Mesino – Antimesino Oscillations

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The phenomenological implications of supersymmetric theories with low scale supersymmetry breaking and a squark as the lightest standard model superpartner are investigated. Such squarks hadronize with light quarks, forming sbaryons and mesinos before decaying. Production of these supersymmetric bound states at a high energy collider can lead to displaced displaced jets with large negative impact parameter. Neutral mesino–antimesino oscillations are not forbidden and could provide a very sensitive probe of sflavor violation in the squark sector, and can provide a discovery channel for supersymmetry through events with a same-sign top-top topology.

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Supersymmetry (SUSY) allows the standard model to be embedded in more fundamental theories characterized by much higher energy scales, such as the Grand Unified or Planck scales, by stabilizing the electroweak scale against quadratic radiative corrections. In order to maintain this stability, the supersymmetry breaking masses for the superpartners of the ordinary particles should be of order the electroweak scale. However, the underlying mechanism and scale of this spontaneous breaking, as well as the superpartner spectrum, remain at present largely unknown.

If the intrinsic scale of spontaneous supersymmetry breaking is below a scale intermediate between the electroweak and Planck scales, the lightest supersymmetric particle (LSP) is the gravitino superpartner of the graviton. The identity of the next-to-lightest supersymmetric particle (NLSP) is model-dependent, and largely determines the phenomenological signatures for supersymmetry.

In this letter the consequences of a squark NLSP are explored. While perhaps unconventional, a squark NLSP can occur in theories of gauge-mediated supersymmetry breaking in which the strongly interacting messenger fields have suppressed couplings to spontaneous supersymmetry breaking. Beyond the theoretical motivation, this scenario leads to very novel phenomenological predictions. Squarks hadronize in sbaryon or mesino bound states. Decay of these states can give rise to displaced jets with angular distributions which differ significantly from displaced jets from heavy quark decay. In addition, neutral mesino–antimesino oscillations are not forbidden and could provide a very sensitive probe of sflavor violation in the squark sector. Rather than representing a very specialized measurement which could only be attempted once the existence of superpartners is established, mesino–antimesino oscillations can in fact provide a discovery channel for SUSY at high energy colliders.

\textbf{Squark Decay and Hadronization.}— With low scale supersymmetry breaking and conserved R-parity, the NLSP is metastable. The only available coupling for decay is through the Goldstino components, $\tilde{G}$, of the gravitino. The two-body decay rate for an up-type squark NLSP, $\tilde{Q} \rightarrow q \tilde{G}$, including general (s)flavor misalignment between the quark and squark mass eigenstates, is given by

$$\Gamma(\tilde{Q}_a \rightarrow q_b \tilde{G}) = \frac{m_{\tilde{Q}_a}^5}{16\pi F^2} c_{(N)}^2 \left( 1 - \frac{m_q^2}{m_{\tilde{q}}^2} \right)^4$$

where $F$ is the supersymmetry breaking scale, and $c_{(N)}^2 = c_{(L)}^2 + c_{(R)}^2 = |U_{Li}U_{Li}^\dagger|_a^2 + |U_{Ri}U_{Ri}^\dagger|_a^2$. The left- and right-handed up-type squark flavor-mass eigenstates are related to the gauge eigenstates by $q_{Li} = U_{Li}q^\dagger_{Lj}$ and $q_{Ri} = U_{Ri}q^\dagger_{Lj}$ where $i,j = 1,2,3$, and the up-type squark mass eigenstates are related to flavor eigenstates by $Q_a = \tilde{U}_{La}\tilde{Q}_{La} + \tilde{U}_{Ra}\tilde{Q}_{Ra}$ where $a = 1,\ldots,6$, and likewise for the down-type (s)quarks.

The lightest squark is likely to be mostly stop-like because of left-right stop level repulsion, and negative renormalization group evolution contribution to the mass, both proportional to the top Yukawa. For a stop-like squark lighter than the top quark, the only kinematically allowed two-body decays are through flavor violating suppressed modes to light quarks, such as $t \rightarrow c \tilde{G}$. Three body decay through a charged current interaction, $t \rightarrow b \tilde{W} \tilde{G}$, is not suppressed by flavor violation, but is phase space suppressed. The three-body decay rate in the limit in which the charginos and all squarks expect the NLSP are heavy is given by

$$\Gamma(\tilde{Q}_a \rightarrow q_b W^\pm \tilde{G}) = \frac{\alpha_2 m_{\tilde{Q}_a}^5}{128\pi F^2} \left[ \sum_j \epsilon_{(L)}^{(q_j)} \right]^2 \left[ J \left( \frac{m_W^2}{m_{\tilde{q}}^2}, \frac{m_q^2}{m_{\tilde{q}}^2} \right) \right]$$

where

$$\epsilon_{(L)}^{(q_j)} = (\tilde{U}_L U_L^\dagger)_{aj}(U_L D_L^\dagger)_{ji}$$

and

$$\epsilon_{(R)}^{(q_j)} = (\tilde{U}_R U_R^\dagger)_{aj}(U_L D_L^\dagger)_{ji}$$

and $J = V_{ji}$ is the CKM matrix.
quark mixing matrix. The phase space integrals are

\[ I(a, b) = \int_a^1 dx \left( \frac{(1 - x)^4(x - a)^2}{12x^3a} \right) \left( \frac{6x^3(3a + x)}{(x - b)^2} \right) + \frac{4x^2(4a - x)}{(x - b)} + x^2 + 2xa + 3a^2 \]

\[ J(a, b) = \int_a^1 dx \frac{b(1 - x)^3(x - a)^2(2a + x)}{2x^3a(x - b)^2} \]

For a stop-like squark the three-body mode \( \tilde{t} \to bW\tilde{G} \) dominates if the sflavor violation is very small, while the two-body mode(s) \( \tilde{t} \to q_i\tilde{G} \), \( i = 1, 2 \), dominate for larger sflavor violation. Numerically, for \( m_{\tilde{t}} = 150 \) GeV the three-body decay \( \tilde{t}_R \to bW\tilde{G} \) dominates for \( \epsilon_{(R)3i} \lesssim 4 \times 10^{-3} \). For a stop-like squark much heavier than the top, \( t \to t\tilde{G} \) dominates for \( \epsilon_{(N)3i} \lesssim (1 - m_{\tilde{t}}^2/m_{\tilde{G}}^2)^2 \).

For either the two- or three-body modes, decay of a squark NLSP to the Goldstino can take place over macroscopic distances \[ \left( \frac{L}{\text{GeV}} \right)^{1/3} \] and easily exceeds the hadronization length scale \[ \left( \frac{\text{GeV}}{\Lambda} \right)^{1/2} \]. For example, with \( m_{\tilde{t}} = 150 \) GeV \( \Gamma^{-1}(\tilde{t}_R \to bW\tilde{G}) \approx 75 \) cm \( (\sqrt{8}/100 \text{ TeV})^4 \), while for \( m_{\tilde{t}} = 190 \) GeV \( \Gamma^{-1}(\tilde{t} \to t\tilde{G}) \approx 0.75 \) cm \( (\sqrt{8}/100 \text{ TeV})^4 \).

A NLSP squark therefore always hadronizes before decaying. Hadronization with a light antiquark leads to a neutral or charged mesino bound state, \( \mathcal{M}_{\tilde{Q}\tilde{G}} \equiv (\tilde{Q}\tilde{G}) \), while hadronization with two light quarks leads to a neutral or charged sbaryon bound state \( B_{Qqq} \equiv (QQq) \), and likewise for the antiparticle states.

A long lived mesino or sbaryon might provide an interesting system in which to study heavy (s)quark aspects of QCD. In this work we concentrate on the implications for supersymmetric and sflavor phenomenology.

**Mesino Oscillations.** The mesino bound states are spin \( \frac{1}{2} \) Dirac fermions. A neutral mesino and antimesino differ by two units of (s)flavor, fermion number, \( F \), and \( R \)-charge. All of these quantum numbers are, however, manifestly violated in any supersymmetric theory. (S)quark flavor is violated by Yukawa couplings and squark flavor may also be violated by scalar tri-linear couplings and possibly the scalar mass-squared matrices. Fermion number and \( R \)-symmetry are violated by gaugino masses. So hadronization of squarks into neutral mesino bound states allows for the interesting phenomenon of particle–antiparticle oscillations which is impossible for an isolated charged particle. Operators which violate the above symmetries appear as Majorana mass terms which mix the mesino and antimesino states. Including these effects, mesinos are therefore pseudo-Dirac fermions.

Mesino oscillations are analogous to meson oscillations. At the microscopic level the \( \Delta Q = 0 = \Delta F = \Delta R = 2 \) amplitudes which mix mesino and antimesino arise from tree-level gluino and neutralino exchange as illustrated in Fig. 1(a) for \( \mathcal{M}_{\tilde{q}_a\tilde{u}_i} \leftrightarrow \overline{\mathcal{M}}_{\tilde{g}^2\tilde{u}_a} \). The tree level gluino contribution to the oscillation amplitude for a single linear combination of the Weyl components of the light quark in the color singlet channel is

\[ A_g(\tilde{Q}_a\tilde{q}_i \to \tilde{Q}_a^*\tilde{q}_i) = \epsilon_{(N)ai}^2 \left( 1 - \frac{1}{N_f} \right) \frac{g_s^2 m_{\tilde{g}}^2}{m_{\tilde{g}}^2 - m_{Q_a}^2} \]

where \( \epsilon_{(N)ai} \) is the same flavor matrix which appears in the two-body decay \( \tilde{q}_i \), and \( N_f = 3 \) is the number of colors. Neutralino contributions are comparable depending on the precise spectrum.

![Fig. 1. Mesino oscillations arise (a) from tree-level gaugino exchange and (b) from one-loop charged current–chargino box diagrams. Arrows indicate the flow of fermion number and crosses represent fermion number violating gaugino mass insertions. (S)flavor violation may be isolated in the gaugino and gauge interactions. Diagrams for other neutralinos and charginos and those related by crossing are not shown.](image)
but are GIM suppressed by $O(m_\tilde{g}^2/m_Q^2)$ and numerically unimportant for oscillations which could be observed in flight.

The mesino–antimesino oscillation frequency is related to the short distance amplitudes given above by

$$\omega = \Delta m_{\tilde{M}N} = \frac{N_c}{2\tilde{m}_Q} |\psi(0)|^2 \left| A(\tilde{Q}_a \bar{\tau}_i \to \tilde{Q}_c^* g_i) \right|$$  \hspace{1cm} (7)

The light (anti)quark wave function at the origin in the (anti)mesino is defined here in terms of the matrix element of the Dirac scalar bilinear, $|\psi(0)|^2 \equiv \langle \bar{q}(r)|\mathcal{M}|q(r)\rangle/\langle \bar{q}|\mathcal{M}|q\rangle V$, where $V$ is the normalization volume. This may be related to the mesino decay constant by $|\psi(0)|^2 = f_M^2 m_\tilde{Q}/(4N_c)$. In the heavy (s)quark limit, this is a purely QCD quantity which may be approximated using the $B$-meson decay constant $f_B \simeq 160$ MeV giving $|\psi(0)|^2 \simeq (220$ MeV$)^2$. Independent of $m_\tilde{Q}$ and $N_c$ in the heavy (s)quark and large $N_c$ limits.

Numerically, the gluino contribution to the $\tilde{M} \leftrightarrow \tilde{M}^* u$ oscillation wavelength is $\beta \gamma \lambda$ where $\lambda \equiv 2\pi/\omega$ is

$$\lambda \simeq (4 \text{ nm}) \left(\frac{m_{\tilde{g}}}{250 \text{ GeV}}\right)^2 y (1 - y^2) \epsilon_{(N)13}^2$$  \hspace{1cm} (8)

where $y = m_\tilde{g}/m_\tilde{q}$ and by assumption $y < 1$ so $0 < y(1 - y^2) < \sqrt{2}/3 \simeq 0.38$. Oscillations on the scale of a detector could occur for $\epsilon_{(N)13}$ as small as $5 \times 10^{-2}$. Up-type sflavor violation involving the third generation is essentially unconstrained by present data, so extremely rapid oscillations compared with the decay length and scale of a detector are conceivable.

The time-integrated probability for a mesino to decay as an antimesino depends on the oscillation frequency and decay rate

$$\mathcal{P} = \frac{x^2}{2(1 + \delta^2 + x^2)}$$  \hspace{1cm} (9)

where $x = \Delta m_{\tilde{M}N}/\Gamma$, and $\delta = (m_{\tilde{M}} - m_{\tilde{N}})/\Gamma$ allows for a possible diagonal flavor-conserving splitting discussed below. Rapid oscillations, $x \gg 1$, yield $\mathcal{P} = \frac{1}{2}$, while for slow oscillations, $x \ll 1$, $\mathcal{P} \to \frac{1}{4}x^2$.

**Experimental Signatures.**—Since a squark NLSP is strongly interacting it is likely to be the most abundantly produced SUSY particle at a hadron collider. The experimental signatures depend on the decay length. For a decay length of order or larger than a meter, non-relativistic squarks which hadronize as charged mesinos and sbaryons appear as highly-ionizing tracks (HITs) in a tracking chamber. Using the stop production cross section \[4\] and preliminary results of a CDF search for HITs in Run I at the Tevatron \[5\] we estimate a current bound on the mass of long lived stops of roughly 150 GeV.

Mesino or sbaryon decay lengths shorter than roughly a meter can lead to observably displaced jets with both large transverse energy ($E_T$) and large missing transverse energy ($E_T^\text{miss}$). For sufficiently long squark decay lengths, these may be distinguished from analogous heavy quark decays by large beam axis impact parameters. In addition, since the massive mesinos and sbaryons are non-relativistic, the decay products are not significantly boosted in the lab frame and are therefore roughly uniformly distributed in $\cos \varphi$, where $\varphi$ is the angle between the reconstructed momentum vector of the displaced jet and the unit normal between the beam axis and the origin of the displaced jet. In contrast, the distribution of high $E_T$ displaced jets from direct heavy quark production and decay is peaked near $\cos \varphi \sim 1$ since the visible decay products are boosted in a direction away from the production vertex. Mesino or sbaryon decay may therefore be distinguished by high $E_T$ jets with large $E_T^\text{miss}$ and with large negative impact parameters (LNIPs), $\cos \varphi \lesssim 0$. These observables result if the visible decay products recoil against the invisible Goldstino in a direction towards, rather than away from the production vertex. LNIPs provide an efficient means to search for exotic massive metastable particles which decay to hadronic final states \[6\].

Neutral mesino–antimesino oscillations present the possibility of another novel experimental signature, even for decay lengths which are too short to be resolved in real space. Oscillations may be revealed in any decay mode which tags the sign of the (anti)squark in a neutral (anti)mesino. Squark–antisquark production events in combination with mesino–antimesino oscillation can then lead to same-sign events. For example, the antitquark may hadronize as a neutral antimesino which oscillates to a mesino before decaying, while the squark hadronizes as a charged mesino or sbaryon which can not oscillate. Summing over all possibilities, the time-integrated ratio of same- to- opposite-sign events is

$$R = N_{++} + N_{--} = \frac{2Pf_0(1 - Pf_0)}{1 - 2Pf_0 + 2P^2f_0^2} \simeq 2Pf_0 + 2P^2f_0^2$$  \hspace{1cm} (10)

where $P \equiv \mathcal{P} = \mathcal{P}(M \to \bar{M})$, and $f_0$ is the neutral mesino hadronization fraction (the strange quark finite mass implies $\frac{1}{4} \lesssim f_0 \lesssim \frac{1}{2}$ for up-type squarks). Thus, for $x \gtrsim 1$ a significant fraction of squark–antisquark events will yield same-sign events.

The feasibility of determining the sign of an (anti)quark at decay depends on the decay products. For stop-like squark decays $t \to bW\tilde{G}$ or $t \to t\tilde{G}$ with $t \to bW$, the $W$-bosons reliably tag the sign of the (anti)squark. The $W$-bosons signs may in turn be determined with the leptonic decay mode $W \to \ell\nu$ where $\ell = e, \mu$. This requires isolating these primary leptons from any secondary leptons arising from $b$-quark decay. Such distinctive, essentially background free events have the topology of same-sign top-top events, and provide
a possible discovery mode for SUSY. The largest background is probably from top-antitop production with the very small probability of misidentification of the primary leptons or mismeasurement of the charges. At the Fermilab Tevatron Run IIa with 2 fb\(^{-1}\) of integrated luminosity, a 175 GeV stop squark with dominant decay \(\tilde{t} \to bW^+\) and oscillation parameter \(x \sim 1\) would yield \(\sim 10\) same-sign dilepton top-top events, while \(x \gg 1\) would yield \(\sim 20\) events. A detection acceptance times efficiency \(\geq 30\%\) should give a detectable signal for these parameters.

Observation of stop mesino oscillations requires, and very sensitively probes, up-type squark sflavor violation. For example, for a stop decay length \(\Gamma^{-1} \sim 10\) cm, maximal \(M_{f\bar{u}} \sim \overline{\nu}_{f\bar{u}}\) mixing, \(x \geq 1\), occurs for all \(\epsilon_{(N)13} \gtrsim 5 \times 10^{-5}\). Even for \(\Gamma^{-1} \sim 2 \mu m\) (which could not be resolved as a displaced vertex), maximal mixing occurs for any \(\epsilon_{(N)13} \gtrsim 10^{-2}\). The magnitude of squark sflavor violation depends on the scale at which (s)quark flavor is broken. If the flavor scale is not too much larger than the messenger scale for transmitting supersymmetry breaking, interesting levels of sflavor mixing are expected, and observable mesino oscillations can occur.

The flavor violating two-body decay \(\tilde{t} \to cG\) can dominate if sflavor violation is large enough, as discussed above. This mode also dominates if the NLSP squark is scharm-like, \(\tilde{c} \to cG\). Semi-leptonic decay of the c-quarks hadronized in \(D^{0,\pm}\) mesons could then be used to tag same-sign events in high \(E_T\) charm-jets with large \(E_T\). \(D^0 \leftrightarrow \overline{D}^0\) oscillation is negligible and would not contaminate a mesino oscillation signal at the discovery level in a relatively clean sample of LNIPs. However, squark decays in this mode with a decay length that is too short to resolve using LNIPs would be contaminated by standard model production of \(b\)-jets which are not easily distinguished from charm-jets. This standard model background could be significant since \(B^0 \leftrightarrow \overline{B}^0\) oscillations are non-negligible. Self-tagging of the heavy flavor at production to determine its sign \([1]\), or measuring total jet charge after decay to isolate \(D^\pm\) mesons which do not oscillate could reduce this background, but requires large statistics, and is probably not applicable at the discovery level.

Observing oscillations for a squark NLSP which decays to other flavors is more problematic. For a sbottom-like squark which decays by \(\tilde{b} \to bG\), the \(B^0\)-meson backgrounds discussed above are important. Decays to lighter quarks, \(\tilde{Q} \to (u,d,s)G\), are difficult to sign using self tagging. So a stop-like NLSP squark provides the best opportunity to observe mesino oscillations.

Charge conjugate non-invariant environmental effects give rise to flavor conserving diagonal mesino–antimesino splitting, indicated by \(\delta \neq 0\) in \([2]\), and could potentially suppress oscillations. The mesino spin couples to the ambient magnetic field, \(B\), and induces a diagonal splitting. Using the chiral quark value for the mesino magnetic moment, \(\mu_M \simeq \frac{2}{3} \mu_p\), gives \(\delta \Lambda \equiv (2\pi/\omega)(x/\delta) \simeq 10.5 \text{~fm}/B/\text{T}\). Forward scattering off nuclei in matter through operators of the form \((4\pi/\Lambda^2)^2 \overline{\nu}_M \gamma_\mu \gamma_\nu N\) where \(\Lambda \sim 1.1\text{~GeV}\) is the chiral symmetry breaking scale, give \(\delta \Lambda \simeq 1.2\text{~fm}/[\rho/(\text{gm cm}^{-3})]\). So for oscillations which could be observed in flight through the (low density) tracking region of a detector, these effects do not dominate, \(\delta \Lambda \gtrsim 0\) or \(\delta/x \lesssim 1\) \([2]\).

Conclusions. – A squark NLSP can give rise to novel experimental signatures including HITs or LNIPs. The possibility of mesino–antimesino oscillations provides a discovery channel for SUSY through same-sign dilepton events in association with high \(E_T\) heavy flavor jets and large \(E_T\). Oscillations are most easily observed for a stop-like squark in same-sign top-top events, or same sign charm-jets in a sample of LNIPs. Mesino oscillations would provide a very sensitive probe of sflavor violation. If the mesino decay length is macroscopic and the oscillation length is fortuitously of the same order, \(x \sim 1\), mesino oscillations could be observed in real space in the signed decay length distributions.

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