $\bar{t}$ decay, for example). The computation is being performed in the double-pole approximation, keeping only contributions from terms which contain two resonant top quarks, in analogy to the RacoonWW approach [17] to corrections to W pair production. The loop corrections are nearly complete and will be combined with the result for real gluon radiation [18] to give a complete NLO description of off-shell top production and decay.

In Monte Carlo programs, gluon radiation is often treated in the parton shower approximation, using parton splitting functions. This involves soft and collinear approximations for the radiated gluons. The shower approximation incorporates the leading QCD effects to high orders in α_s and works well for massless particles. Radiation from massive particles like the top quark is more complicate, however. In particular, from massless particles is characterized by a collinear singularity, whereas the mass of a heavy particle suppresses collinear radiation, creating a "dead cone" in the vicinity of the radiating particle. Parton showers have difficulty approximating the dead cone, and in addition they have difficulty populating large angles.

The solution is to incorporate matrix element corrections to the parton shower approach, and corrections to the programs HERWIG [15] and Pythia [16] were reported at this workshop. Corcella showed results for matrix element corrections to top decays in HERWIG; the program now reproduces the matrix element calculation for radiation in top events at linear colliders not too far above threshold. Corrections for radiation in top production are in progress, for hadron colliders as well. Also underway are the incorporation of spin correlations, and ISR and beamstrahlung for linear colliders.

Sjöstrand reported on improvements to Pythia [16], including matrix element corrections to radiation from *all* heavy particles: not only for top and the other SM particles but for supersymmetric particles as well. For radiation in top production at $E_{cm} = 500$ GeV, the corrections increase emissions off the $t\bar{t}$ pair but decrease emissions in the top decays, for a net decrease in the entire production and decay process. An interesting point to note about the corrections is a strong dependence of the radiation on the spin structure of the underlying process, in constrast to the universal behavior of massless splitting functions.

Corcella also discussed briefly some studies of top mass reconstruction in dilepton events using HERWIG and Pythia [15]. The lepton energy and bl invariant mass spectra were not very sensitive to m_t, but the E_b spectrum near threshold appeared more promising. However he also showed that differences between HERWIG and Pythia can amount to hundreds of MeV, which already saturates the desired uncertainty in the mass.

TOP AT $\gamma\gamma$ COLLIDERS

Finally, Boos gave a very nice review of top physics at $\gamma\gamma$ colliders [19]. Many processes and measurements are similar to those at e^+e^- colliders. The pair production cross section can be higher at $\gamma\gamma$ colliders for some polarizations and center of mass energies, and NLO corrections increase the $\gamma\gamma$ cross section. The threshold has similar NNLO problems to e^+e^- colliders, but these presumably can also be resolved.

A variety of top couplings and non-SM effects can be studied at a photon collider. The γtt coupling, for example, enters top pair production to the fourth power, and is already separate from the top coupling to the Z. Boos showed that CP properties of the Higgs boson can be studied, as can effects of large extra dimensions. Single top production probes the Wtb vertex and is sensitive to some technicolor models; ironically, its biggest background is $t\bar{t}$ pair production.

SUMMARY

We have seen at this workshop a lot of progress in top studies as we move from looking primarily at the big picture to perfoming more detailed analyses. Some very good news was that the theory of top production at threshold is once more under control. In continuum production, calculations of QCD corrections are becoming more sophisticated, and anomalous couplings are being studied in more detail. In addition, the experimental side of top reconstruction is becoming better understood. Much work is still under way, so we anticipate even more progress soon.

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