Top quark spin and QCD corrections in event generation
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Citation for published version (APA):
Chapter 4

Top Polarization in Stop Production

In the previous chapter we have explored the robustness of top quark polarization under the influence of NLO corrections. These corrections were studied for the production of a top quark with associated charged Higgs boson for a 2HDM. The influence of polarization measured in the angular distributions of the top quark decay product was compared to the mass of the Higgs boson and found to be an interesting probe. In this chapter we will explore a more stringent model that naturally requires the existence of such an additional Higgs doublet. We will investigate a significant top quark production mode, and examine whether polarization can be used as a probe for such a model’s parameters.

4.1 Supersymmetry

As explained in the introduction, the SM leaves a few questions unanswered, for instance it failed to include gravity. At LHC energies one is still able to ignore this fundamental force but gravity inevitably becomes more important as we approach the Planck scale. Other weaknesses of the SM include its inadequacy to provide a dark matter candidate. These shortcomings create space for new models, based on somewhat more exotic assumptions, to provide a more accurate description. One of these is supersymmetry.

The mass of the Higgs boson in the SM is extraordinarily sensitive to loop corrections of the fermions as it is not protected by any symmetry in the way chiral symmetry protects fermion masses. If the SM is regarded as an effective theory, the corrections to the Higgs mass depend quadratically on the energy scale \( \Lambda \), where new physics sets in. Therefore a large amount of fine-tuning is required between the bare mass and the loop corrections to remain with a Higgs mass of 125 GeV as \( \Lambda \) will be at least a few orders higher. This artifact of the SM is commonly referred to as the Hierarchy Problem, as it is related to the hierarchy of energy scales. Supersymmetry (SUSY) postulates the existence of a symmetry between fermions and bosons that allows for a natural cancellation of these
quadratic divergences, leaving more benign logarithmic divergences. It also implies the existence of supersymmetric partners to all known SM particles, with the same mass and electric charge, but differing by spin-$\frac{1}{2}$. Regarding nomenclature, fermionic partners receive $+$(calar) in front of their name while the names of the supersymmetric partners of the bosons are appended with $+$(ino) in the rear. For a detailed review of supersymmetry we refer the reader to [16, 69].

Searches for light-flavoured squarks and gluinos at the Large Hadron Collider (LHC) have so far come up empty [70–73]. Theoretical pointers for the expected mass scales for SUSY breaking, accounting for SUSY particles to be massive, come from naturalness arguments [74–76]. In SUSY, the low mass of the observed Higgs boson, is naturally stable under large radiative corrections, provided the supersymmetry breaking scale is not too large. In particular, the gluinos and most squarks can be quite heavy, as long as the top squark, or stop, is relatively light so that SUSY has a solution to offer to the hierarchy problem as suggested originally [77, 78]. The upper limit on the allowed stop masses for a given Higgs mass depends on the amount of fine tuning that is tolerated [79–81].

The recent Higgs results [82, 83] suggest, in the context of SUSY, a Higgs boson mass quite close to the upper bound on the mass of the lightest Higgs state. This points towards at least one relatively heavy stop [84, 85], which naturally leads us to consider models with one light stop and at least one light neutralino. The lightest neutralino is a mixed state of the superpartner of the $U(1)$ hypercharge, the superpartner of the $W$ boson and the neutral higgsinos. This is the minimal ‘light’ SUSY particle content that one needs in order to account for the observational hints of BSM physics such as Dark Matter (DM) and Baryon Asymmetry in the Universe (BAU). It is therefore interesting to investigate possibilities of such a light stop search at the LHC. Current constraints on the gluino mass increase the interest for a direct stop pair search, even though the cross section is much smaller than the total squark-gluino cross-section. For example at $\sqrt{s} = 8$ TeV the direct stop cross section at NLL level is $\sim 85$ fb for $m_{\tilde{t}} = 500$ GeV, [86–89] a value for the stop mass that is currently allowed by the data. Results on stop searches in direct stop pair production have been presented both by the ATLAS [90–93], and the CMS [94–97] collaborations. However, the interpretation of these searches has some model-dependence and usually limits are quoted in simplified models. In any case, present data allows for top squarks well below the TeV scale.

One new aspect of the stop search phenomenology is the possible presence of a top quark, a stop decay product, with possibly non-zero polarization. Since the top quark decays before it hadronizes, the polarization can have implications for the kinematic distributions of the decay products of the stop and hence on the search strategies. If a stop is discovered, the top polarization can play a role in determining the properties of the stop and light neutralino.

### 4.2 Top Polarization from Stop Decay

In [98] it was shown that for a top quark originating from stop $\tilde{t}$ decay
where \( \tilde{t}_i \rightarrow t \tilde{\chi}_i^0 \), (4.1)

where \( \tilde{\chi}_i^0, i = 1, 4 \) accounts for the four neutralinos, the following expression for the polarization holds

\[
P_t(\tilde{t}_1 \rightarrow t \tilde{\chi}_i^0) = \frac{((G^R_i)^2 - (G^L_i)^2)f_1}{(G^R_i)^2 + (G^L_i)^2 - 2G^R_iG^L_i f_2},
\]

where \( f_1 \) and \( f_2 \) are kinematical factors which in the stop rest frame reduce to

\[
f_1 = \frac{\lambda(z(m^2_t, m^2_t, m^2_{\tilde{\chi}}))}{m^2_t - m^2_t - m^2_{\tilde{\chi}}}, \quad f_2 = \frac{2m_t m_{\tilde{\chi}}}{m^2_t - m^2_t - m^2_{\tilde{\chi}}},
\]

with \( \lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz \) the Källén function. The quantities \( G^L_i \) and \( G^R_i \) are the stop couplings to the neutralino \( \tilde{\chi}_i^0 \) and a left- or right-handed top respectively. If we ignore mixing in the flavour sector and choose the mixing matrices to be real, they are given by [99]

\[
G^L_i = -\sqrt{2}g_2 \left( \frac{1}{2}Z_{i2} + \frac{1}{6} \tan \theta_W Z_{i1} \right) \cos \theta_{\tilde{t}} - \frac{g_2 m_t}{\sqrt{2}M_W \sin \beta} Z_{i4} \sin \theta_{\tilde{t}},
\]

\[
G^R_i = \frac{2\sqrt{2}}{3} g_2 \tan \theta_W Z_{i1} \sin \theta_{\tilde{t}} - \frac{g_2 m_t}{\sqrt{2}M_W \sin \beta} Z_{i4} \cos \theta_{\tilde{t}},
\]

where \( g_2 \) is defined in section. [2.4] \( \theta_W \) is the weak mixing angle and \( M_W \) is the W mass. The polarization then depends on the SUSY parameters through the neutralino mixing matrix \( Z \), the stop mixing angle \( \theta_{\tilde{t}} \) and the ratio of the two Higgs vacuum expectation values, \( \tan \beta \). Moreover it is clear from eq. (4.2) that the top polarization is affected by the masses involved and, perhaps less obviously, by the stop boost. Let us now discuss these effects in turn.

### 4.2.1 Stop and Neutralino Mixing

The top polarization eq. (2.5) depends on the couplings \( G^L,R_i \), eq. (4.4), which contain the stop mixing \( \theta_{\tilde{t}} \) and neutralino mixing. The neutralino mixing matrix is constructed from the neutral section of the SUSY Lagrangian [100],

\[
\mathcal{L}^n = -\frac{g_2}{2} \lambda_3 (v_1 \tilde{h}_0^1 - v_2 \tilde{h}_0^2) + \frac{g_Y}{2} \lambda_0 (v_1 \tilde{h}_1^0 - v_2 \tilde{h}_2^0) + \mu \tilde{h}_1^0 \tilde{h}_2^0
\]

\[
- \frac{1}{2} M_2 \lambda_3 \lambda_3 - \frac{1}{2} M_1 \lambda_0 \lambda_0 + h.c.
\]

The first and second term arise from mixing terms of the electroweak sector, the third term comes from the Higgs superfield in the superpotential and the last two terms are soft
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breaking gaugino mass terms contracting using the fully antisymmetric tensor. The Higgs scalars have taken their vacuum expectation values $v_1$ and $v_2$, $\lambda_0$, $\lambda_3$ denote two gaugino fields and $\tilde{h}_1^0, \tilde{h}_2^0$ two higgsino field components, $g_1$ is the $U(1)_Y$ hyper charge coupling and $g_2$ as defined in the previous section. Eq. (4.5) can be rewritten as

$$\mathcal{L}^n = -\frac{1}{2} (\psi^0)^T M_n \psi^0 + h.c. \quad (4.6)$$

with $(\psi^0)^T = (\lambda_0, \lambda_3, \tilde{h}_1^0, \tilde{h}_2^0)$. The neutralino mixing matrix, $Z$ is determined by the diagonalization of the neutralino mass matrix $M_n$

$$M_n = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \quad (4.7)$$

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = Z \begin{pmatrix} \lambda_0 = \tilde{B}^0 \\ \lambda_3 = \tilde{W}^0 \\ \tilde{h}_1^0 \\ \tilde{h}_2^0 \end{pmatrix}, \quad (4.8)$$

with $M_1$ and $M_2$ the bino and Wino gaugino masses and $M_Z$ the $Z^0$ mass, $s_W = \sin \theta_W$, $c_W = \cos \theta_W$, $s_\beta = \sin \beta$ and $c_\beta = \cos \beta$.

The stop mixing angle $\theta_i$ is derived in a similar way by diagonalization of the stop mass matrix in the $L - R$ basis, leading to the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{t}_L} + \Delta_L + m^2_{\tilde{t}} & -m_t (A_t + \mu \cot \beta) \\ -m_t (A_t + \mu \cot \beta) & m^2_{\tilde{t}_R} + \Delta_R + m^2_{\tilde{t}} \end{pmatrix}, \quad (4.9)$$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (4.10)$$

with $m_{\tilde{t}}$ the soft masses of the left- and right-handed stop, $A_t$ the top trilinear coupling, $\mu$ the Higgs mass parameter, and $\Delta_L = (1 - \frac{2}{3} \sin \theta_W^2) M_Z^2 \cos 2\beta$, $\Delta_R = (\frac{2}{3} \sin \theta_W^2) M_Z^2 \cos 2\beta$.

Our subsequent investigations of the top polarization will be guided by a few salient aspects in this mixing, which we now discuss.

Firstly, one notes that the strength of the bino ($\tilde{B}$) coupling to stop-top is proportional to the top hypercharge. As a result, a bino-like neutralino couples more strongly to the right-handed (RH) components than to the left-handed (LH) ones, yielding a more positive top polarization than one might naively expect from a given stop mixing.

Secondly, recall that the Wino $\tilde{W}$ only couples to the left-handed stop components, producing left-handed top quarks only. According to eq. (4.2), a pure Wino thus always leads to $P_t = -f_1$ in the stop rest frame. As a result, polarization cannot be used to distinguish between different stop mixing for Wino-type neutralinos. In the rest of the paper we will thus limit ourselves to neutralinos with a small Wino component.
Thirdly, for the intermediate to large values of $\tan \beta$ that are allowed for the Higgs mass constraint, $\sin \beta \approx 1$, therefore the couplings in eq. (4.4) and hence the top polarization only mildly depend on $\tan \beta$.

Finally, the stop-top-neutralino coupling does not involve the first higgsino component $\tilde{h}^0_1$. Ignoring the Wino component, the key variables in the neutralino mixing matrix are thus the bino component $Z_i^1$ and the second higgsino component $Z_i^4$. The relative sign between the bino and the higgsino components can impact the polarization because of the term proportional to $G_i^R G_i^L$ in eq. (4.2). This can be seen in fig. 4.1 where the top polarization in the stop rest frame is plotted as a function of the bino content for both left- and right-handed stops. The righthand pane in fig. 4.1 zooms into the region with high bino-content. The results are shown for both relative signs of $Z_i^1$ and $Z_i^4$ and also for stops that are not entirely left- or right-handed.

The figure shows that in general the polarization behavior is as expected: dominantly right-handed stops produce a negative top polarization when they decay to a higgsino, and a positive polarization when they decay to a bino. Left-handed stops have the opposite behaviour. Notice that in correspondence to the first aspect mentioned above, for right-handed stops in particular, even a slight change in the stop mixing angle has a large effect on the polarization. We observe that the polarization for left-handed stops is not very sensitive to the exact neutralino content when it is higgsino-like and that the polarization varies very rapidly from 1 to -1 for an almost pure bino. Moreover, the maximum polarization $P_t = \pm 1$ cannot occur for a decay into a pure bino or higgsino due to the mass effects in eq. (4.2). This effect becomes more pronounced for smaller stop-neutralino mass differences.

For a complementary perspective we show in fig. 4.2 the dependence of the top polarization on the stop mixing for a top quark that originates from a stop that is at rest. For both the pure bino state and the dominantly higgsino state, the polarization indeed behaves as one would expect from eq. (4.2). As in fig. 4.1 we see that the polarization...
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![Graph showing dependence of top polarization on stop mixing in the stop rest frame.](image)

Figure 4.2: Dependence of the top polarization on the stop mixing in the stop rest frame. The red thin lines correspond to higgsino-like neutralinos, while the black thick lines correspond to bino-like neutralinos. Results are shown for pure as well as slightly mixed neutralinos, and for different signs of $\mu$. We fix the parameters as in fig. 4.1

is very sensitive to small fluctuations in the bino component for $Z_{i1} \approx 1$. In this case, both terms in the $G^R_i$ coupling in eq. (4.4) become relevant, the first is suppressed by the stop mixing and the second by the higgsino mixing, hence the large fluctuation in the polarization for small values of $\sin \theta_{\tilde{t}}$.

4.2.2 Masses

We have already seen that the stop and neutralino masses influence the polarization. This effect is shown in fig. 4.3

![Graph showing dependence of top polarization on stop-neutralino mass difference for a neutralino that is purely bino and different stop mixing.](image)

Figure 4.3: Dependence of the top polarization in the stop rest frame on the stop-neutralino mass difference for a neutralino that is purely bino and different stop mixing. We have taken $m_t = 173.1$ GeV, $m_{\tilde{\chi}} = 100$ GeV and $\tan \beta = 10$.

We see that a small mass difference between the stop and the neutralino leads to a smaller polarization due to the $f_1$ and $f_2$ functions in eq. (4.3). For mass differences of 200-300 GeV, this dependence is negligible as the polarization tends to $\pm 1$ as is seen in the figure. Note that the top originating from a completely mixed stop resembles a right-handed stop because of the effect of the hypercharge mentioned in the previous section.
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We have seen in figs. 4.1 and 4.2 that masses can have more intricate effects for mixed states due to the contribution of the \( f_2 \) function.

### 4.2.3 Stop Boost

So far we have studied the top polarization in the stop rest frame. However, as we can see from eq. (2.4), the polarization vector \( S^3 \) is not a Lorentz vector. Thus the polarization is frame-dependent. We can quantify this effect using the stop boost parameter

\[
B_{\tilde{t}} = \frac{|\vec{p}_{\tilde{t}}|}{E_{\tilde{t}}}. \tag{4.11}
\]

The dependence of the polarization is plotted in fig. 4.4, showing that the polarization is reduced with increasing stop boost.

![Figure 4.4: The dependence of the top polarization on the stop boost for a neutralino that is purely bino \((Z_{11} = 1)\) and different stop mixing is shown. We have taken \(m_t = 173.1\) GeV, \(m_{\tilde{t}} = 500\) GeV, \(m_{\tilde{\chi}} = 100\) GeV and \(\tan \beta = 10\).](image)

![Figure 4.5: The distribution of the stop boost at the LHC with an 8 TeV CM energy for different stop masses is shown on the left-hand side and 14 TeV CM energy on the right-hand side. Both distributions have been generated with Madgraph [13, 14].](image)

Note that the polarization is obtained after integration over the top direction, and hence depends only on the boost. The precise magnitude of the effect depends on the masses.
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involved, since the boost-dependence of the result originates from the large mass of the
top quark, more precisely from the fact that the produced top quark is non-relativistic.
For relevant stop and neutralino masses, the boost that the top obtains from the stop decay
has the same order of magnitude as the stop boost. Although this sounds like a serious
complication for studying the polarization at the LHC, the situation is in fact not that
bad. The plots of fig. 4.5 show the distribution of the stop boost at the LHC with a CM
energy of 8 and 14 TeV. We see that within the relevant range of stop masses, the boost
distribution is fairly constant. Thus, the effect of the boost will reduce the polarization for
all stop masses, but the explicit mass dependence due to the boost is small.

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The top polarization in the stop rest frame is thus mostly sensitive to the stop and neu-
tralino masses and mixing. In the previous section, we have varied one of the relevant
parameters at a time. In this section, we examine the dependence of the polarization on
the MSSM parameters. We choose parameters such that the value of the light stop mass
is around 500 GeV. This mass leads to a large production cross section and has sufficient
phase space for the stop to decay in a top and a neutralino for a wide range of values for
the neutralino mass. Furthermore, this mass satisfies the limits from direct stop produc-
tion at the 7 TeV LHC. The ATLAS Collaboration has excluded a stop up to nearly 500
GeV when the neutralino is massless, but they provide no limit if the LSP is heavier than
150 GeV [91].

First we choose fixed values for the soft parameters in the stop sector, and then vary
$M_1$ and $\mu$, given in eq. (4.5), which show the dependence on the neutralino composition.
The four sets of soft parameters are given in tab. 4.1. We set $M_2 = 4M_1$ to decouple
the wino-state by making the wino mass inaccessible and we fix $M_3 = 1.5$ TeV, $M_A =
1$ TeV. For the soft parameters in the sfermion sector, we choose a common mass for all
sleptons, $M_{\tilde{l}} = 800$ GeV, and for the first and second generation of squarks, $M_{\tilde{q}_i} = 2$ TeV.
All trilinear couplings except $A_t$ are set to zero. The supersymmetric spectrum and the
Higgs masses are computed with the program SuSPect [101], which includes radiative
corrections to the masses.

We do not impose any constraints on the model at this point. However, the parameters
of the stop sector are chosen such that the Higgs mass is within the measured range
($m_H = 125.7 \pm 0.4$ GeV, the average of CMS and ATLAS results [82, 83]) for a large
fraction of the explored parameter space while allowing for an additional 2-3 GeV theo-
retical uncertainty. Expectations for different observables from the flavour or dark matter
sector are not taken into account at this point. They will be briefly discussed at the end of
this section.

The dependence of the top polarization and stop branching ratio $BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$ on the
Higgs mass parameter $\mu$ and gaugino mass $M_1$ is displayed in fig. 4.6 - 4.9 for the four
different choices of stop parameters presented in tab. 4.1. We only consider the region
where the decay $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ is kinematically accessible. Note that the maximal variation
of the Higgs mass in the $|\mu| < 1$ TeV, $M_1 < 750$ GeV plane is about 3 GeV, within the
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<table>
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<th>$M_{Q_3}$ (TeV)</th>
<th>$M_{A_3}$ (TeV)</th>
<th>$A_t$ (TeV)</th>
<th>$\tan \beta$</th>
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<td>3.00</td>
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<td>2.40</td>
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<table>
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<th>$\cos \theta_{\tilde{t}}$</th>
<th>$M_h$(GeV)</th>
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<tr>
<td>XLH</td>
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<tr>
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<tr>
<td>RH</td>
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<td>0.996</td>
<td>-0.095</td>
</tr>
</tbody>
</table>

Table 4.1: Choices of parameters in the stop sector for two mostly LH and two mostly RH stops. In each case we also consider a partly mixed light stop (XLH and XRH). The bottom rows specify the light stop mass, the stop mixing and the Higgs mass for $|\mu| = 300$ GeV, $M_1 = 250$ GeV.

Theorem uncertainties, while corrections to $m_{\tilde{t}_1}$ of the order of 30 GeV can be found for large values of $M_2$ due to the quark/gaugino loop correction.

The dominantly left-handed stop

As we have discussed in the previous section, the case of a left-handed stop implies $P_t \approx -1$ when the LSP is bino-like ($|\mu| \gg M_1$) and $P_t \approx 1$ when the LSP is higgsino-like ($|\mu| \ll M_1$). This behavior is illustrated on the left-hand side of fig. 4.6 for $\mu < 0$. Note the rapid transition between $P_t = 1 \rightarrow -1$ in the region where one goes from a bino to a higgsino LSP ($M_1 \approx \mu$). When the LSP almost becomes pure bino, the top polarization starts to deviate from $-1$. For instance at the point $M_1 = 100$ GeV, $\mu = -600$ GeV the top polarization is only $P_t \approx -0.73$. This is caused by the stop becoming mixed instead of purely LH, with $\sin \theta_{\tilde{t}} = -0.127$. Finally, the kinematic effects which induce $P_t \rightarrow 0$ arise at the boundary of the white region.

In order to exploit the top polarization as an observable, the branching ratio for $\tilde{t}_1 \rightarrow t \chi_1^0$ must be large enough. The contours of the stop to LSP branching ratio are displayed in the right panel of fig. 4.6. Large branching ratios are found over most of the parameter space, with two exceptions. The first occurs near the kinematic limit where the three-body decay $\tilde{t}_1 \rightarrow bW \chi_1^0$ dominates and the second occurs for low values of $M_1$. The latter behaviour is a peculiarity due to the fact that we have set $M_2 = 4M_1$. Thus for low values of $M_1$ and of $M_2$ the lightest chargino, which is dominantly wino, drops below the mass of the stop and the decay $\tilde{t}_1 \rightarrow b \chi_1^+$ becomes dominant. If in addition $\mu$ is small, the decay into the second chargino becomes possible as well.

In the region where the LSP is mostly higgsino $|\mu| < M_1$, the mass of the two lightest neutralinos and of the lightest chargino are of the same order. Thus the stop can decay into $t \chi_1^0, t \chi_2^0$ as well as into $b \chi_1^+$. The chargino channel is only at the few percent level while the decay into the LSP increases with the higgsino component, reaching a maximum of 70%. An important fact to keep in mind is that the two lightest neutralinos will have

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higgsino-components of similar magnitude. Thus the polarization of the top in the two processes $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1,2$ is similar for the higgsino LSP. Therefore both decay modes can be exploited to measure the top polarization, as will be demonstrated below. In the region where the LSP is a bino, $M_1 < |\mu|$, the branching ratio into the LSP is nearly 100%, except for low values of $\mu$, where the channels $b\tilde{\chi}_1^+$ (for $|\mu| < 500$ GeV) and $t\tilde{\chi}_2^0$ (for $|\mu| < 380$ GeV) also become accessible.

![Figure 4.6: Contours of the top polarization in the top rest frame for $\mu < 0$ and a dominantly LH stop (left panel) with the LH parameters in tab. 4.1. Branching ratios for $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$ (right panel). In the bottom right corner, the decay is not kinematically accessible.](image1)

For $\mu > 0$, the polarization and the branching ratio contours have roughly the same behaviour, so we do not illustrate this case. Rather, we consider a case where the light stop is still dominantly left-handed but where the mixing angle is larger, $\sin \theta_{\tilde{t}} = -0.223$, see the XLH parameters in tab. 4.1. Fig. 4.7 shows that for the mixed case the polarization and branching ratio contours are rather similar to the previously discussed LH case. The main difference lies in the bino region at large $\mu$ and small $M_1$, where the polarization is generally not maximal. As we have explained above, the mixing implies that the main contribution to the $G_l^R$ coupling comes from the first term in eq. (4.4), causing $|P_t| < 1$.  

![Figure 4.7: Same as fig. 4.6 for $\mu > 0$ and a mixed but dominantly LH stop corresponding to the XLH parameters in tab. 4.1. In the upper right corner the decay is not kinematically accessible.](image2)
We therefore conclude that in the bino case, the top polarization is quite sensitive to the mixing in the stop sector.

The dominantly right-handed stop

Next we consider the case of a dominantly right-handed stop. The polarization contours for $\mu < 0$ are shown in fig. 4.8 for a mixed RH stop and fig. 4.9 for a pure RH stop. We notice the expected behaviour of $P_t \approx 1$ when the LSP is bino-like ($|\mu| \gg M_1$) and $P_t \approx -1$ when the LSP is higgsino-like ($|\mu| \ll M_1$). As before, the kinematic effects (at the boundary of the white region) bring $P_t \to 0$. Note the rapid sign flip in the polarization as one goes from the bino/higgsino region. The only impact of larger stop mixing, as illustrated in fig. 4.8, lies in the higgsino region ($\mu < M_1$): when the mixing in the stop sector is larger, the top polarization is not maximal. This is due to the second term in eq. (4.4) dominating the $G_i^{R}$ coupling, thus leading to a larger value for $G_i^{R}$ and $|P_t| < 1$.

In both the pure and mixed RH stop cases, the behaviour of the branching ratio contours are rather similar. The branching ratio $\tilde{t}_1 \to t \tilde{\chi}_i^0$ is above 90% in the bino region, except near the kinematic limit where the stop decays only into 3-body, and at low values of $M_1$ for the mixed RH stop. As mentioned above, this is caused by the channel $\tilde{t}_1 \to b \tilde{\chi}_i^+$ becoming kinematically accessible, which is only possible through the LH component of the light stop. In the higgsino LSP region, the BR never becomes very large (up to roughly 25% for $t\tilde{\chi}_1$ and to 20% for $\tilde{\chi}_2, \tilde{\chi}_3$). Here the main decay channel is into $b \tilde{\chi}_1^+$ which has a partial width that is proportional to the top Yukawa coupling for a RH stop and is therefore much larger than in the case of a LH stop where the width is determined by the bottom Yukawa coupling. Thus for a RH stop and a higgsino LSP, it will be more difficult to measure the top polarization due to the suppressed rate.

Decays into heavier neutralinos

For a higgsino LSP, the branching ratio of the stop into the lightest neutralino can be rather small. However, in this case the top polarization is almost the same when one considers the decay $\tilde{t}_1 \to t \tilde{\chi}_1^0$ or $t \tilde{\chi}_2^0$ as illustrated in fig. 4.10. For the dominantly LH stop (left panel), the difference between the polarizations in the two channels never exceeds 10% when $M_1 > \mu$ which marks the onset of the higgsino LSP region. For the RH stop (right panel) the difference between the polarizations can reach 30% when $M_1 \approx \mu = 280$GeV although both polarizations quickly become almost equal as $M_1$ is increased and thus the higgsino fraction of the neutralinos. The difference between the top polarization in the two higgsino channels is purely a kinematic effect due to the smaller mass splitting between the stop and the second neutralino. This effect is more pronounced for the RH stop case simply because the mass of $\tilde{t}_1$ is lower. Note that since the two lightest neutralinos are almost degenerate, the decay of the second neutralino into the LSP is accompanied by soft leptons and basically has the same missing $E_T$ signature as the LSP. Therefore both decay channels can be used to determine the top polarization.

In the above, we have considered the behaviour of the top polarization without worrying about other constraints on the model. We will now briefly comment on the impact
4.3. Sensitivity to SUSY Parameters

Figure 4.8: Contours of the top polarization in the top rest frame for $\mu < 0$ and a mixed dominantly RH stop (left). Branching ratios for $t_1 \rightarrow t \tilde{\chi}_1^0$ (right).

Figure 4.9: Same as fig. 4.8 for $\mu > 0$ and dominantly RH stop.

Figure 4.10: Comparison of the top polarization for the decay $t_1 \rightarrow t \tilde{\chi}_1^0$ (full line) and $t_1 \rightarrow t \tilde{\chi}_2^0$ (dashed line) as a function of the gaugino mass $M_1$ for $|\mu| = 150$ GeV (blue) and $|\mu| = 300$ GeV (red). SUSY parameters are fixed as in tab. 4.1 for a dominantly LH stop (left panel) and a dominantly RH stop (right panel).
of these constraints. The dark matter relic density for the bino case is typically much too large. It is however possible to bring it to a reasonable value. Decreasing the mass of the sleptons to just above the LSP mass adds an important contribution from coannihilation processes. This would have no impact on the polarization observables discussed here. By contrast the relic density is typically too small in the higgsino region. This only means that the neutralino cannot form all of the dark matter. Moreover constraints on observables from the flavour sector can easily be satisfied. The branching ratio for $B_s \to \mu^+ \mu^-$, for instance, remains near the SM value since we are considering only moderate values of $\tan \beta$ and a heavy pseudoscalar.

\section{Top Polarization: Effect on Decay Kinematics and Observables}

We first study the effect of the polarization of the decaying top on the kinematics of the lepton produced in its semi-leptonic decay in this section, eq. (2.8), and assess the possible effects top polarization can have for the search strategies for the stop. Further we study qualitatively if top polarization at the LHC, measured via this semi-leptonic decay can be a useful probe for the neutralino and stop mixing parameters when there is prior knowledge on SUSY masses.

To examine the effect of the top polarization on the kinematic distributions of the semi-leptonic top quark decay product we have generated sets of events with Madgraph \cite{13,14}. This set of benchmarks has been selected based on the degree of top polarization in the stop rest frame as well as a roughly constant mass difference between stop and neutralino. The physical parameters corresponding to these benchmarks are listed in tab. 4.2. We have generated the process

$$ pp \to \tilde{t} \bar{\tilde{t}} \to t \tilde{\chi}_1^0 \bar{t} \to l^+ \nu_l b \tilde{\chi}_1^0 \bar{t} \quad (4.12) $$

We took 8 TeV as LHC centre of mass energy and use the following parameter values: the top mass and width are $m_t = 173.1$ GeV and $\Gamma_t = 1.50$ GeV, and the $W$ mass and width are $m_W = 79.82$ GeV and $\Gamma_W = 2.0$ GeV. The factorization and renormalization scales were set to $\mu_R = \mu_F = m_{\tilde{t}}$. It was shown in the previous chapter that NLO corrections do not change the qualitative features of the lab-frame observables constructed out of the angular variables, so we show leading-order (LO) results, which were calculated using the CTEQ6L1 \cite{102} pdf set. Here we implicitly assume that the anti-stop decays hadronically and have generated events where only the stop has decayed. Note however that the antitop could easily be distinguished from the top using the sign of the lepton. Hence, exploiting the information from events where the stop decays hadronically and the anti-stop leads to a final state with an (anti)lepton would provide increased sensitivity.

\subsection{Effect of Top Polarization on $E_l$ and $p_T^l$}

In this subsection we show the effect of the top polarization on the energy $E_l$ and the transverse momentum $p_T^l$ of the lepton produced in the decay of the top in the laboratory
4.4. Top Polarization: Effect on Decay Kinematics and Observables

<table>
<thead>
<tr>
<th>$P_t$ (GeV)</th>
<th>$m_{	ilde{t}}$ (GeV)</th>
<th>$m_{\tilde{\chi}_0^0}$ (GeV)</th>
<th>$\sin(\theta_\tilde{t})$</th>
<th>$Z_{11}$</th>
<th>$Z_{14}$</th>
<th>$\tan(\beta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500.0</td>
<td>318.6</td>
<td>0.998</td>
<td>0.958</td>
<td>-0.176</td>
<td>7.8</td>
</tr>
<tr>
<td>0.5</td>
<td>500.0</td>
<td>321.1</td>
<td>0.998</td>
<td>0.988</td>
<td>-0.0866</td>
<td>7.8</td>
</tr>
<tr>
<td>0</td>
<td>500.0</td>
<td>320.5</td>
<td>-0.124</td>
<td>0.975</td>
<td>-0.128</td>
<td>10.0</td>
</tr>
<tr>
<td>-0.5</td>
<td>501.1</td>
<td>319.2</td>
<td>0.995</td>
<td>0.440</td>
<td>-0.618</td>
<td>20.0</td>
</tr>
<tr>
<td>-0.8</td>
<td>502.0</td>
<td>319.3</td>
<td>-0.0988</td>
<td>0.0232</td>
<td>-0.190</td>
<td>35.0</td>
</tr>
<tr>
<td>1</td>
<td>500.7</td>
<td>130.2</td>
<td>0.9928</td>
<td>0.9976</td>
<td>-0.0188</td>
<td>10.0</td>
</tr>
<tr>
<td>0.5</td>
<td>499.6</td>
<td>129.7</td>
<td>0.9987</td>
<td>0.9164</td>
<td>-0.2112</td>
<td>29.6</td>
</tr>
<tr>
<td>0</td>
<td>500.1</td>
<td>129.3</td>
<td>-0.05954</td>
<td>0.9729</td>
<td>-0.1017</td>
<td>35.0</td>
</tr>
<tr>
<td>-0.5</td>
<td>500.1</td>
<td>130.3</td>
<td>-0.05948</td>
<td>0.9865</td>
<td>-0.06113</td>
<td>35.0</td>
</tr>
<tr>
<td>-1</td>
<td>499.4</td>
<td>130.0</td>
<td>-0.05911</td>
<td>0.9990</td>
<td>-0.007184</td>
<td>35.0</td>
</tr>
</tbody>
</table>

Table 4.2: Set of benchmarks sorted by polarization. The upper five correspond to small mass differences and the lower five to large mass differences. The mass of the second neutralino is shown for the cases where its branching is non-zero.

frame for our benchmark points. These two distributions in the laboratory depend on the angular distribution of the lepton given in eq. (2.8) in the top rest frame, as well as the energy and the $p_T$ of the decaying top which decides the direction and the magnitude of the boost to the laboratory frame. Since the angular distribution of eq. (2.8) depends on the polarization of the decaying top, the $E_l$ and $p_T^l$ distributions have a dependence on the top polarization. Most of the decay leptons in the rest frame come in the forward direction for a positively polarized $t$ quark, i.e. the direction of the would-be momentum of the $t$ quark in the laboratory. Thus after a boost from the rest frame to the lab frame the energies of these leptons are increased. Similarly, for negative polarized $t$ quarks most of the decay leptons come out in the backward direction w.r.t. the lab momentum of the $t$ quark. This results in an opposite boost direction and hence a decrease in the energy of the leptons. The effect on the $p_T$ distribution of the lepton in the laboratory is further also affected by the $p_T$ of the $t$ quark as well.

Fig. 4.11 shows the $E_l$ distribution in the laboratory for three different polarizations of the parent top quark: 1, 0 and $-1$, being depicted in blue, red and black respectively. Since, for the three cases in each figure, the mass difference between the stop and the top is nearly the same, the entire difference in the distributions can only be due to polarization of the decay top. Consistent with the qualitative argument given above, the peak of the $E_l$ distribution shifts to lower energies for the left polarized top with respect to an unpolarized top and to higher energies for the right polarized one. The shift is higher for the case of large mass differences (with peaks occurring at respectively 26, 42 and 66 GeV) compared to the small mass difference (with peaks occurring at 34.5, 37.5 and 40.5 GeV). Since one puts cuts on the lepton kinematic variables to reduce the background from the SM tops (which would have polarization zero) one sees that such cuts will be less effective for a left polarized top and it will be even more so for the case of large mass differences. The distributions for the transverse momentum of the lepton, shown in fig. 4.12, shows similar features. For small mass differences the transverse momentum distribution of a
Figure 4.11: The distribution in the energy of the lepton coming from the decay of the top quark, for three different polarizations of the decaying $t$ quark: 1, 0 and -1 being given by the blue, red and the black lines respectively. The left graph represents benchmarks with a small mass difference and the right graph benchmarks with a large mass difference between stop and neutralino.

polarization of $-1$, 0 and $+1$ respectively peaks at 24, 26 and 31 GeV. For large mass differences the distribution of a polarization of $-1$, 0 and $+1$ respectively peaks at 23, 23 and 40 GeV. In fact we also notice that the shifts in the $p_T^j$ distributions are substantial compared to the possible effects which would come from changes in the $p_T^j$ distribution coming from NLO effects [87, 103, 104]. So, this effect needs to be taken into account even in an analysis that neglects the NLO effects on the stop production.

Figure 4.12: The distribution in $P_T^l$ of the lepton coming from the decay of the top quark. The left graph represents benchmarks with a small mass difference and the right graph benchmarks with a large mass differences between stop and neutralino.

Thus we clearly see that the current limits quoted on the stop quark mass from direct production, using the $t\tilde{\chi}_1^0$ channel, will depend on the amount of top polarization and in addition the effect of the mass difference $m_t - m_{\tilde{\chi}_1^0}$. This needs to be kept in mind while assessing the limits being quoted currently. The observation above also means that the searches for the stop with SUSY parameters, that give rise to negatively polarized tops are in fact doubly challenged as the single top background will also produce top quarks.
that are negatively polarized. Whereas for the case of positively polarized top quarks being produced by SUSY, one can use the above distribution to discriminate effectively against the background coming from single top quark production.

This also means that, in principle, information on the energy of the lepton may be used as a ‘measure’ of the parent top polarization. In fact, for heavily boosted top quarks, studying distributions in fractional energy of the decay lepton and $b$ quark has been shown to carry information about the top polarization [12]. In fact a recent study demonstrates their use for the case of hadronically decaying tops, at the 14 TeV LHC [105]. It should be noted, however, as mentioned earlier, that the energy distributions of the decay products can be affected by the anomalous $tbW$ coupling and hence are less robust a measure of the top polarization of the parent top quark, than the angular observables as discussed in the previous chapter and [4]. We discuss these in the next subsection.

4.4.2 Observables

In this subsection we focus on the observables that will give us a measure of the polarization of the top quark, using angular observables of the decay lepton. The leptonic decay has the highest analyzing power and is furthermore unaffected by an anomalous $tbW$ coupling to leading order as explained in chapter [2]. We explore utility of various asymmetries constructed out of the $\phi_l$ and $\theta_l$ distributions, as in [17, 106, 107] and chapter [3].

**Azimuthal asymmetries**

The azimuthal distributions of the charged lepton from top decay for selected benchmarks are plotted in fig. 4.13. The left plot contains the benchmarks with a small mass difference between stop and neutralino, and the right plot those with a large mass difference. The distributions, in general, follow the behavior as described in section 2.3.

![Azimuthal asymmetries](image)

Figure 4.13: The azimuthal $\phi_l$ distribution of the decay lepton of the top quark. The left graph represents benchmarks with a small mass difference between stop and neutralino, and the right graph benchmarks with a large mass difference between stop and neutralino.

The distributions in fig. 4.13 seem to be well separated by their polarization value. Therefore we quantify this with the asymmetry parameter $A_\phi$, eq. 2.9.
Chapter 4. Top Polarization in Stop Production

The polarization is influenced by the boost to the stop labframe (section 4.2.3). We will treat the transverse momentum ($p_T$) of the top as a crude qualifier of this boost and apply a cut on $p_T$ [9]. Thereby attempting to reduce the polluting effect of the kinematics on the angular distribution. We have defined an adaptive cut as

$$\frac{p_T^{\text{max}}}{x} < p_T < x p_T^{\text{max}}. \quad (4.13)$$

We define both a strict ($x = 1.5$) and loose ($x = 2$) cut. The results for these choices are given in tab. 4.3.

<table>
<thead>
<tr>
<th>$p_T$ (cut)</th>
<th>$A_\phi$ (nc)</th>
<th>$A_\phi$ (lc)</th>
<th>$A_\phi$ (sc)</th>
<th>$A_\phi$ (nc)</th>
<th>$A_\phi$ (lc)</th>
<th>$A_\phi$ (sc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>0.57</td>
<td>0.51</td>
<td>0.48</td>
<td>0.87</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>+0.5</td>
<td>0.53</td>
<td>0.45</td>
<td>0.41</td>
<td>0.81</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>0</td>
<td>0.48</td>
<td>0.42</td>
<td>0.39</td>
<td>0.69</td>
<td>0.67</td>
<td>0.64</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.44</td>
<td>0.37</td>
<td>0.34</td>
<td>0.61</td>
<td>0.60</td>
<td>0.58</td>
</tr>
<tr>
<td>-1.0</td>
<td>0.39</td>
<td>0.33</td>
<td>0.29</td>
<td>0.55</td>
<td>0.50</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 4.3: Relative azimuthal asymmetry parameter for the process as defined in eq. (4.12). The left side of the table denotes small mass differences and the right side large mass differences between stop and neutralino. An adaptive cut is applied on the transverse momentum as defined in eq. (4.13). The abbreviations following the asymmetry variable, denoted between brackets: nc, lc and sc respectively indicate no cut, a loose cut and a strict cut.

From tab. 4.3 we notice that the asymmetry parameter $A_\phi$ is large for positive polarizations, decreases for lower polarizations and reaches its lowest value at a negative polarization. As expected, the $p_T$ cut improves the asymmetry parameter. In the case of a small mass difference, the effect is small. For large mass differences however, the two $p_T$ cuts in eq. (4.13) enhance the separation of different polarizations. This is natural, as a large stop-neutralino mass difference endows the top with more kinetic energy.

Polar asymmetries

We can apply a similar analysis to the distribution in the polar angle, defined as the angle between top direction and decay lepton in the lab frame. The distributions are shown in fig. 4.14. We notice a peaking in the direction of the top boost which is again strongest for a positive polarization and weakest for a negative polarization. Again the large mass difference cases show a stronger correlation with the polarization $P_t$ than the small mass difference cases. Because the distribution of $\theta_l$ is non-symmetric we have more choice for an asymmetry parameter definition that quantifies the shape differences and have chosen the definition of eq. (3.3).

This definition allows for a negative $A_\theta$. It is of course possible to define the asymmetry parameter such that all values are positive. However, in an experimental analysis, the definition of $A_\theta$ will be tuned to enhance the effects of polarization. As the outcome of this procedure will depend on the masses of the sparticles, we will use the definition given in eq. (3.3) to show the qualitative effect. The value of $A_\theta$, shown in tab. 4.4, is lowest for
4.4. Top Polarization: Effect on Decay Kinematics and Observables

Figure 4.14: The polar distribution $\theta_l$ of the decay lepton of the top quark. Polarizations in the left figure are chosen such that there is a small mass difference between stop and neutralino. In the right figure the mass difference is large.

Table 4.4: Relative polar asymmetry parameter for the process as defined in eq. (4.12). The left side denotes benchmarks with a small mass difference and the right side large mass differences between stop and neutralino. An adaptive cut is applied on the transverse momentum as defined in eq. (4.13). The abbreviations following the asymmetry variable, denoted between brackets: nc, lc and sc respectively indicate no cut, a loose cut and a strict cut.

<table>
<thead>
<tr>
<th>$P_t$ (cut)</th>
<th>$A_\theta$ (nc)</th>
<th>$A_\theta$ (lc)</th>
<th>$A_\theta$ (sc)</th>
<th>$A_\theta$ (nc)</th>
<th>$A_\theta$ (lc)</th>
<th>$A_\theta$ (sc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>0.12</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.66</td>
<td>0.66</td>
<td>0.64</td>
</tr>
<tr>
<td>+0.5</td>
<td>0.06</td>
<td>-0.05</td>
<td>-0.08</td>
<td>0.55</td>
<td>0.55</td>
<td>0.52</td>
</tr>
<tr>
<td>0</td>
<td>-0.001</td>
<td>-0.10</td>
<td>-0.13</td>
<td>0.32</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>-0.5</td>
<td>-0.06</td>
<td>-0.14</td>
<td>-0.17</td>
<td>0.18</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>-1.0</td>
<td>-0.12</td>
<td>-0.20</td>
<td>-0.22</td>
<td>0.06</td>
<td>-0.03</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

negative polarization, increases as the polarization increases and reaches its highest value at a polarization of $P_t = +1$. The adaptive cut again has little effect for the small mass differences but enhances mildly the separation of $A_\theta$ for large mass differences and can therefore be a useful probe for polarization.

Impact of the stop neutralino mass difference

We have seen in section 4.2.2 that the polarization depends on the mass difference between the stop and the neutralino, more precisely on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t$, and that the asymmetry parameter $A_\phi$ is highest for a high polarization for both mass differences. So far we have been studying the effects of polarization whilst keeping this difference constant. However, when we vary $\Delta m$, the asymmetry values corresponding to different polarizations are not well separated anymore. For example, we consider a new benchmark with a mass difference that falls in between the two cases in tab. 4.2. For this point $P_t = 0$, $m_{\tilde{t}} = 508.9$ GeV, $m_{\tilde{\chi}_1^0} = 292.4$ GeV, $\sin \theta_{\tilde{t}} = 0.1234$, and yet the asymmetry $A_\phi = 0.56$ is quite similar to the value for the benchmark $P_t = 0.5$ in tab. 4.3 which has $A_\phi = 0.53$. 

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The mass difference for these points varies from \(\Delta m = 43\) GeV for the former and \(\Delta m = 6\) GeV for the latter. Imposing the adaptive cut on the \(p_T\) of the top enhances the differences between the two benchmarks, but neither cuts are able to isolate the purely polarization induced behavior. For the \(P_t = 0\) benchmark we get \(A_\phi = 0.55(0.53)\) for the loose (strict) cut to be compared with \(A_\phi = 0.45(0.41)\) for the \(P_t = 0.5\) benchmark.

We conclude that varying the mass difference slightly has a large effect on the angular distributions and therefore pollutes the information about polarization present in these angular distributions. Thus, detailed mass measurements will be needed in addition to the polarization-dependent observables, to extract information about the top polarization from these.

Decays to \(\tilde{\chi}^0_2, \tilde{\chi}^0_3\)

Thus far we have studied the case where the stop decays to one, generic neutralino type. We next examine the case where we allow for a decay to multiple neutralino types. Two large mass difference benchmarks of tab. 4.2 have stop branching ratios to several neutralino types, those with A) \(P_t = 0.5\) and B) \(P_t = 0\). In case A the heavier neutralino masses are \(m_{\tilde{\chi}^0_2} = 207\) GeV, \(m_{\tilde{\chi}^0_3} = 213\) GeV while in case B, \(m_{\tilde{\chi}^0_2} = 276\) GeV, \(m_{\tilde{\chi}^0_3} = 282\) GeV. The heavier neutralinos are higgsino-like so that the polarization is close to \(P_t = -1\) in case A which has a RH stop and to \(P_t = 1\) in case B with a LH stop.

We have listed the separate contributions to \(P_t\) and the asymmetries \(A_\phi\) and \(A_\theta\) in tab. 4.5. The difference in the asymmetries between various neutralino channels is somewhat less than naively expected. This is because the mass difference \(\Delta m\) is smaller for heavier neutralinos, thus reducing the difference in the asymmetries as discussed above. This effect is particularly noticeable for the second case where despite the fact that \(P_t = 0(1)\) for the light (heavier) neutralinos, all three neutralinos give rise to almost the same asymmetries.

<table>
<thead>
<tr>
<th>decay to</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(A_\phi)</td>
<td>(A_\theta)</td>
</tr>
<tr>
<td>(\chi^0_1)</td>
<td>0.81</td>
<td>0.55</td>
</tr>
<tr>
<td>(\chi^0_2)</td>
<td>0.53</td>
<td>0.04</td>
</tr>
<tr>
<td>(\chi^0_3)</td>
<td>0.53</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 4.5: Azimuthal and polar asymmetry parameter for the process as defined in eq. (4.12) allowing for decays of the stop to a certain neutralino type. The polarization and branching fraction for the decay into each neutralino channel is also specified. Case A and Case B correspond respectively to the second and third rows of the large mass difference benchmarks in tab. 4.2.

With the theoretical prediction on the rest frame polarization per decay mode on the basis of eqs. (4.3) and (4.4), the lab frame distributions can then be predicted after combination with the appropriate Lorentz transformations. The asymmetry parameter for all decays is a sum of the individual values weighted by branching ratios. The extent to which \(A_\phi\) depends on the angular distribution of a certain decay mode therefore depends strongly on the branching fractions. The results including adaptive cuts for the two benchmarks of tab. 4.5 are shown in tab. 4.6. Clearly the asymmetries are dominated by
4.5 Conclusion

the heavier neutralino decay channels for case A while they receive similar contributions from all three neutralino channels for case B.

<table>
<thead>
<tr>
<th></th>
<th>$p_t(t\tilde{\chi}_1^0)$</th>
<th>$A_\phi$ (nc)</th>
<th>$A_\phi$ (lc)</th>
<th>$A_\phi$ (sc)</th>
<th>$A_\theta$ (nc)</th>
<th>$A_\theta$ (lc)</th>
<th>$A_\theta$ (sc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>+0.5</td>
<td>0.58</td>
<td>0.53</td>
<td>0.50</td>
<td>0.13</td>
<td>0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0.70</td>
<td>0.69</td>
<td>0.68</td>
<td>0.32</td>
<td>0.26</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 4.6: Azimuthal and polar asymmetry parameter for the process as defined in eq. (4.12) allowing for decays of the stop to all neutralino types. An adaptive cut is applied on the transverse momentum as defined in eq. (4.13). The abbreviations following the asymmetry variable, denoted between brackets: nc, lc and sc respectively indicate no cut, a loose cut and a strict cut.

4.5 Conclusion

The phenomenology of the third generation sfermions has always been an interesting subject to explore as this can yield non-trivial information about SUSY parameters. In view of the ever increasing upper limits on the masses of the strongly interacting sparticles that are being extracted from LHC data and the observation of a light, single Higgs-like particle, naturalness considerations within the MSSM leads to the possibility of third generation sfermions that are much lighter than the first two generations. Thus direct pair production cross-sections of both stops and sbottoms can be large enough to be probed within the 8 TeV run of the LHC. The top quarks produced in these decays are generally polarized and this polarization holds information about mixing in the squark sector, mixing in the chargino/neutralino sectors as well as on the top velocity, hence on the mass difference between the squark and the neutralino/chargino. The parameters that affect the top polarization will influence the effectiveness of the searches for stops. Thus, the limits extracted will not only depend on the stop and neutralino mass but also on the assumed polarization. Indeed, the polarization can affect the energies of decay leptons and hence the optimization of cuts to reduce the background from the QCD produced unpolarized top. Since the top polarization goes to zero in the limit of a small stop-neutralino mass difference, the polarization-induced kinematic effects will be particularly important for models where this mass difference is large. This is an important factor to keep in mind in analyses using simplified models with large mass differences. To obtain a conservative limit, one should use a model which produces a completely negatively polarized top quark.

Let us briefly summarize our findings. We have explored the possible values of the top polarization in the decay of the lightest stop into a top and a neutralino and we have scanned the parameter space which is consistent with a 125.7 GeV Higgs. We find that the bino content of the neutralino is a critical parameter and that due to the largeness of the hypercharge for the right-handed top which drives the bino-stop-top coupling, a mixed stop often behaves like a RH stop. A dominantly RH stop produces a negative top polarization when it decays into a higgsino and a positive polarization when the decay is into a bino, and vice-versa for a LH stop. This implies that these events can be separated more
easily from the top pair background, as a positive top polarization leads to more energetic leptons. The LH stop with a higgsino LSP and the RH stop with a bino LSP could be more tightly constrained at the LHC than the other two combinations. We have also shown that although small branching ratios into the lightest neutralino can occur especially for the decay into a higgsino, similar polarizations for the decay into the two higgsino states imply that we can exploit both decay modes to measure the top polarization. Finally, a small mass difference between the stop and the neutralino leads to a very small polarization.

We then analyzed the kinematics of the decay products of the top arising from stop decay into a top and a neutralino in the laboratory frame. Since the majority of the top quarks in the SM background are unpolarized the stop search is particularly challenging in the $t\tilde{\chi}^0_1$ mode for points in the parameter space which give rise to tops with negative polarization. The spectrum of the electron energy as well as transverse momentum of the lepton, softens (hardens) for negatively (positively) polarized top quarks respectively, compared to an unpolarized top quark. This modification of the position of the peak increases with increasing value of $m_{\tilde{t}} - m_{\tilde{\chi}^0_1}$. For the electron energy spectrum the shift is $-30$ GeV for $m_{\tilde{t}} - m_{\tilde{\chi}^0_1} \sim 320$ GeV and $-16$ GeV for $m_{\tilde{t}} - m_{\tilde{\chi}^0_1} \sim 130$ GeV. Thus we see that even with the same kinematics, the reach of a particular search using the lepton is less efficient for negatively polarized tops. This effect is more pronounced for large mass differences between the stop and the neutralino.

Finally, as in chapter [3] we have studied lab-frame observables and defined asymmetries in the polar and azimuthal angle. These asymmetries have both a polarization-dependent and independent part and provide a useful probe for top polarization provided the masses of the particles involved are known, since the polarization is very sensitive to mass differences. In conclusion, study of the top polarization can provide useful information on supersymmetric parameters at the LHC when the supersymmetric partner of the top is discovered.