What Will LC Tell Us on Top/QCD? *

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ABSTRACT

Current status of Top/QCD studies at linear colliders (LC) is briefly viewed, classifying topics into two categories: those within the standard model and those beyond the standard model.

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*Summary Talk of Top/QCD session at International Workshop on Physics and Experiments with Future Electron-Positron Linear Colliders (LCWS2004), April 19-23, 2004, Le Carre des Sciences, Paris, France.

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First I would like to classify the topics on Top/QCD into two categories: those within the SM (standard model) and those beyond the SM. From this point of view, QCD is main part of the standard model, while the top-quark could join both part since we do not know it definitely yet whether it is a standard quark or not. At this workshop, six talks were presented in Top/QCD session, and in addition two related talks were given in $\gamma\gamma$ session. The former six talks were all on the top quark in the SM and/or QCD, which are therefore summarized in the SM part although their studies cannot be totally independent of new-physics search, while the latter two talks were on studying anomalous top-quark interactions, which are put in the beyond-the-SM part.

1. **Within the SM**

What do we need for more precise tests of the SM? Important parameters are $m_t$ and $\alpha_{\text{QCD}}$. At present, they are known with the following uncertainties:

$$\Delta m_t^{\text{exp}} = 4.3 \text{ GeV}, \quad \Delta \alpha_{\text{QCD}}^{\text{exp}}(M_Z) = 0.003.$$  \hspace{1cm} (1)

Why do we have to know them more precisely? Weiglein gave a talk on this theme \[1\]. Knowing them is important for

- EW precision tests and Higgs-boson mass prediction
- Testing the idea of Grand Unification

Let me take the most precise EW formula on the $M_W$-$M_Z$ relation as an example:

$$M_W^2(1 - M_W^2/M_Z^2) = \frac{\pi \alpha}{\sqrt{2} G_F}(1 + \Delta r),$$  \hspace{1cm} (2)

where $\Delta r$ expresses all the higher order corrections, and it is presently known at complete two-loop plus leading three-loop level. If $m_t$ is measured with $\Delta m_t = 1.5$ GeV (0.1 GeV), $M_W$ can be calculated with $\Delta M_W = 9$ MeV (1 MeV). On the other hand, LC is expected to measure $M_W$ with about 7 MeV uncertainty, which realizes an extremely high-precision test of the SM. Of course, they will also give a strong constraint on SUSY models and others.

Then how can we measure $m_t$ at LC? One effective way is to use the threshold behavior of $\sigma(e\bar{e} \rightarrow t\bar{t})$, on which a talk was given by Steinhauser \[2\]. In the threshold region, $t\bar{t}$ CM frame is a kind of $t\bar{t}$ rest frame. This enables us to take
a non-relativistic QCD approximation. Calculating the QCD potential within this approximation and comparing thus-calculated cross section with experimental data, it was shown that we could expect $\Delta m_t = 80$ MeV. This technique is also applicable to $b$- and $c$-quark systems.

On the other hand, we need QCD higher order corrections in order to measure the strong coupling constant $\alpha_{\text{QCD}}$. Weinzierl gave a talk [3] on their calculations for NNLO corrections to

$$e\bar{e} \rightarrow q\bar{q} \rightarrow 3 \text{jets.}$$

It is not hard to imagine they are quite tough work: what have to be computed are not only the two-loop amplitudes of the process, but also one-loop 4-jet amplitudes plus Born 5-jet amplitudes to cancel the IR divergence. The theoretical error in the extraction of $\alpha_{\text{QCD}}$ will be thereby reduced down to 1%.

Measuring $t\bar{t}H$ coupling is also a significant work, on which Besson gave a talk [4]. This will enable a test of the SM-vertex, i.e., a coupling proportional to $m_t$. The Feynman diagrams are those of $H$ emissions from $t$ or $\bar{t}$ in $e\bar{e} \rightarrow t\bar{t}$. After a careful study of possible backgrounds, they are expecting

$$\Delta g_{t\bar{t}H}/g_{t\bar{t}H} \lesssim 10\% \quad \text{for } m_H \leq 190 \text{ GeV} \quad (3)$$

$$\sim 5-6\% \quad \text{for } m_H \simeq 120 \text{ GeV} \quad (4)$$

for $\sqrt{s} = 800$ GeV.

LC can also offer a good opportunity for a traditional hadron physics “Pomeron” (and “Odderon”), which is the theme of Wallon’s talk [5]. Pomeron is something exchanged in $NN$ forward scattering, that has vacuum quantum number. In terms of QCD, it is interpreted as the exchange of a bound state of two gluons. Wallon proposes to use $J/\psi, \rho$ productions in the two-photon process in $e\bar{e}$ collisions, which will work as a test of soft IR part of QCD.

In order to perform those measurements/analyses with small systematic errors, careful studies of Beam spread, Beam strahlung, and Initial-state radiation are required. This was discussed in the talk by Boogert [6]. They are trying to parameterize those effects into one function, $\rho(x)$, with which we can calculate cross
sections as
\[ \sigma(\sqrt{s}) = \int_0^1 dx \, p(x) \sigma'(x\sqrt{s}) , \]
where \( x \) is an energy fraction. According to their fit results using \( m_t = 175 \) GeV and \( \alpha_{\text{QCD}} = 0.118 \), the following systematic shifts were observed:
\[ \Delta m_t = -48 \text{ MeV}, \quad \Delta \alpha_{\text{QCD}}(M_Z) = -0.0017. \]

2. Beyond the SM

The top-quark mass is even close to the EW breaking scale. This fact may be an indication that the top-quark possesses some information which the other quarks do not have. This consideration leads us to tests of top-quark couplings. For this purpose, one good signal will be \( CP \) violation, since \( CP \) violation in the SM top-quark couplings occurs at three-loop level and therefore negligible.

a. \( ee \) collision

Since \( t\bar{t} \) is produced via \( s \)-channel \( \gamma/Z \) exchanges and \( m_e \) is negligible comparing to \( \sqrt{s} \), initial \( |ee\rangle \) must be always \( CP \) even. Therefore, we have to construct \( CP \)-odd observables from final-state products:
\[ ee \to t\bar{t} \to \ell^\pm X, \ell^+\ell^- X, bX. \]

Many authors have studied and shown that we have good chances to detect anomalous effects from \( t\bar{t}\gamma/Z \) and/or \( tbW \) couplings unless the size of them is extremely small, and for those studies the use of polarized beams is quite effective.

b. \( \gamma\gamma \) collision

In this case, initial states can be \( CP \) odd, which means we can make \( CP \)-violating quantities without relying on the final top-quark (and their decay products) distributions. We could also study anomalous top-Higgs couplings. Related talks were given by Asakawa and Hioki in \( \gamma\gamma \) session [7, 8]. Although \( \sqrt{s_{\gamma\gamma}} \) is not a constant and consequently necessary calculations are more complicated, similar precision can be expected for some coupling determination by adjusting initial beam polarizations.

Those \( ee \) and \( \gamma\gamma \) colliders will work complementary to each other. Let me remind the readers of two useful tools for performing non-SM interaction analyses
through these processes. One is a decoupling theorem on the final-lepton angular distributions [9] and the other is the optimal-observable analysis [10]. The former decoupling theorem says that the lepton angular distribution is free from anomalous top-decay interactions whatever type of couplings we assume and it holds not only for the final lepton in $e\bar{e}$, $\gamma\gamma$ collisions but also for the one in single top-quark productions at hadron colliders. On the other hand, the latter procedure tells us how to determine several unknown parameters altogether with the least statistical uncertainty.

Finally let me ask all of us again “Is the top-quark a standard quark?” Many people will answer “Yes, I believe so”, I suppose, considering the great success of the EW precision analyses. However, “No” must be a much much more exciting answer (at least we could write many papers!). Anyway we hope LC will be able to give us a clear answer in the near future. Merci beaucoup!

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