Scalar Top Quark Production at $\mu^+\mu^-$ Colliders

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Abstract

We discuss the production of stops at a $\mu^+\mu^-$ collider. We present numerical predictions for the cross sections within the Minimal Supersymmetric Standard Model. In particular we consider stop production near $\sqrt{s} = m_{H^0}$ and $\sqrt{s} = m_{A^0}$.

Introduction

The search for supersymmetric particles plays an important rôle at LEP2 and TEVATRON. It will play an even more important rôle at the future colliders LHC, an $e^+e^-$ linear collider with an energy range up to 2 TeV, and a $\mu^+\mu^-$ collider with an energy range up to 4 TeV. We assume that at the time when a $\mu^+\mu^-$ collider starts operation, supersymmetry will have been discovered at TEVATRON or LHC. While proton colliders are good discovery machines [1, 2, 3], one can do precision measurements at $\mu^+\mu^-$ colliders [4]. Another exciting feature of a $\mu^+\mu^-$ collider is the possibility of producing Higgs bosons in the s–channel [4, 5]. This allows one to measure various Higgs couplings at the Higgs resonances.

In the following our framework is the Minimal Supersymmetric Standard Model (MSSM) [6]. The MSSM implies the existence of five physical Higgs bosons: two scalars $h^0, H^0$, one pseudoscalar $A^0$, and two charged ones $H^\pm$ [7]. The top quark has two supersymmetric partners, the lighter stop $\tilde{t}_1$ and the heavier stop $\tilde{t}_2$. The top quark and the stops give important contributions to Higgs masses due to radiative corrections (see e.g. [8]). Moreover, their contributions to the renormalization group equations can lead to electroweak symmetry breaking when the Higgs parameters evolve from the GUT scale to the electroweak scale [9]. Therefore, the couplings of

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the stops to the neutral Higgs bosons are of special interest. In this contribution we study stop production in $\mu^+\mu^-$ collisions paying particular attention to the energy range near the Higgs resonances.

**Production of Stops**

The mass terms of the stops is given by a $2 \times 2$ mass matrix. The diagonal elements are $M_{\tilde{t}_L}^2 = M_Q^2 + m_2^2 \cos 2\beta (\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W) + m_t^2$ and $M_{\tilde{t}_R}^2 = M_U^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2 \theta_W + m_t^2$, and the off–diagonal element is given by $m_t (A_t - \mu \cot \beta)$.

The physical states are characterized by their mass eigenvalues $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and the mixing angle $\cos \theta_{\tilde{t}}$.

Figure 1 shows the Feynman–graphs for the processes $\mu^+\mu^- \rightarrow \tilde{t}_i \tilde{t}_j$ ($i, j = 1, 2$). The differential cross section reads

$$\frac{d\sigma}{d \cos \vartheta} = C_{ij} \left( \frac{\kappa_{ij}^2}{s} T_{VV} \sin^2 \vartheta + \frac{\kappa_{ij}}{s} T_{VH} \cos \vartheta + \frac{m_i^2 - m_j^2}{s} T_{HH} \right)$$

(1)

with $s$ the center–of–mass energy squared, $\kappa_{ij}^2 = (s - m_i^2 - m_j^2)^2 - 4m_i^2 m_j^2$, and $\vartheta$ the angle between $\mu^-$ and $\tilde{t}_i$. $T_{VV}$ denotes the contribution from $\gamma$ and $Z^0$ exchange, $T_{VH}^{a,b}$ the interference terms between gauge and Higgs bosons, and $T_{HH}$ the contribution stemming from the exchange of Higgs bosons. The pure gauge boson contribution, the first part of Equation 1, is the same as for $e^+e^- \rightarrow \tilde{t}_i \tilde{t}_j$ and given in [10]. The explicit form of $T_{VH}^{a,b}$ and $T_{HH}$ will be given in a forthcoming paper [11]. Notice
that the gauge boson term has a $\sin^2 \vartheta$ dependence whereas $T_{HH}$ and $T_{VH}$ are independent of $\vartheta$. The $T_{VH}$ term is proportional to $\cos \vartheta$ giving rise to a forward backward asymmetry. However, this asymmetry is proportional to $m_t$ and of the order $\lesssim 10^{-4}$ [1]. The following parameters enter the couplings of the stops to the Higgs bosons: $A_t$, $\mu$, $\cos \theta_t$, $\cos \alpha$, and $\tan \beta$.

In Figure 2 we show the total cross section as a function of $\sqrt{s}$ for $M_{\tilde{Q}} = 160$ GeV, $M_{\tilde{b}} = 145$ GeV, $M_D = 175$ GeV, $A_t = A_b = 350$ GeV, $\mu = 300$ GeV, $M = 140$ GeV, $\tan \beta = 2$, and $m_{A^0} = 480$ GeV. The full lines show the total cross sections and the dotted lines show the gauge boson contributions. The latter ones are identical with the cross sections of $e^+e^- \rightarrow \tilde{t}_i \tilde{\mu}$ for $\tilde{t}_i \tilde{t}_j$ production the peak results from the $H^0$ exchange leading to an enhancement of $\sim 20$ fb compared to the gauge boson contribution. For $\tilde{t}_i \tilde{t}_2$ production the peak is an overlap of the $H^0$ and $A^0$ resonances because $m_{A^0} \simeq m_{H^0}$ and the widths of $A^0$ and $H^0$ are of the order of several GeV (see e.g. [2, 3, 4, 5]).

In Figure 3 we show the total cross section near the Higgs resonances for various values of $A_t$ and the other parameters as above. For $A_t = -50 (350)$ GeV one has $m_{\tilde{t}_1} = 133$ GeV, $m_{\tilde{t}_2} = 296$ GeV, and $\cos \theta_{\tilde{t}} = 0.69 (-0.69)$. $A_t = 50 (250)$ GeV gives $m_{\tilde{t}_1} = 187$ GeV, $m_{\tilde{t}_2} = 265$ GeV, and $\cos \theta_{\tilde{t}} = 0.67 (-0.67)$. For $A_t = 150$ GeV one gets $m_{\tilde{t}_1} = 226$ GeV, $m_{\tilde{t}_2} = 233$ GeV, and $\cos \theta_{\tilde{t}} = 0$. The shifts of the peaks are due to radiative corrections to $m_{H^0}$. One can clearly see that the widths of the peaks depend on $A_t$ and therefore also on the sign of $\cos \theta_{\tilde{t}}$. Note that for $\cos \theta_{\tilde{t}} = 0$ the $H^0 \tilde{t}_1 \tilde{t}_1$ coupling is rather small and, therefore, the peak nearly vanishes. However, at the same time the $A^0 \tilde{t}_1 \tilde{t}_2$ coupling is large leading to the enhancement and to the shift of the corresponding peak compared to the other $A_t$ values. Note that the decay widths of $A^0$ and $H^0$ into stops are an essential part of the total widths. Therefore, when the peaks are narrower for $\tilde{t}_1 \tilde{t}_1$ production then they are broader for $\tilde{t}_1 \tilde{t}_2$ production and vice versa.
Figure 3: Production cross section (in fb) for a) $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_1$ and b) $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_2 + \tilde{t}_1\tilde{t}_2$ as a function of $\sqrt{s}$. The parameters are: $M_{\tilde{Q}} = 160$ GeV, $M_{\tilde{U}} = 145$ GeV, $M_{\tilde{D}} = 175$ GeV, $\mu = 300$ GeV, $M = 140$ GeV, $\tan\beta = 2$ and $m_{A^0} = 480$ GeV. The graphs correspond to ($A_t = A_b$): $A_t = -50$ GeV (dash–dotted line), $A_t = 50$ GeV (full line), $A_t = 150$ GeV (dotted line), $A_t = 250$ GeV (dashed line) and $A_t = 350$ GeV (dash–dot–dotted line).

Figure 4: Production cross section (in fb) for $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_2 + \tilde{t}_1\tilde{t}_2$ as a function of $A_t$. The parameters are: $M_{\tilde{Q}} = 160$ GeV, $M_{\tilde{U}} = 145$ GeV, $M_{\tilde{D}} = 175$ GeV, $A_b = A_t$, $\mu = 300$ GeV, $M = 140$ GeV, $\tan\beta = 2$ and $\sqrt{s} = m_{A^0} = 480$ GeV. The graphs correspond to: total cross section $\sigma_{tot}$ (full line), Higgs boson contribution $\sigma_H$ (dash–dotted line), and gauge boson contribution $\sigma_V$ (dashed line).

Figure 4 shows the $A_t$ dependence of the cross section $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_2 + \tilde{t}_1\tilde{t}_2$ for $\sqrt{s} = m_{A^0} = 480$ GeV and the other parameters as above. The Higgs exchange contributes to the total cross section at least 30%. For $\cos \theta_{\tilde{t}} = 0$ ($A_t = 150$ GeV) this contribution reaches 100%. The smaller peak near $A_t = 200$ GeV is due to the
$H^0$ resonance.

![Figure 5](image)

**Figure 5:** Production cross section for the process $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_1$ (in fb) as a function of $\cos \theta_{\tilde{t}}$ for a) $\sqrt{s} = 475$ GeV and b) $\sqrt{s} = 485$ GeV. The parameters are: $m_{\tilde{t}_1} = 180$ GeV, $M_{\tilde{Q}} = 160$ GeV, $M_{\tilde{D}} = 175$ GeV, $\mu = 300$ GeV, $M = 140$ GeV, $\tan \beta = 2$ and $m_{A^0} = 480$ GeV. The graphs correspond to: total cross section $\sigma_{\text{tot}}$ (full line), gauge boson contribution $\sigma_{\mathcal{V}}$ (dashed line), and Higgs boson contribution (dash–dot–dotted line).

Figure 5 shows the $\cos \theta_{\tilde{t}}$ dependence of the $\mu^+\mu^- \rightarrow \tilde{t}_1\tilde{t}_1$ cross section in the energy range close to the $H^0$ resonance. The parameters are $m_{\tilde{t}_1} = 180$ GeV, $M_{\tilde{Q}} = 160$ GeV, $M_{\tilde{D}} = 175$ GeV, $\mu = 300$ GeV, $M = 140$ GeV, $\tan \beta = 2$, and $m_{A^0} = 480$ GeV. Notice that the Higgs contribution depends on the sign of $\cos \theta_{\tilde{t}}$.

**Conclusions**

We have studied the production of $\tilde{t}_1\tilde{t}_1$ and $\tilde{t}_1\tilde{t}_2$ in $\mu^+\mu^-$ annihilation focusing on the impact of the Higgs resonances in these processes. In particular we have found that one gets important information on the $H^0\tilde{t}_1\tilde{t}_1$, $H^0\tilde{t}_1\tilde{t}_2$ and $A^0\tilde{t}_1\tilde{t}_2$ couplings.

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