Using Tau Polarization for Charged Higgs Boson and SUSY searches at LHC

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The $\tau$ polarization can be easily measured at LHC in the 1-prong hadronic $\tau$ decay channel by measuring what fraction of the $\tau$-jet momentum is carried by the charged track. A simple cut requiring this fraction to be $>0.8$ retains most of the $P_{\tau}=+1$ $\tau$-jet signal while suppressing the $P_{\tau}=-1$ $\tau$-jet background and practically eliminating the fake $\tau$ background. This can be utilized to extract the charged Higgs signal. It can be also utilized to extract the SUSY signal in the stau NLSP region, and in particular the stau co-annihilation region.

1. Introduction

It is easy to measure $\tau$ polarization $P_{\tau}$ as it is reflected in the kinematic distribution of its decay products. Moreover, the best channel for measuring $\tau$ polarization is also the best channel for $\tau$ identification, i.e. the 1-prong hadronic $\tau$ decay channel. In particular a simple kinematic cut, requiring the single charged prong to carry $>80\%$ of the hadronic $\tau$-jet momentum retains most of the $P_{\tau}=+1$ $\tau$-jet events, while suppressing the $P_{\tau}=-1$ $\tau$-jet background and practically eliminating the fake $\tau$ background from standard hadronic jets. Interestingly the most important channel for charged Higgs boson search at LHC is its $\tau$ decay channel, $H^- \rightarrow \tau_R \bar{\nu}_R$, giving $P_{\tau}=+1$. Similarly a very important part of the parameter space of the minimal supergravity(mSUGRA) model has $\tilde{B}$ as the lightest superparticle, while the next to the lightest one is a stau($\tilde{\tau}_1$) with a dominant $\tilde{\tau}_R$ component. In this case one expects the supersymmetric(SUSY) signal at LHC to contain a $P_{\tau}=+1$ $\tau$ from the cascade decay of squarks and gluinos via $\tilde{\tau}_1 \rightarrow \tau_R \tilde{B}$. In both cases one can use the above kinematic cut to enhance the $P_{\tau}=+1$ signal over the $P_{\tau}=-1$ background as well as the fake $\tau$ background.

The paper is organised as follows. In section 2 we summarise the formalism of $\tau$ polarization in the 1-prong hadronic decay channel and discuss how the abovementioned kinematic cut retains most of the detectable $P_{\tau}=+1$ $\tau$-jet signal while supressing the $P_{\tau}=-1$ $\tau$-jet as well as the fake $\tau$-jet background. Section 3 briefly introduces the SUSY search programme at LHC via SUSY as well as SUSY Higgs(and in particular $H^\pm$) signals. In section 4, we describe the most important $H^\pm$ signal in both $m_{H^\pm} < m_{\tilde{\chi}}$ and $m_{H^\pm} > m_{\tilde{\chi}}$ regions, which contains a hard $\tau$ with $P_{\tau}=+1$ from the abovementioned $H^\pm$ decay. In section 5 we show Monte Carlo simulations using the above kinematic cut for extraction of the $H^\pm$ signal at LHC for both the $m_{H^\pm} < m_{\tilde{\chi}}$ and $m_{H^\pm} > m_{\tilde{\chi}}$ regions. In the latter case we also briefly discuss a corresponding kinematic cut for extracting the $m_{H^\pm}$ signal in the 3-prong hadronic decay channel of $\tau$. In section 6 we briefly describe the SUSY signal coming from the abovementioned cascade decay process. We also emphasize a very important part of the SUSY parameter space, called the stau co-annihilation region, where the signal contains a soft $\tau$ with $P_{\tau}=+1$. In section 7 we show the use of the kinematic cut for extracting the SUSY signal at LHC in the 1-prong hadronic $\tau$-decay channel, with particular emphasis on the stau co-annihilation region.

2. $\tau$ Polarization:

The best channel for $\tau$ polarization is its 1-prong hadronic decay channel, accounting for 50% of its decay width. Over 90% this comes from

$$\tau \rightarrow \pi^\pm \nu(12.5\%), \rho^\pm \nu(26\%), a_1^\pm \nu(7.5\%),$$  \hspace{1cm} (1)

where the branching fraction for $\pi$ and $\rho$ include the small $K$ and $K^*$ contributions, which have identical polarization effects [1]. The CM angular distributions of
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3. SUSY and SUSY Higgs searches at LHC

The minimal supersymmetric standard model (MSSM), has been the most popular extension of the standard model (SM) for four reasons. It provides (1) a natural solution to the hierarchy problem of the
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electroweak symmetry breaking (EWSB) scale of the SM, (2) a natural (radiative) mechanism for EWSB, (3) a natural candidate for the dark matter of the universe in terms of the lightest superparticle (LSP), and (4) unification of the gauge couplings at the grand unification (GUT) scale. Therefore, there is a great deal of current interest in probing this model at LHC. This is based on a two-prong search strategy. On the one hand we are looking for the signal of supersymmetric (SUSY) particle production at LHC. On the other hand we are looking for the signal of the extended Higgs boson sector of the MSSM, and in particular the charged Higgs boson ($H^\pm$). We shall see below that the \(\tau\) channel plays a very important role for both SUSY and the \(H^\pm\) signals and one can use the abovementioned \(\tau\) polarization effect in extracting both these signals at LHC.

4. \(H^\pm\) Signal

As mentioned above, the MSSM contains two Higgs doublets \(H_u\) and \(H_d\), the ratio of whose vevs is denoted by tan \(\beta\). The two complex doublets correspond to 8 degrees of freedom, 3 of which are absorbed as Goldstone bosons to give masses and longitudinal components to the \(W^\pm\) and \(Z\) bosons. This leaves 5 physical states: two neutral scalars \(h\) and \(H\), a pseudo scalar \(A\) and a pair of charged Higgs bosons \(H^\pm = H_u^\pm \cos \beta + H_d^\pm \sin \beta\).

While it may be hard to distinguish any of these neutral Higgs bosons from that of the SM, the \(H^\pm\) pair carry the distinctive hallmark of the MSSM. Hence the \(H^\pm\) search plays a very important role in probing the SUSY Higgs sector [5]. All the tree level masses and couplings of the MSSM Higgs bosons are given in terms of tan \(\beta\) and any one of their masses, usually taken to be \(m_A\). It is simply related to \(m_{H^\pm}\) via,

\[m_{H^\pm}^2 = m_A^2 + m_W^2.\]  

The most important \(H^\pm\) couplings are

\[H^\pm tb(cs): \frac{g}{\sqrt{2}M_W} (m_{t(c)} \cot \beta + m_{b(s)} \tan \beta),\]

\[H^\pm \tau\nu : \frac{g}{\sqrt{2}M_W} m_\tau \tan \beta.\]  

Assuming the \(H^\pm tb\) coupling to remain perturbative up to the GUT scale implies \(1 < \tan \beta < m_t/m_b\).

For \(m_{H^\pm} < m_t\), eq.8 imply large branching fractions for

\[t \rightarrow bH^\pm\]  

decay at the two ends of the above range, \(\tan \beta \sim 1\) and \(\tan \beta \sim m_t/m_b \sim 50\), driven by the \(m_t\) and \(m_b\) terms respectively. But there is a huge dip in the intermediate region around

\[\tan \beta \sim \sqrt{m_t/m_b} \sim 7,\]  

which is overwhelmed by the SM decay \(t \rightarrow bW\). Eq.8 also implies that the dominant decay mode for this \(H^\pm\) over the theoretically favored region of \(\tan \beta > 1\) is,

\[H^- \rightarrow \tau^- \nu_R; \quad P_\tau = +1\]  

where the polarization follows simply from angular momentum conservation, requiring the \(\tau^-\) to be right handed. It implies the opposite polarization for the SM process

\[W^- \rightarrow \tau^- \bar{\nu}_R; \quad P_\tau = -1\]  

since the \(\tau^-\) is now required to be left-handed. One can use the opposite polarizations to distinguish the \(H^\pm\) signal from the SM background [2, 3]. In particular one can use the kinematic cut, mentioned in the introduction, to enhance the signal/background ratio and extend the \(H^\pm\) search at LHC over the intermediate \(\tan \beta\) range [10], which would not be possible otherwise [3].

For \(m_{H^\pm} > m_t\), the dominant production process at LHC is the LO process

\[gb \rightarrow tH^- + h.c.\]  

The dominant decay channel is \(H^- \rightarrow \bar{t}b\), which has unfortunately a very large QCD background. By far the most viable signal comes from the second largest decay channel [11], which has a branching fraction of \(\geq 10\%\) in the moderate to large \(\tan \beta\) (\(\geq 10\)) region. The largest background comes from \(t\bar{t}\) production, followed by the decay of one of the top quarks into the SM channel [12]. One can again exploit the opposite \(\tau\) polarizations to enhance the signal/background ratio and extend the \(H^\pm\) search to several hundreds of GeV for \(\tan \beta \approx 10\) [5, 6, 7]. This will be discussed in detail in the next section.

5. \(\tau\) polarization in the \(H^\pm\) search

A parton level Monte Carlo simulation of the \(H^\pm\) signal in the \(m_{H^\pm} < m_t\) region [8] showed that using the polarization cut [5] enhances the signal/background ratio substantially and makes it possible to extend the \(H^\pm\) search at LHC over most of the intermediate \(\tan \beta\) region [10]. This has been confirmed now by more exact simulations with particle level event generators. Fig.2
shows the $H^\pm$ discovery contours at LHC using this polarization cut\textsuperscript{[7]}. The vertical contour on left shows $H^\pm$ discovery contour via $t \rightarrow bH^\pm$ decay. The mild dip in the middle shows the remaining gap in this intermediate $\tan \beta$ region.

For $m_{H^\pm} > m_t$, the signal comes from \textsuperscript{[13]} and \textsuperscript{[11]}, while the background comes from $t\bar{t}$ production, followed by the decay of one top into $\tau^-\nu$ (vertical). To start with the background is over two orders of magnitude larger than the signal; but the signal has a harder $\tau$-jet. Thus a $p_T^{\tau\text{-jet}} > 100$ GeV cut improves the signal/background ratio. Fig.3 shows the $R(X')$ distribution of the resulting signal and background. One can see that increasing the R cut from 0.2 to 0.8 suppresses the background substantially while retaining most of the detectable(R>0.2) signal events. The remaining signal and background can be separated by looking at their distributions in the transverse mass of the $\tau$-jet with the missing $p_T$, coming from the accompanying $\nu$. Fig.4 shows these distributions from a recent simulation\textsuperscript{[6]} using PYTHIA Monte Carlo event generation\textsuperscript{[8]}, interfaced with TAUOLA\textsuperscript{[9]} for handling $\tau$ decay. One can clearly separate the $H^\pm$ signal from the W background and also measure the $H^\pm$ mass using this plot.

Finally, one can also use the polarization effect in the 3-prong hadronic $\tau$-decay channel,

$$\tau^\pm \rightarrow \pi^\pm\pi^\mp\pi^\mp\nu,$$

with no neutrals. This has a branching fraction of 10%, which accounts for 2/3rd of inclusive 3-prong $\tau$-decay (including neutrals). Excluding neutrals effectively eliminates the fake $\tau$-jet background from common hadronic jets. About 3/4 of the branching fraction for eq.\textsuperscript{[14]} comes from $a_1$. The momentum fraction $R$ of $\pi^+\pi^0\pi^0$ channel is equivalent to the momentum fraction carried by the unlike sign pion in $a_1 \rightarrow \pi^\pm\pi^\mp\pi^\mp$ channel. Thus one sees from Fig.1 that one can retain the $a_{1L}$ peak while suppressing $a_{1T}$ by restricting this momentum fraction to $<0.2$, which is accessible in this case. This will suppress the hard $\tau$-jet background events from $P_\tau = -1$ while retaining them for the $P_\tau = +1$ signal. This simple result holds even after the inclusion of the non-resonant contribution.

Fig.5 shows the $H^\pm$ discovery contours of LHC using 1-prong and (1+3)-prong channels \textsuperscript{[6]}. One sees a modest improvement of the discovery reach by including the 3-prong channel. Note also that the 1-prong $H^\pm$ discovery contour for 100$fb^{-1}$ luminosity is consistent with that of Fig.2 for the ultimate 300$fb^{-1}$ luminosity of LHC.

6. SUSY signal

We shall concentrate in the mSUGRA model as a simple and well-motivated parametrization of the MSSM. This is described by four and half parameters
the radiative EWSB condition, is a very important weak scale scalar mass, appearing in the Higgs mass limit from LEP \cite{1}. The masses of charged Higgs are 300 GeV and 600 GeV and \( m_{H^\pm} \), where the last equality holds at \( \tan \beta > 5 \), favored by the Higgs mass limit from LEP \cite{1}. The sign of \( M_9 \) turning negative by RGE triggers EWSB, as required by \cite{17}. The RHS is related to the GUT scale parameters by the RGE,

\[
-M_{H_u^2} = C_1(\alpha_i, y_t, \tan \beta)m_0^2 + C_2(\alpha_i, y_t, \tan \beta)m_{1/2}^2
\]

\[
\simeq -\epsilon m_0^2 + 2m_{1/2}^2.
\]

The tiny co-efficient of \( m_0^2 \) results from an almost exact cancellation of the GUT scale value by a negative top yukawa(\( y_t \)) contribution. We see from eq.( \cite{10,18} ) that apart from a narrow strip of \( m_0 >> m_{1/2} \), the mSUGRA parameter space satisfies the mass hierarchy \( M_1 < M_2 < \mu \).

Thus the lighter neutralinos and chargino are dominated by the gaugino components

\[
\chi_1^0 \simeq \tilde{B}; \quad \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \simeq \tilde{W}_3,
\]

while the heavier ones are dominated by the higgsino. The lightest neutralino \( \tilde{\chi}_1^0 (\equiv \tilde{\chi}) \) is the LSP. The lightest sfermions are the right-handed sleptons, getting only the U(1) gauge contributions to the RGE, i.e

\[
m_{\tilde{\tau}_R} \simeq m_0^2 + 0.15m_{1/2}^2.
\]

The Yukawa coupling contribution drives the \( \tilde{\tau}_R \) mass still lower. Moreover, the mixing between the \( \tilde{\tau}_{L,R} \) states, represented by the off-diagonal term,

\[
m_{\tilde{\tau}_{L,R}}^2 = m_{\tau}(A_{\tau} + \mu \tan \beta),
\]

drives the lighter mass eigenvalues further down. Thus the lighter stau mass eigenstate,

\[
\tilde{\tau}_1 = \tilde{\tau}_R \sin \theta_{\tilde{\tau}} + \tilde{\tau}_L \cos \theta_{\tilde{\tau}},
\]
is predicted to be the lightest sfermion. Moreover, one sees from eqs. [16, 19] and [21] that \( \tilde{\tau}_1 \) is predicted to be the next to lightest superparticle (NLSP) over half of the parameter space

\[
m_0 < m_{1/2}.
\]

Thanks to the modest \( \tilde{\tau}_L \) component in eq. (23), a large part of the SUSY cascade decay signal at LHC proceeds via

\[
\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1 \nu \rightarrow \tau \nu \tilde{\chi}_1^0,
\]

(25)

\[
\tilde{\chi}_2^0 \rightarrow \tau' \tilde{\tau}_1 \rightarrow \tau' \tau \tilde{\chi}_1^0.
\]

(26)

The dominance of the \( \tilde{\tau}_R \) component in \( \tilde{\tau}_1 \) implies that the polarization

\[
P_{\tau} \simeq +1,
\]

(27)

while \( P_{\tau'} \simeq -1 \). We shall see in the next section that the polarization effect can be utilized to extract the SUSY signal containing a positively polarized \( \tau \) from eqs. (23,26).

A very important part of the abovementioned parameter space is the stau co-annihilation region [11], where the \( \tilde{\tau} \) LSP co-annihilates with a nearly degenerate \( \tilde{\tau}_1 \), \( \tilde{\chi}_1^1 \tilde{\tau}_1 \rightarrow \tau \gamma \), to give a cosmologically compatible relic density [12]. The mass degeneracy \( m_{\tilde{\tau}_1} \simeq m_{\tilde{\chi}_1^0} \) is required to hold to \( \sim 5\% \), since the freeze out temperature is \( \sim 5\% \) of the LSP mass. Because of this mass degeneracy the positively polarized \( \tau \) lepton coming from eqs. (25,26) is rather soft. We shall see in the next section how the polarization effect can be utilized to extract the soft \( \tau \) signal and also to measure the tiny mass difference between the co-annihilating particles.

7. \( \tau \) polarization in SUSY search:

The polarization of \( \tau \) coming from the \( \tilde{\tau}_1 \) decay of eqs. (23) and (26) is given in the collinear approximation by [13]

\[
P_{\tau} = \frac{\Gamma(\tau R) - \Gamma(\tau L)}{\Gamma(\tau R) + \Gamma(\tau L)} = \frac{(a_{11}^R)^2 - (a_{11}^L)^2}{(a_{11}^L)^2 + (a_{11}^L)^2}
\]

(28)

\[
a_{11}^R = -\frac{2q}{\sqrt{2}m_W} N_{11} \tan \theta_W \sin \theta_{\tau'}
\]

\[
- \frac{gm_{\tau}}{\sqrt{2}m_W \cos \beta} N_{13} \cos \theta_{\tau'}
\]

\[
a_{11}^L = \frac{q}{\sqrt{2}} [N_{12} + N_{11} \tan \theta_W] \cos \theta_{\tau'}
\]

\[
- \frac{gm_{\tau}}{\sqrt{2}m_W \cos \beta} \sin \theta_{\tau'} N_{13}
\]

where the 1st and 2nd subscript of \( a_{ij} \) refer to \( \tilde{\tau}_1 \) and \( \tilde{\chi}_1^0 \), and

\[
\tilde{\chi} \equiv \tilde{\chi}_1^0 = N_{11} \hat{B} + N_{12} \hat{W}_3 + N_{13} \hat{H}_d + N_{14} \hat{H}_u.
\]

(29)

gives the composition of LSP. Thus the dominant term is \( a_{11}^R \sim -\frac{2q}{\sqrt{2}} N_{11} \tan \theta_W \sin \theta_{\tau'} \), implying \( P_{\tau} \equiv +1 \). In fact in the mSUGRA model there is a cancellation between the subdominant terms, so that one gets \( P_{\tau} > 0.9 \) throughout the allowed parameter space [14]. Moreover, in the \( \tilde{\tau}_1 \) NLSP region of eq. (24) \( P_{\tau'} > 0.95 \), so that one can approximate it to \( P_{\tau'} = +1 \). The polarization of the \( \tau' \) from eq. (24) is obtained from eq. (28) by replacing \( a_{11}^{R,L} \) by \( a_{12}^{L,R} \). The dominant contribution comes from \( a_{12}^L \sim \frac{q}{\sqrt{2}} N_{22} \cos \theta_{\tau'} \), implying \( P_{\tau'} \equiv -1 \). There is a similar cancellation of the subdominant contributions, leading to \( P_{\tau'} < -0.95 \) in the \( \tilde{\tau}_1 \) NLSP region. Thus one can safely approximate \( P_{\tau'} = -1 \).

Figure 6. BR(\( \tilde{W}_1 \rightarrow \tilde{\tau}_1 \nu_\tau \)) is shown as contour plots(dashed lines) in \( m_0 \) and \( m_{1/2} \) plane for \( A_0 = 0 \), \( \tan \beta = 30 \) and positive \( \mu \). The kinematic boundaries(dotted lines) are shown for \( \tilde{W}_1 \rightarrow W \tilde{Z}_1 \) and \( \tilde{W}_1 \rightarrow \tilde{\tau}_1 \nu_\tau \) decay. The entire region to the right of the boundary(dot-dashed line) corresponds to \( P_{\tau'} > 0.9 \). The excluded region on the right is due to the \( \tilde{\tau}_1 \) being the LSP while that on the left is due to the LEP constraint \( m_{\tilde{\tau}_1}^\pm > 102 \) GeV [14]. Note that here \( \tilde{W}_1 \) and \( \tilde{Z}_1 \) correspond to \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_1^0 \) in the text.

shows that \( P_{\tau'} > 0.9 \) for \( \tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_1^0 \) decay throughout the mSUGRA parameter space [14]. It also shows that the branching fraction of the decay (25) is large over the \( \tilde{\tau}_1 \) NLSP region of eq. (24), so that one expects a large part of the SUSY signal in the \( \hat{B}_T \) channel to contain a \( \tau \)-jet with \( P_{\tau'} = +1 \). Fig.7 shows the R distribution
of this $P_T=+1$ $\tau$-jet at LHC[14]. For comparison the $R$-distributions are also shown for $P_T=0$ and -1 for this $\tau$-jet. Thus one can test the SUSY model or check the composition of $\tilde{\tau}_1(\tilde{\chi}^0_1)$ by measuring this distribution.

Let us conclude by briefly discussing the use of $\tau$ polarization in probing the stau co-annihilation region at LSP, corresponding to $m_{\tilde{\tau}_1} \simeq m_{\chi^0_1}$[15]. This is one of the very few regions of mSUGRA parameter space compatible with the cosmological measurement of the dark matter relic density, and the only one which is also compatible with the muon magnetic moment anomaly[16]. It corresponds to a narrow strip adjacent to the lower boundary of Fig.6, which can be totally covered at LHC. Therefore, the stau co-annihilation region is a region of special interest to the SUSY search programme at LHC. In particular one is looking for a distinctive signature, which will identify the SUSY signal at LHC to this region and also enable us to measure the tiny mass difference between the co-annihilating particles, $\Delta M = m_{\tilde{\tau}_1} - m_{\chi^0_1}$. Such a distinctive signature is provided by the presence of a soft ($P_T = +1$) $\tau$-jet from the $\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}^0_1$ decay of eqs. [25,26] in the canonical multijet+$E_T$ SUSY signal. Fig.8[15] shows the $p_T$ distributions of this soft ($P_T = +1$) $\tau$ jet signal along with the ($P_T = -1$) $\tau$-jet background coming mainly from the $\tilde{\chi}^0_2$ decay of eq. [26] and $W$ decay. It also shows a significant fake $\tau$ background from the accompanying hadronic jets in these events. Fig.9 shows that the $R > 0.8$ cut of eq. [6] effectively suppresses the ($P_T = -1$) background to a little over half the signal size and practically eliminates the fake $\tau$ background.

A distinctive signal with a very steep slope is clearly sticking above the background at the low $p_T$ end. One can use this slope to extract the signal from the background $\tau$ jets at $3\sigma$ level with a $10 fb^{-1}$ luminosity run of LHC, going up to $10\sigma$ with luminosity of $100 fb^{-1}$. Moreover, one can estimate $\Delta M$ to an accuracy of 50% at the $\sim 1.5\sigma$ level with $10 fb^{-1}$, going up to $5\sigma$ with $100 fb^{-1}$ luminosity[15].

8. Summary

The $\tau$ polarization can be easily measured at LHC in its 1-prong hadronic decay channel by measuring what fraction of the hadronic $\tau$-jet momentum is carried by the charged $p_T$. A simple cut requiring this fraction to be $>0.8$ retains most of the detectable $P_T = +1$ $\tau$-jet events, while effectively suppressing the $P_T = -1$ $\tau$-jet events and practically eliminating the fake $\tau$-jet events. We show with the help of Monte Carlo simulations that this cut can be effectively used for (1) Charged Higgs boson and (2) SUSY searches at LHC. (1) The most important channel for the $H^\pm$ signal at LHC contains a $P_T = +1$ $\tau$-jet from $H^\pm \rightarrow \tau \nu$ decay. The above polarization cut can effectively suppress the $P_T = -1$ $\tau$-jet background from $W$ decay, while retaining most of the detectable signal ($P_T = +1$) $\tau$-jet events. So it can be used to extract the $H^\pm$ signal at LHC. (2) Over half of the mSUGRA parameter space the NLSP is the $\tilde{\tau}_1$, which is dominated by the right-handed component, while the
LSP($\chi$) is dominantly bino. In this region a large part of the SUSY cascade decay is predicted to proceed via $\tilde{\tau}_1 \rightarrow \tau \chi$, giving a $P_{\tau} = +1$ $\tau$-jet along with the canonical $E_T + \text{jets}$. One can use the above polarization cut to extract this SUSY signal. A very important part of this region is the co-annihilation region, corresponding to $m_{\tilde{\tau}_1} \approx m_\chi$. So the $P_{\tau} = +1$ $\tau$-jet signal is expected to be soft in this region. However, one can use this polarization cut to extract this signal from the $P_{\tau} = -1$ $\tau$-jet and fake $\tau$-jet backgrounds, and also to measure the small mass difference between the co-annihilating superparticles.

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