Is polarization effect visible in leptonic SUSY searches?

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On-shell effective theory approach has been widely used in search of various supersymmetric signals, in particular, gluino/squark pairs with long cascade decay chains in which complete matrix element calculations may encounter over-20 dimensional integrations. On the other hand, leptons from polarized chargino decays may show significant boost or anti-boost effect in some scenarios and simulation without polarization information may underestimate or overestimate the lepton $p_T$ cut efficiencies in the first place. We study the polarization effects in supersymmetry searches of multi-jets plus leptons final states. We find it justifiable for first two generations to only use on-shell effective theories. While for measurements related to third generation squarks, for instance, polarization effect of charginos from stop may reduce the lepton $p_T$ cut efficiencies in cross section measurements by 25% when slepton contributions dominate in chargino decay or $W$ are on-shell. The signal is then underestimated if only on-shell effective theory approach is taken in simulation of signal and the real bound on squark/gluino should be more stringent.
With two years’ running, Large Hadron Collider (LHC) at CERN has accumulated data of 30 fb\(^{-1}\) integrated luminosity. In the early stage, most of the discoveries are kinematics dominated. On-shell effective theories (OSET) which characterize hadron collider data in terms of masses, production cross sections, and decay modes of candidate new particles plays important role in new physics searches \[1\]. In principle, if there exists the precision predictions of production cross section and decay mode for given mass of candidate new particle, one can also obtain information on its spin. However, direct confirmation of spin state measurement only comes from measurement of angular correlation. With only about 28 fb\(^{-1}\), a Higgs boson has been discovered with over 7-\(\sigma\) significance via measurement of invariant masses for four-lepton final states. Both ATLAS and CMS collaborations have found a resonance of four-lepton with invariant mass of 125 GeV and the reconstructed di-photon invariant mass also peaks at the same place. The di-photon final state has excluded the boson to be spin-one state based on argument from Landau-Yang theorem. The further analysis of spin/parity measurement of the boson based on data on the angular correlation in four-lepton channel is very compatible with the scalar boson expectations of 0\(^{+}\). The data disfavors the 2\(^{+}\) hypothesis with a Confidence Levels value of 0.6\% \[2\]. Whether the boson is the standard model (SM) Higgs then requires additional measurements of its Yukawa couplings to the SM fermions.

On the other hand, the transverse momentum distribution \(d\sigma/dp_T\) is not only a result of mass spectrum but also dependent on polarization of spin-1 or spin-1/2 particles, while the measurement of cross section significantly depend on the simulated cut efficiency. Consequently, polarization effect may in principle come in for the very early stage measurement of cross section. A full matrix element simulation automatically contains all spin and polarization information. However, in many cases, searches may involve multi-body final states which correspond multi-body phase-space integration. A \(n\)-body phase space is \(3n - 4\) dimensional integration with the additional two dimensions over the two initial parton distributions so \(3n - 2\) dimensional integration is then required. High dimensional integration is technically extremely challenging. Therefore, simulation based on kinematic decay is sometimes inevitable. For instance, Gluino cascade decay into lepton final state

\[
\tilde{g} \rightarrow jj\chi^{\pm}_{1} \rightarrow jj\ell^{\pm} \nu_{\ell} \chi^{0}_{1} (1)
\]

involves 5 body final states in one chain. Gluino pair production with di-lepton final states then
corresponds to 10 body and the total integration is 28 dimensional integration [3]. The di-lepton plus jets arising from squark pair or gluino-squark production then corresponds to 8 or 9 body final states and 22 or 25 dimensional integration. The simulation of these final states are typically done by only kinematics in Pythia. In this paper, we study how polarization effect changes the measurement of production cross section in particular. We compare the lepton $p_T$ cut efficiency between study involving polarization and study with pure kinematic decays in different scenarios.

In the next section, we discuss two examples where polarization play important role in measurements. Then we discuss the chargino polarization in squark/gluino decay and its leptonic decay distribution in different scenarios, for instance, light sleptons, off-shell $W$ or on-shell $W$. We then gives the numeric results of comparison before we conclude.

II. POLARIZATION EFFECTS

Polarization effect has been widely studied in LEP era. We use two examples to illustrate the polarization effects used in collider physics.

In one-prong decay of $\tau$ lepton $\tau^- \rightarrow \pi^- \nu_\tau$, the nearly massless $\nu_\tau$ is of left-handed helicity and pion $\pi^-$ is a pseudo-scalar state. In the left-handed $\tau^-_L$ rest frame, neutrino $\nu_\tau$ is moving in the direction of $\tau^-_L$ boosted direction and pion is boosted in the opposite direction of $\tau^-_L$ moving direction. While for right-handed $\tau^-_R$, the pion $\pi^-$ is boosted in the $\tau^-_R$ moving direction. Therefore, left-handed or right-handed $\tau$ can be clearly distinguished via the $p_T$ measurement of pions [4].

This feature can be applied to search of new charged Higgs state $H^\pm$ since $\tau^\pm$ from $H^\pm$ decay and the leading irreducible background of $W^\pm$ decay are in different helicity states. A simple $p_T$ cut in charged pion of $\tau$-tag can significantly reduce the SM background from $W^\pm$ decay.

A second and more similar example is the measurement of $W$-polarization in top quark decay $t \rightarrow bW^+$ which plays role as test of the Higgs mechanism in SM [5]. In so-called “Higgs” mechanism, the Goldstone degree of freedom becomes the longitudinal polarization of $W$ boson, $\epsilon^0$. Since top quark is the heaviest particle which acquire mass through electroweak symmetry breaking (EWSB), top quark couples to the Goldstone boson strongly which results in $m_t/m_W$ enhancement in $\epsilon^0 \bar{u}_b P_L \gamma^\mu u_t \propto m_t/m_W$. The $W$ bosons from top quark decay can be produced longitudinal, left-handed and right-handed, with the helicity fractions $F_0$, $F_L$ and $F_R$ respectively. Due to $m_t/m_W$ enhancement, one has $F_0 = \frac{(m_t/m_W)^2}{(m_t/m_W)^2+2} = 70\%$, $F_L = \frac{2}{(m_t/m_W)^2+2} = 30\%$ and $F_R = 0$ in the limit $m_b = 0$. Theoretically, the precision predictions of helicity fractions are ob-
tained by next-to-next-to-leading order (NNLO) pQCD calculations. Given the full reconstruction of semi-leptonic $t\bar{t}$ system, polarizations can be measured by measuring the angle between the lepton and $W$ in the $W$-rest frame. In left-handed polarized $W^+ W^+ \rightarrow (e^+)_{R}(\nu_e)_{L}$, the lepton is boosted in the opposite moving direction of $W^+$ with

$$|\mathcal{M}(W^+_L \rightarrow e^+\nu_e)|^2 \propto (1 - \cos \theta)^2$$

(2)

where $\cos \theta$ is defined as the angle between electron and the opposite direction of $b$-jet in the $W$-rest frame. The measured lepton momentum in the lab frame are then softer than the ones in $W$ rest frame and softer leptons may not pass the lepton $p_T$ cut. Therefore, the portion of $F_L$ measurement also depends on the lepton $p_T$ cut. Figure 1 shows the $d\Gamma/d\cos \theta$ distribution in SM semi-leptonic $t\bar{t}$ with different $p_T$ selection cuts as labelled in plot from $p_T: 20 - 40$ GeV.

![Graph showing dΓ/dcos θ distribution](image)

**FIG. 1.** $d\Gamma/d\cos \theta$ distribution in SM semi-leptonic $t\bar{t}$ with different $p_T$ selection cuts as labelled in plot.

### III. POLARIZED CHARGINO

In this section, we focus on the multi-body final states with leptons due to gluino or squark cascade decays. Similar to $Z$ decay, Leptonic decay branching ratio (BR) of heavy neutralino $\tilde{\chi}^0_2$ is typically much smaller than its of $\tilde{\chi}^+_1$. In addition, BR of $\tilde{\chi}^0_2$ final state in squark decay is also smaller than squark decay BR into charginos $\tilde{\chi}^+_1$. Therefore, leptons largely arise from chargino
decay $\tilde{\chi}_i^\pm \to \ell^\pm \nu \tilde{\chi}_1^0$ and in this paper, we focus on studying the effect of $\tilde{\chi}_i^\pm \to \ell^\pm \nu \tilde{\chi}_1^0$ of polarized $\tilde{\chi}_i^\pm$.

Chargino states are mixture of both Wino and Higgsino which is determined by $M_2$ and $\mu$ in the mixing matrix. We first discuss Wino chargino for general squark decay. Decay BR into Higgsino of squark is only significant for third generations and we discuss later as a special case. Wino is a super-partner of $SU(2)_L$ weak gauge boson $W$ and the squark-quark-wino vertex

$$\mathcal{L} = [-g V_{11} \tilde{u}_L] \bar{d}_R \tilde{\chi}_1^{+c}$$

(3)

corresponds to weak interaction where only left-handed quark or right-handed anti-quark participates the interaction. As shown in Fig. 2 left-handed up-type scalar quark $\tilde{u}_L$ decay into left-handed $b$-quark, which results in $\tilde{\chi}_1^+$ to be only left-handed. Since the scalar propagator does not carry any spin information, the two fermion lines between the scalar mediator have no correlation which does not depend on whether the scalar is on-shell or off-shell. If squarks are heavier than gluino, gluino three body decay

$$\tilde{g} \to \bar{u}d\tilde{\chi}_1^+, \quad (4)$$

the polarization is identical to the case when squarks are on-shell and hence, the discussion on chargino polarization stays the same for off-shell squarks. When the chargino is Wino, for all squarks and anti-squarks, one can write down the similar relations as

$$\tilde{u}_L \to d_L(\tilde{\chi}_1^+)_L, \quad \tilde{u}_L^* \to (\bar{d})_R(\tilde{\chi}_1^-)_R, \quad \tilde{d}_L \to u_L(\tilde{\chi}_1^-)_L, \quad \tilde{d}_L^* \to (\bar{u})_R(\tilde{\chi}_1^+)_R. \quad (5)$$

On the other hand, for first two generations, scalar quarks decay into light quark states which hadronize immediately at $1/\Lambda_{QCD} \sim 10^{-24}$ s. It is impossible to distinguish whether the light quark jet is from up-type or down-type quarks. The identical final states then leads to simultaneous
measurements of first two generation scalar quarks. However, decay final state of stop is clearly identifiable \[6\].

\[
\tilde{t}_L \rightarrow b_L(\tilde{\chi}_1^+) L, \quad \tilde{t}_L^* \rightarrow (\bar{b})_R(\tilde{\chi}_1^-)_R
\]  (6)

The argument then applies to the stop search. When top A-term \(A_t\) is large which is preferred by MSSM parameter space for \(m_h = 125\) GeV, stops are a mixture of left-handed and right-handed stop states. The stop \(\tilde{t}_1, \tilde{t}_2\) can then decay into

\[
\tilde{t}_i \rightarrow t\tilde{\chi}_1^0, b\tilde{\chi}_1^+
\]  (7)

where \(b\tilde{\chi}_1^+\) final state only comes from left-handed stop state \(\tilde{t}_L\). When \(\tilde{t}_i\) has significant \(\tilde{t}_L\) portion, for instance 50%, \(b\tilde{\chi}_1^+\) will usually take 70% of \(\tilde{t}_i\) decay. When \(t\) is not on-shell where mass difference \(M_{\tilde{t}_i} - M_{\tilde{\chi}_1^0} < m_t\), the multi-body phase space will further suppress the decay of \(\tilde{t}_i \rightarrow t^*\tilde{\chi}_1^0\). However, in this degenerate spectrum limit, the boost of chargino is small and the polarization effect is then limited.

Direct search of Chargino via tri-lepton channels at LHC \[7\] has pushed the chargino mass to be over 350 GeV when \(\tilde{\chi}_1^0\) is massless but the bound is certainly weaker when the mass difference between chargino and lightest neutralino is smaller. We use two un-excluded benchmark points to illustrate the feature. One benchmark is the light chargino with nearly degenerate spectrum where \(M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0} \simeq 50\) GeV with \(M_{\tilde{\chi}_1^+} \simeq 250\) GeV. The second benchmark is \(M_{\tilde{\chi}_1^+} \simeq 285\) GeV and the same Bino mass as the first one so that \(M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0} > m_W\) and \(W\) is on-shell.

For the first benchmark point of chargino three body decay

\[
\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + e^+ + \nu_e,
\]  (8)

can be realized by three processes shown in Fig.3 with slepton mediation and Fig.5 of W mediation.

**FIG. 3.** \(\tilde{\chi}_1^+ \rightarrow e^+ \nu_e \tilde{\chi}_1^0\) via sleptons
In sneutrino mediation as in Fig 3-a, sneutrino propagator does not carry any spin so the spin direction of positron is identical to the initial chargino spin. Only right-handed positron participates in weak interaction and therefore, positron moves in the opposite direction of the initial chargino as shown in Fig 4.

![Diagram](image)

FIG. 4. Spin correlation in left-handed $\tilde{\chi}^+_1$ decay into sneutrino $\tilde{\nu}$.

In selectron mediation as in Fig 3-b, electron decay from spin-zero selectron does not correlate with the initial polarization of chargino in both on-shell and off-shell selectron case. The electron is therefore completely universal distributed in space.

For $W$-mediation, the situation then depends on whether $W$ is on-shell or off-shell. For the first benchmark point, $W$ is off-shell. It is known that there exist four polarizations in the off-shell $W$ case including additional scalar contribution. However, in the nearly massless final state in the leptonic decay case, scalar contribution and the scalar-longitudinal interference contribution becomes negligible [8].

The contributions also destructively interfere with each other. Figure 6 shows the angle $\theta$ between the positron and chargino in the reconstructed chargino rest frame for three choices of slepton masses. For simplicity, we assume $M_{\tilde{\ell}} = M_\ell$ with negligible lepton $A$-terms. $M_2$ is fixed at 250 GeV while $M_1$ is taken to be 200 GeV. For $M_{\tilde{\ell}} = 250$ and 500 GeV, the sneutrino and selectron contributions are both significant. Since Bino is SM singlet, $W$ contribution is only realized through Wino-Bino mixing which is small. Therefore, we find the slepton contribution does not decouple even when $M_{\tilde{\ell}} = 1.5$ TeV.
FIG. 6. Normalized distribution $1/\Gamma d\Gamma/d\cos\theta$ where $\theta$ is the angle between charged lepton and chargino moving direction in reconstructed $\chi_1^+$ frame for $\Delta M = 50$ GeV with different slepton masses $M_{\tilde{\ell}}$.

When $W$ is on-shell for the second benchmark point, the two-body decay contribution completely takes over and we plot the $\cos\theta$ for on-shell $W$ case in Fig. 7. The positron is always moving in the opposite direction of the left-handed polarized chargino.

Higgsino couples to squarks via Yukawa couplings and hence squarks of first two generations mostly decay into wino states. The third generation squarks, stop or sbottom of relatively large
\[ \tan \beta, \text{ can dominantly decay into Higgsino states. Equation 9 gives the interaction between stop and charginos} \]
\[
L_{b\tilde{t}\tilde{\chi}^\pm} = [-g V_{i1} \tilde{t}_L + y_t V_{i2} \tilde{t}_R] (\tilde{b} P_R \tilde{\nu}) + y_b U_{i2} \tilde{t}_L (\tilde{b} P_L \tilde{\chi}^{+c}) ,
\]
where \( U_{ij} \) and \( V_{ij} \) are standard chargino mixing matrices. If \( \tilde{\chi}_1^\pm \) is dominated by Higgsino component and \( y_t \) is much larger then \( y_b \), \( \tilde{\chi}_1^\pm \) polarization in the decay is identical to the case of wino \( \tilde{\chi}_1^\pm \). Only \( \tan \beta \sim 30 \) or greater, bottom Yukawa \( y_b \) is then close to \( y_t \) and \( \tilde{\chi}_1^\pm \) polarization then has both significantly left-handed and right-handed portions. However, supersymmetric scenario with large \( \tan \beta \) is severely constrained by rare decay process like \( B_s \to \mu^+ \mu^- \). For small \( \tan \beta \) cases, Higgsino behavior is then similar to the Wino. On the other hand, since the electron/muon Yukawa couplings are negligible Higgsino decay into lepton is only an effect of on-shell or off-shell \( W \) which has been discussed in the last part of Wino case.

**IV. LEPTON IN CASCADE DECAY CHAIN**

As discussed in previous section, polarization of chargino can be distinguished in third generations squarks decays since the up-type and down-type squarks have different and identifiable final states. Chargino from sbottom decay is associated with top quark which complicates the studies of final states. Therefore, in this section, we focus on chargino from stop decay to illustrate the polarization feature. In this case, only left-handed \( \tilde{\chi}_1^\pm \) can arise from the stop decay
\[
\tilde{t}_i \to b_L (\tilde{\chi}_1^\pm)_L ,
\]
where left-handed polarized chargino decaying into lepton final states may show significant anti-boost effect. Consequently, it may make the leptons softer in the lab frame than the ones in chargino rest frame. Since it’s a boosted effect, the effect is visible only when chargino has significant kinematic boost. If the chargino is produced nearly at rest which corresponds to the scenario with small mass difference between chargino and stop/gluino, the effect is then tiny. On the other hand, if the mass difference between chargino and stop/gluino is too large, the chargino is highly boosted in the system and lepton momentum in the lower end are then completely dominated by the boost effect. Since we are only looked at the consequence of lepton \( p_T \) cut which only affects softer leptons, the effect is only significant in some intermediate mass range.

Figure 8 shows the lepton \( p_T \) distribution of chargino decay \( \tilde{\chi}_1^\pm \to b \nu \tilde{\chi}_1^0 \) in comparison of full matrix element method vs. kinematic method for \( M_{\tilde{t}} = 1.3 \) TeV and \( M_{\tilde{\chi}_1^\pm} = 150 \) GeV. Blue line
FIG. 8. Lepton $p_T$ distribution of chargino decay $\tilde{\chi}_1^\pm \to \ell^\pm \nu \tilde{\chi}_1^0$ in comparison of full matrix element method vs. kinematic method. Blue line is the full matrix element result from MadEvent while the red line is the kinematic decay from Pythia.

is the full matrix element result from MadEvent\[9\] while the red line is the kinematic decay from Pythia\[10\] which shows the full matrix element result is significant softer than the result from kinematic decay.

The lepton $p_T$ cut survival probabilities for two benchmark points with the same chargino mass $M_{\tilde{\chi}_1^\pm} = \text{GeV}$ but $M_t = 1.3$ and 1.5 TeV are listed for different $p_T$ cut respectively in Table [IV]. The reduction of efficiencies is about 25% for both cases in Table [IV]. Therefore, if one only use

| $M_t$ | Category | $p_T > 20$ GeV | $p_T > 25$ GeV | $p_T > 30$ GeV |
|-------|----------|----------------|----------------|----------------|
| 1.3 TeV | Polarized | 52% | 46% | 40% |
|       | Kinematic | 64% | 59% | 54% |
| 1.5 TeV | Polarized | 54% | 48% | 44% |
|       | Kinematic | 65% | 61% | 57% |

TABLE I. Lepton $p_T$ cut survival probability for benchmark points $M_t = 1.3$ and 1.5 TeV. Category named polarized is for situation with polarization taken into account while Kinematic stands for the kinematic decay only cases.
on-shell effective field theory approach for this search, the signal is actually under-estimated.

V. CONCLUSIONS

We study the polarization effects in supersymmetry searches of multi-jets plus leptons final states. We find it justifiable for first two generations to only use on-shell effective theories. While for measurements related to third generation squarks, for instance, polarization effect of charginos from stop may reduce the lepton $p_T$ cut efficiencies in cross section measurements by 25% when slepton contributions dominate in chargino decay or $W$ are on-shell. The signal is then underestimated if only on-shell effective theory approach is taken in simulation of signal and the real bound on squark/gluino should be more stringent.

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