Phenomenology of “inos” in the Light Gaugino Scenario, and Possible Evidence for a $\sim 53$ GeV Chargino

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Abstract: The tree-level-massless gaugino scenario predicts that the lighter chargino mass is less than $m_W$ and that gluino and lightest neutralino masses are $\lesssim 1$ GeV. In this case the dominant decay mode of charginos and non-LSP neutralinos is generically to three jets. The excess of ”4j” events with total invariant mass $\sim 105$ GeV observed in LEP running at 130-136 GeV is noted to be consistent with pair production of $\sim 53$ GeV charginos. Data at 161 and 172 GeV from Fall, 1996, cannot conclusively test this hypothesis (because cuts to eliminate $W^+W^-$ background reduce the efficiency significantly) but is suggestive that the signal persists.

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Some supersymmetry (SUSY) breaking scenarios produce negligible tree-level gaugino masses and scalar trilinear couplings \((M_1 = M_2 = M_3 = A = 0)\). This has several attractive theoretical consequences such as the absence of the “SUSY CP problem” and avoidance of certain cosmological problems\(^1\). Although massless at tree level, gauginos get calculable masses through radiative corrections from electroweak (gaugino/higgsino-Higgs/gauge boson) and top-stop loops. Evaluating these within the constrained parameter space leads to a gluino mass range \(m_{\tilde{g}} \sim \frac{1}{10} - \frac{1}{2}\) GeV and photino mass range \(m_{\tilde{\gamma}} \sim \frac{1}{10} - 1\frac{1}{2}\) GeV\(^1\). The chargino and other neutralino masses are, at tree level, functions only of \(\mu\) and \(\tan\beta\). In particular,

\[
2M^2_{\chi^\pm} = \mu^2 + 2m^2_W \pm \sqrt{\mu^4 + 4m^4_W \cos^2 2\beta + 4m^2_W \mu^2},
\]

so one chargino is lighter, and the other heavier, than \(m_W\). The photino is an attractive dark matter candidate, with a correct abundance for parameters in the predicted ranges\(^2\).

Due to the non-negligible mass of the photino compared to the lightest gluino-containing hadron, prompt photinos\(^3\) are not a useful signature for the light gluinos and the energy they carry\(^4\). Gluino masses less than about \(1\frac{1}{2}\) GeV are largely unconstrained\(^5\). \([The recent claims\(^6\) that LEP \(Z^0 \rightarrow 4j\) data can be used to exclude light gluinos are premature. The statistical power of the data is indeed sufficient, however the relevant angular distributions are sensitive to jet definition and higher order effects such as 5-jet production, so systematic uncertainties dominate and no conclusions can be drawn until such effects can be controlled\(^6\).] The lifetime of the gluon-gluino bound state \((R^0)\) is predicted to be \(10^{-5} - 10^{-10}\) sec\(^1\). Proposals for direct searches for hadrons containing gluinos, via their decays in \(K^0\) beams and otherwise, are given in Ref. \([7, 8]\).

For the purposes of detecting squarks and charginos, the crucial phenomenological difference arising when the gluino is light rather than heavy

\(^2\)C.f., J. W. Gary, CTEQ Workshop on QCD, FNAL, Nov. 1996.
as is usually assumed, is that the gluino is long-lived. Therefore it makes a jet rather than missing energy\(^4\). Squarks decay to gluino and quark, thus generating two jets with negligible missing energy. QCD background makes it impossible, with present jet resolution, to search at hadron colliders in the dijet channel for masses lower than about 200 GeV; a search for equal-mass dijet pairs as suggested in \(^3\) has not yet been completed. At present, the best squark mass limits come from the hadronic width of the \(Z^0\) and are only \(\sim 50 - 60\) GeV\(^{10, 9}\).

If the gluino is light, the lighter chargino and the three heavier neutralinos will usually decay to \(q\bar{q}'\tilde{g}\), via a virtual or real squark\(^3\) unless all flavors of squarks are much more massive than sneutrinos, sleptons and \(W\)'s. The heavier chargino generally has the kinematically allowed two-body decay \(\chi^\pm_2 \to W^\pm + \tilde{\gamma}\).

Although \(\chi^{\pm}_1 \to q\bar{q}'\tilde{g}\) gives a 3-parton final state, it may be reconstructed as \(2j\), particularly when one jet is much softer than the others. Then, the hadrons of the soft jet have low invariant mass with respect to hadrons of the other jets and the jet finding algorithm can interpret the multijet system as \(2j\). The likelihood of this increases when \(M_{\chi^\pm} - M_{\tilde{q}} \ll M_{\chi^\pm}\), as is illustrated by the cascade chain \(\chi^{\pm} \to \tilde{q} + q' \to \tilde{q} q\), for which \(E(q') \approx M_{\chi^{\pm}} - M_{\tilde{q}}\) and \(E(\tilde{q}) = E(q) = M_{\tilde{q}}/2\), in the \(\chi^{\pm}\) rest frame. Below we will use \(P_6\), \(P_5\), \(P_4\) to denote the probabilities that \(\chi^{\pm}\chi^{\mp}\) decay produces events which are designated \(6j\), \(5j\), \(4j\) in the experimental analysis. Since these depend strongly on \(M_{\chi^\pm} - M_{\tilde{q}}\), a limit on, say, \(P_6/P_4\) implies a limit on the mass splitting between chargino and intermediate squark.

In the LEP 130 and 136 GeV run, ALEPH observed 16 \(4j\) events when 8.6

\(^3\)For \(M_{\tilde{q}} \sim m_W\), decay via virtual squark is a factor \(\frac{2\alpha_3}{\alpha_2}\) smaller than via a virtual \(W\), summing over the two generations of light quarks and three generations of leptons, and a factor \(\frac{2\alpha_3}{\alpha_2}\) smaller than via virtual slepton or sneutrino. When \(\tan\beta \approx 1\), \(\chi^0_3 \approx \tilde{h}_U + \tilde{h}_D\) and has very little \(\tilde{\epsilon}\) component; its dominant decay mode may be \(\chi^0_3 \to \gamma\tilde{\gamma}\), through a stop-top loop.
were expected. Their jet-reconstruction algorithm explicitly merged 5j to 4j (i.e., $P_5 \equiv 0$), and ignored the small number of clear 6j events. Nine events were observed in the total-dijet-mass range 102-108 GeV when 0.8 event was expected. Most of the events in the peak region are not characteristic of the SM expectation in their kinematic distribution, and they have a dijet charge-difference $\Delta Q$ larger than expected in the SM and well-described by a parton-level $\Delta Q = 2$ as predicted for $\chi^\pm \chi^\mp$ events. A statistical fluctuation or experimental reconstruction artifact would not readily account for such deviations from SM event characteristics.

The other three LEP experiments, using the ALEPH analysis procedure, found 6 events in the 102-108 GeV bin, when 2.6 were expected. Including events from 19 pb$^{-1}$ of data at $E_{cm} = 161$ and 171 GeV, ALEPH finds a total of 18 events in the peak region when 3.1 are expected. The other experiments have reported neither a significant signal nor upper limit, so far.

It should be emphasized that there is a substantial uncertainty in the expected rate of $\geq 4$ jet events due to the renormalization scale sensitivity of the tree-level cross sections which have been used. For instance, the observed rate of $Z^0 \rightarrow 4j$ ($5j$) is a factor 3 (5) higher than predicted taking the scale $\mu = m_Z$.[12] Thus the important feature of the LEP 4j anomaly is the peaking in total invariant mass and the anomalous properties of the correct fraction of peak region events.

In order to quote a cross section corresponding to the observed rate of anomalous events it is necessary to make an assumption as to the source of the signal. Taking it to be due to pair production of equal mass particles which decay to two jets implies a cross section at 130-136 GeV of 3.1 $\pm$ 1.7

\[\text{\footnotesize[4]M. Schmitt, private communication.}\]
\[\text{\footnotesize[5]F. Ragusa, LEPC Nov. 19, 1996}\]
\[\text{\footnotesize[6]C.f., joint LEP seminar, CERN, Oct. 8, 1996.}\]
\[\text{\footnotesize[7]E.g., $h \ A$, although that is unlikely to be the origin of the excess events, since the predicted cross section is 0.49 pb for $M(h) = M(A) = 53$ GeV and there is no observed}\]
pb using ALEPH alone, or 1.2 ± 0.4 pb averaging all LEP experiments [3].

Averaging the 161 GeV data available at Warsaw, Mattig quotes a 95% cl upper limit of 0.85 pb assuming the same efficiency as at 130-136 GeV. Extrapolating 1.2 pb from 130-136 GeV with 1/s gives 0.8 pb.

Pair production of ~ 53 GeV charginos could give rise to “4j” events with total dijet mass of 105 GeV at the observed rate and with the observed ΔQ values. Let us denote by ε6/4 the ratio of probabilities that a χ±χ± → 6j or a hA → 4j event is accepted by the ALEPH cuts. Like the P_i’s defined above, ε6/4 depends on M_q as well as E_{cm}. A careful Monte Carlo calculation is needed to determine these quantities. The two (hard) gluino jets contain R_0's which may decay before reaching the calorimeter (typically, to π^+π^- R_0). Due to experimental imprecision in energy measurements, the ALEPH 4j analysis rescales the momenta and energies of jets to obtain an improvement in precision by enforcing overall energy momentum conservation. The directions of the jets are assumed to be accurately measured, and the jets taken to be massless. Energy-momentum conservation provides 4 equations, so up to 4 jets can be independently rescaled. If an event actually contains 6 jets, possibly with some energy and directional imprecision due to R_0 decays, the rescaling procedure distorts the dijet invariant masses. Detailed Monte Carlo study is needed to estimate the P_i’s, ε6/4 and predict the dijet mass-sum and mass-difference distributions and other observables.

The chargino production cross section depends on μ, tan β and M_χ_0.

M_χ_0 = 53 GeV requires a relation between μ and tan β, eq. (1). Imposing M_χ_0 ≥ 38 GeV (see below), causes [μ, tan β] to range between [45, 1.6] and [70, 1]. In this constrained parameter space the chargino contains com-

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8 Refs. [8, 14] estimate their x_F.

9 We take tan β ≥ 1 without loss of generality because in the absence of tree-level gaugino masses and scalar trilinear couplings, the chargino and neutralino spectrum is unchanged by tan β → 1/(tan β); only the roles of the higgsinos, h_U and h_D, are interchanged in the eigenstates.
parable higgsino and wino components. The main uncertainty in the cross section comes from its sensitivity to the electron sneutrino mass, $M_{\tilde{\nu}_e}$. For $M_{\tilde{\nu}_e} = 60$ GeV, $\tan\beta = 1.4$ and $\mu = 56$ GeV, one finds $\sigma(\chi^+\chi^-) = 3.6$ pb at $E = 130 - 136$ GeV, and 2.1 (1.9) pb at $E = 161 (190)$ GeV. For $M_{\tilde{\nu}_e} = 50$ GeV the lowest $\sigma_{\chi^+_1\chi^-_1}(130 - 136\text{GeV}) = 2.4$ pb, while for $M_{\tilde{\nu}_e} >> M_{\chi^+_1}$ the 130-136 GeV cross section could be as large as 14 pb, for $\tan\beta = 1$ and $\mu = 68.4$ GeV.

Comparing to the LEP average ($1.2 \pm 0.4$ pb, assuming $hA$ for the efficiency) these predicted cross sections are compatible with $br(\chi^+ \rightarrow 3j) = 1$ if $\epsilon_{6/4} \lesssim \frac{1}{2}$. If $\epsilon_{6/4} > \frac{1}{2}$, a competing decay mode to reduce $br(\chi^+ \rightarrow 3j)$ would be indicated. This could be $\chi^{\pm}_1 \rightarrow l\tilde{\nu}$, with the $\tilde{\nu}$ decaying to lsp and neutrino. The branching fraction for $\chi^{\pm}_1 \rightarrow l\tilde{\nu}$ is a very sensitive function of the sneutrino mass and also depends on the squark mass and the number of light sneutrinos. The mass splitting $M(\chi^\pm) - M(\tilde{\nu})$ must be $\lesssim 1$ GeV in order not to excessively reduce the branching fraction to the hadronic channel. With such a small splitting, the lepton energy is too low for lepton identification so the events with one or both charginos decaying leptonically would not be noticed. However $\chi^\pm \rightarrow l\tilde{\nu}$ would give rise to a hard lepton and thus would show up in conventional SUSY searches, so we can infer $M(\tilde{l}) \gtrsim M(\chi^{\pm}_1)$.

A stop lighter than the chargino, decaying through FCNC mixing to a gluino and charm quark, may be excludable by ALEPH. It would lead to two hard $c$ jets in each event (plus two soft $b$ jets if $\chi^{\pm}_1 \rightarrow \tilde{t}_1 + b$ were allowed). ALEPH has searched for hard $b$ jets in their $4j$ sample. They found only a single event consistent with a displaced vertex, or excess lepton activity from the $e$ or $\mu$, which would be expected in 20% of hard $b$ decays. Although the detection efficiency of hard $c$’s and soft $b$’s is lower than for hard $b$’s, it may still be large enough to exclude the dominant chargino decay being $\chi^{\pm}_1 \rightarrow \tilde{g} + c + b$. This would either mean that $M_{\tilde{t}_1} \gtrsim M_{\chi^\pm_1}$ or that the dominant decay of the stop is $\tilde{t}_1 \rightarrow \tilde{g} + u$. Since FCNC mixing involving the third generation is poorly constrained, the latter possibility should not be
We can hope that higher integrated luminosity will allow the 53 GeV chargino hypothesis to be confirmed or excluded, however this will not be easy. In future runs at higher CM energy the jet systems from each chargino decay will be better collimated and more readily separated from one another, so the angular distribution of the jet systems can be more cleanly determined than at lower energy. It should $\sim 1 + \cos^2 \theta$ because charginos are spin-1/2. On the other hand, Monte Carlo simulations\textsuperscript{11} show that the resolution in dijet mass difference does not improve significantly with energy even for genuine two-body decays of pair-produced particles, due to reduced effectiveness of the energy-momentum constraint at higher energy. This will be an even more severe problem for the $6j$ case at hand. It is ironic that $W^+W^-$ production is a non-trivial background at 161 GeV and above, since $W$’s presumably decay with rather high probability to $\geq 2j$ (40% of $Z^0$ decays contain $\geq 3j$, with $y_{cut} = 0.01$) and their cross section is much larger than that of the $4j$ signal.

Now let us turn to the neutralinos and heavier chargino whose masses are shown in Fig. 1 for $M(\chi^\pm_1) = 53$ GeV. $\chi^0_1\chi^0_1$ and $\chi^0_1\chi^0_2$ production is suppressed because $\chi^0_1$ is practically pure photino. Since the final state of $\chi^0_2\chi^0_2$ is $6j$, existing neutralino searches would not have been sensitive to it, so the best limit comes from the hadronic width of the $Z^0$, whose PDG value is $\Gamma_{had}(Z^0) = 1741 \pm 6$ MeV. Requiring the $\chi^0_2\chi^0_2$ contribution to be $< 10$ MeV implies $M(\chi^0_2) \geq 38$ GeV, which in turn limits the $[\mu, \tan \beta]$ range to [45, 1.6] − [70, 1]. For $M(\chi^0_2) = 38$ GeV, $\chi^0_2$ has a large $\tilde{h}_D$ component\textsuperscript{10}. If $M_{\tilde{t}_1} + m_{\tilde{g}} < m_t$, $br(t \rightarrow \tilde{t}_1 + \tilde{g}) \approx \frac{1}{2}$ and $\tilde{t}_1 \rightarrow \chi^+_1 b, c\tilde{g}$, or $u\tilde{g}$. The rate of purely SM decays in $t\bar{t}$ events would be reduced, but present theoretical and experimental uncertainties in $\sigma(p\bar{p} \rightarrow t\bar{t})$ are too large to exclude this, especially when the stop decays to $b$ quark plus multijets. More promising is to compare the ratio of $t\bar{t}$ events obtained with a single lepton versus dilepton tag. I am indebted to S. Lammel for a discussion of this point.

\textsuperscript{10} If $M_{\tilde{t}_1} + m_{\tilde{g}} < m_t$, $br(t \rightarrow \tilde{t}_1 + \tilde{g}) \approx \frac{1}{2}$ and $\tilde{t}_1 \rightarrow \chi^+_1 b, c\tilde{g}$, or $u\tilde{g}$. The rate of purely SM decays in $t\bar{t}$ events would be reduced, but present theoretical and experimental uncertainties in $\sigma(p\bar{p} \rightarrow t\bar{t})$ are too large to exclude this, especially when the stop decays to $b$ quark plus multijets. More promising is to compare the ratio of $t\bar{t}$ events obtained with a single lepton versus dilepton tag. I am indebted to S. Lammel for a discussion of this point.

\textsuperscript{11} (M. Schmitt, FNAL seminar, Nov. 22, 1996.)
\( \chi_2^\pm = -0.86 \tilde{h}_D - 0.39 \tilde{h}_U + 0.31 \tilde{z}^0 \). This leads to an excess in the \( \bar{b}b\tilde{g} \) final state in \( \chi_2^0 \) decay, but not enough to affect \( R_b \) significantly. At 130-136 GeV, \( \sigma(e^+e^- \rightarrow \chi_2^0\chi_2^0) < 0.5 \) pb for typical parameter choices, although for \( M(\chi_2^0) \lesssim 45 \) GeV the cross section (including enhancement from initial state radiation) is \( \gtrsim 1 \) pb. Thus a small number of events might be present in the LEP multi-jet samples. Such events should exhibit \( \Delta Q \) consistent with zero.

Production of \( \chi_2^0\chi_2^3 \) is at least an order of magnitude lower. Since \( \chi_2^\pm \rightarrow W\tilde{\gamma}, \) Drell-Yan production of \( \chi_2^\pm\chi_2^\pm \) and \( \chi_2^\pm\chi_2^0 \) might be detectable in \( p\bar{p} \) collisions via events with \( 3j + W + E_{miss}, \) where the \( 3j \) system has an invariant mass of \( \chi_2^\pm \) or \( \chi_2^0 \) (see Fig. 1). The \( 6j \) signal would probably be difficult to discriminate from QCD background. For some range of parameters \( \chi_3^0 \rightarrow \gamma\tilde{\gamma} \) might lead to \( \gamma E_{miss} \) at an interesting rate.

To summarize:

- The tree-level-massless gaugino scenario predicts \( m(\chi_1^0) \lesssim 1 \) GeV and \( m(\chi_1^\pm) \lesssim m_W; \) the measured \( Z^0 \) hadronic width requires \( m(\chi_2^0) \gtrsim 38 \) GeV.
- The generic final state for neutralinos and charginos in the light gaugino scenario is three jets, unless \( m(\tilde{\nu}) \) or \( m(\tilde{l}) \) is small enough that two-body leptonic decays are allowed. The heavier chargino has the characteristic 2-body decay \( \chi_2^\pm \rightarrow W^\pm\tilde{\gamma}. \)
- Chargino production and decay may account for the rate and characteristics of “4j” events seen at LEP, for chargino mass of \( \approx 53 \) GeV. No R-parity violation is needed.
- If the present hint of charginos at 53 GeV disappears, experiments should still search for charginos via a \( 6j \) signature until light gluinos are ruled out. At \( E_{cm} = 190 \) GeV the cross section for chargino pair production is greater than 1.4 pb for \( M_{\tilde{g}} = 100 \) GeV, even for the most pessimistic case of degenerate charginos with mass \( m_W. \) Above \( WW \) threshold the \( 6j \) signal is difficult to discriminate from the background, however.

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Figure 1: Masses in GeV of the heavier chargino and second and third neutralinos as a function of $\tan \beta$, fixing the lighter chargino mass to 53 GeV (solid, dash-dot, and dash curves, respectively).