SINGLE TOP QUARK
IN THE SM AND BEYOND

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ABSTRACT

The prospects of single top quark physics at colliders of the TeV energy scale are discussed. Single top quark study allows a direct measurement of the $Wtb$ vertex and a precise probing physics beyond the Standard Model in various scenarios.

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1 Introduction

Single top quark physics has been the subject of intensive studies for more than 10 years. After the discovery of the top-quark it is natural to study its properties. The cross section of the electroweak single top production (see references therein) is of the same order as that for the strong $t\bar{t}$ pair production. Therefore one will have quite enough statistics for a precise measurement of the electroweak properties of the top quark involving directly the $Wtb$ vertex.

The top quark is the only known fermion whose mass is close to the scale of the electroweak symmetry breaking (EWSB). Hence, the study of the electroweak properties of the top quark sector may shed light on the mechanism responsible for the EWSB. Moreover, deviations from the SM predictions might be expected in the large mass top sector. Thus, single top quark physics could probe various fields of physics beyond the Standard Model: anomalous gluon–top quark couplings (references [65-71] in references therein), anomalous $Wtb$ couplings (2 and references therein), new strong dynamics (3 and references therein), flavour changing neutral currents (FCNC) couplings (4 and references therein), R-parity violating SUSY effects (5 and references therein), CP-violation effects (6), effects of Kaluza–Klein excited $W$-boson (7).

2 Hadron colliders

The main processes of single top quark production at hadron colliders are:
1. $p\bar{p} \rightarrow tq b + X$, $p\bar{p} \rightarrow t q + X$, $W - gluon$ fusion process combined with the process involving $b$-quark in the initial state;
2. $p\bar{p} \rightarrow t b + X$, $s$-channel $W^*$ process involving an off-shell $W$-boson;
3. $p\bar{p} \rightarrow t W + X$, where $q$ is a light quark and $X$ represents the remnants of the proton. These processes are ordered according to their rates. However, it is worth noting that the relative contributions of $W^*$ and $tW$ processes change with the collider energy. For example, at the 2 TeV Tevatron collider $W^*$ process contributes around 30% to the single top production rate, while the contribution from the $tW$ process is only 7%. The situation at the 14 TeV LHC collider is just the opposite.

Next-to-leading order (NLO) production rates of the single top at the Tevatron and LHC are ($m_t = 175$ GeV, $Q^2 = m_{top}^2$):

$\sigma(t\bar{b}) = 0.88 \pm 0.05$ pb, $\sigma(tq\bar{b} + tq) = 2.44 \pm 0.4$ pb for the 2 TeV Tevatron and

$\sigma(t\bar{b}) = 10.2 \pm 0.6$ pb, $\sigma(tq\bar{b} + tq) = 245 \pm 9$ pb for the 14 TeV LHC collider.

In comparison with complete tree-level calculations, the NLO results are some 15% higher. The NLO cross section for the $tW$ process is not known yet. The tree-level cross section of $tW$ production at 2 TeV Tevatron is too
small (about 0.2 pb) to be seriously considered. However, at the LHC, the contribution from the $tW$ process to the total rate of single top quark production is significant: $\sigma(pp \rightarrow tW + \bar{t}W + X) = 63^{+16}_{-3.6}$ pb (CTEQ4L, $Q^2 = m_{t_{top}}^2$).

It should be stressed that the task of background reduction is a much more serious and important problem in the case of the single top production than for $t\bar{t}$-pair production. This is because the jet multiplicity of single top quark events is typically less than for $t\bar{t}$-pair production and so QCD $Wjj$ and multi-jet backgrounds are much higher. Therefore the problem of the single top signal extraction is more involved. The main backgrounds to the single top quark production are: $p\bar{p} \rightarrow W + 2(3)$ jets (gluonic, $\alpha_s$ order and electroweak $\alpha^2$ order), $p\bar{p} \rightarrow t\bar{t}$ pair top quark production and, the $j(j)bb$ QCD fake background where one jet imitates the electron. Initially, the total background is about of two orders of magnitude higher than the signal rate but it is possible to work out specific sets of kinematical cuts and finally get signal-to-background ratio of 0.4 and 1.0 at the Tevatron and LHC respectively. Expected statistics is about 150 signal events at the Tevatron (for 2 $fb^{-1}$ luminosity) and $5 \times 10^5$ signal events at the LHC (for 100 $fb^{-1}$ luminosity). With the given statistics one can measure the $Wtb$ vertex with the accuracy of $10\%$ Tevatron RUN2.

In the case of the LHC, the accuracy of the $Wtb$ vertex measurement is basically limited by the uncertainties of parton distributions, top quark mass and theoretical calculations and expected to be of the order of few per cent.

3 Lepton colliders

The cross section of the SM single top production in the $e^+e^- \rightarrow e^+\nu_e \bar{b}b$ reaction at LEP2 energies is of the order of $10^{-5} – 10^{-6}$ pb, which is too small to be observed. However, at TeV energies, for example in the $\gamma e \rightarrow \nu \bar{b}b$ reaction, single top quark production rates are 20–80 fb for 0.5–2.0 TeV collider energy.

The measurement of the single top production cross section at hadron and lepton colliders allows us to put bounds on the anomalous $Wtb$ couplings. The Lagrangian in unitary gauge, in terms of $F^L_2$ and $F^R_2$ magnetic type anomalous couplings, can be written as:

$$L = \frac{g}{\sqrt{2}} \left[ W^- \bar{b} \gamma^\mu P_- t - \frac{1}{2 M_W} W^- \bar{b} \sigma^{\mu\nu} (F^L_2 P_- + F^R_2 P_+) t \right] + h. c., \text{ with } W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu, \sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu], \text{ and } P_\pm = (1 \pm \gamma_5)/2. \text{ The } V + A \text{ coupling has been skipped since it is severely constrained by the CLEO } b \rightarrow s\gamma \text{ data.}$$

In Table 1 potentials of the Tevatron, LHC and $\gamma e$ colliders are compared. One can see that limits on the anomalous couplings that can be obtained at the LHC and 0.5 TeV $\gamma e$ colliders are comparable, while the limits for a 2.0
TeV γe collider are several times better than those for the LHC.

Table 1: Uncorrelated limits on anomalous couplings from measurements at the Tevatron, LHC and γe colliders

|                  | $F_L^T$ | $F_L^R$ | $F_R^T$ | $F_R^R$ |
|------------------|---------|---------|---------|---------|
| Tevatron (∆sys. ≈ 10%) | −0.18   | ...     | +0.55   | ...     |
| LHC (∆sys. ≈ 5%)     | −0.052  | ...     | +0.097  | ...     |
| γe (√s_{e+e−} = 0.5 TeV) | −0.1    | ...     | +0.1    | ...     |
| γe (√s_{e+e−} = 2.0 TeV) | −0.008  | ...     | +0.035  | ...     |

4 FCNC and single top quark production

Single top quark physics is also a very promising place to test the flavour changing neutral current (FCNC) effects for $tqV$ couplings, where $q = u$- or $c$-quark and $V = γ, Z, g$. Those couplings effectively appear in supersymmetry or in the scenario where new dynamics take place in the fermion mass generation. The effective Lagrangian involving such couplings of $(t, q)$ pair to massless bosons is the following:

$$\Delta L^{eff} = \frac{1}{4} [\kappa_γ e^i σ_{μν} q F^{μν} + \kappa_g g_μ g_ν \frac{λ^i}{2} G^{μν} + \text{h.c.}],$$

where $F^{μν}$ and $G^{μν}$ are the usual electromagnetic and gluon field tensors with respective FCNC $κ_γ$ and $κ_g$ couplings. It was found that the strength for the anomalous $tcg$ ($tuγ$) coupling may be probed to $κ_c/Λ = 0.092$ TeV$^{-1}$ ($κ_u/Λ = 0.026$ TeV$^{-1}$) at the Tevatron with 2 fb$^{-1}$ of data and $κ_c/Λ = 0.013$ TeV$^{-1}$ ($κ_u/Λ = 0.0061$ TeV$^{-1}$) at the LHC with 10 fb$^{-1}$ of data. Efficiencies from can be used to put the limits on $κ_{tcγ}, κ_{tuγ}$ couplings ($Λ = m_{top}, 95\%\text{CL}$) at the Tevatron RUN2: $κ_{tcγ} < 0.24, κ_{tuγ} < 0.074$. However, better limits (of the order of 0.044 for TeV2) on these couplings $κ_γ$ are expected to come from the study of decays $t \rightarrow qγ$ of pair-produced tops. This process already allows to derive an upper bound $κ_γ < 0.14$ from the CDF data taken at Tevatron RUN1, which is slightly better than the limit obtained by ALEPH by studying $ee \rightarrow tq$ in LEP2 data.

It is interesting to note that HERA should provide a very good sensitivity on FCNC $tuγ$ coupling via single top production. Even at the present ZEUS+H1 160 pb$^{-1}$ integrated luminosity, in the absence of a signal, the limit should be $κ_γ < 0.05$, which is significantly better than the current most stringent bound. Alternatively, the relatively large ($\sim 1$ pb) cross section still allowed by the current CDF limit on $κ_{γ,u}$ would lead to many single top events. It is interesting to note that H1 observed some events with a high-$P_T$ isolated lepton ($e$ or $μ$), together with missing energy and a large $p_T$ hadronic final
state. Such a final state would be expected from single top events, where the W coming from the top undergoes a semileptonic decay.

5 Conclusions

Single top quark physics is an exciting new window on possible high mass scale new physics. Single top quark study provides a direct measurement of the $Wtb$ vertex with 10% accuracy at the Tevatron RUN2 and a few per cent accuracy at the LHC and linear colliders.

In spite of the fact that the present experimental results on the single top search are consistent with the SM prediction, upcoming experiments are very encouraging. With the new data we can test possible deviations from the Standard model such as anomalous $Wtb$ and FCNC couplings and probably look into the window beyond the SM.

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