A supergravity explanation of the CDF $ee\gamma\gamma$ event

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Abstract

We present a unified no-scale supergravity model with a light gravitino that can naturally explain the observed $ee\gamma\gamma$ event at CDF via right-handed selectron pair-production. The full spectrum of our model can be described in terms of a single parameter and can be distinguished from alternative proposals in the literature. Ongoing and future runs at LEP 2 should be able to probe the full allowed parameter space via acoplanar diphoton events from $e^+e^- \rightarrow \chi^0_1\chi^0_1$ production.
Supersymmetry is widely acknowledged to be the best motivated extension of the Standard Model of particle physics. Yet, experimental searches over the last decade have failed to provide direct and unambiguous evidence for the existence of the predicted rich spectrum of superparticles, although plenty of indirect evidence exists, such as the implied light Higgs-boson mass ($m_h = 76^{+15}_{-50}$ GeV) from fits to the precise electroweak data, and the celebrated unification of the Standard Model gauge couplings in supersymmetric grand unified theories. As it has been recently pointed out, this trend may be coming to an end with the observation by the CDF Collaboration of one event of the type $e^+ e^- \gamma \gamma + E_T$. This event has no conceivable Standard Model explanation, but can be ascribed to supersymmetry in two possible contexts, depending on whether the lightest supersymmetric particle is the lightest neutralino ($\chi^0_1$) or the gravitino ($\tilde{G}$). In both scenarios it is assumed that the CDF event results from selectron pair production. In the ‘neutralino LSP’ scenario the selectrons must decay in a rather cumbersome way: $\tilde{e} \rightarrow e \chi^0_2$, $\chi^0_2 \rightarrow \chi^0_1 \gamma$. The loop-induced radiative neutralino decay may occur in small regions of parameter space, but these regions are inconsistent with the traditional gaugino mass unification condition. In the ‘gravitino LSP’ scenario the selectron decay is much more straightforward: $\tilde{e} \rightarrow e \chi^0_1$, $\chi^0_1 \rightarrow \gamma \tilde{G}$. In neither scenario can one ascertain whether $\tilde{e} = \tilde{e}_R$ or $\tilde{e} = \tilde{e}_L$.

Notably lacking from the above discussion is the presence of the theoretical framework that has propelled the study of supersymmetry, namely grand unification and supergravity. In the neutralino LSP scenario one must seemingly abandon the GUT relation among the gaugino masses, whereas the gravitino LSP scenario has been couched in the context of low-energy gauge-mediated supersymmetry breaking. In this Letter we propose an explanation for the CDF event in the context of grand unification and supergravity. Our framework fits within the class of no-scale supergravity models which illuminate the cosmological constant problem, may allow the dynamical determination of all mass scales, may solve the strong CP problem, and may be derivable from string theories. Our one-parameter model thus realizes the more appealing gravitino LSP scenario, where $m_{3/2} \lesssim 1$ KeV has well-known cosmological advantages and, through the inside-the-detector decay $\chi^0_1 \rightarrow \gamma \tilde{G}$, makes the ever-present lightest neutralino readily identifiable. In practice our proposal amounts to setting the universal scalar mass and the universal trilinear scalar couplings to zero ($m_0 = A_0 = 0$). Our sole source of supersymmetry breaking is the gaugino mass $m_{1/2}$, which entails a low-energy supersymmetric spectrum described in terms of a single parameter, thus providing several correlated and falsifiable predictions, that can be distinguished from those in the alternative models of Refs.

Supergravity is specified in terms of two functions: the Kähler function $G = K + \ln |W|^2$, where $K$ is the Kähler potential and $W$ the superpotential; and the gauge kinetic function $f$. From these one can obtain the supersymmetry-breaking scalar ($\tilde{m}_i$) and gaugino masses and scalar interactions ($A_i$) at the Planck scale, in terms of the gravitino mass $m_{3/2} = e^{G/2} = e^{K/2} |W|$. In all known instances one obtains $\tilde{m}_i \sim c_i m_{3/2}$, where the $c_i = O(1)$ coefficients depend on the specific functional form.
of $K$ and its field dependences. A similar result is obtained for the trilinear scalar couplings, where typically $W$ also enters. These model dependencies and potential non-universalities are however washed out in the case of a light gravitino, where one effectively obtains $m_0 = A_0 = 0$. The bilinear scalar coupling $B_0$ may also vanish along these lines, although this is not a general result as it may depend on the assumed origin of the superpotential Higgs mixing parameter $\mu$. A gravitino mass of suitable size can be easily obtained via gaugino condensation in the hidden sector at the scale $\Lambda \sim 10^k$ GeV: $m_{3/2} \sim |W| \sim \Lambda^3/M^2 \sim 10^{3(k-9)}$ eV, where $M \approx 10^{18}$ GeV is the appropriate gravitational scale. Cosmological and laboratory constraints require $10^{-5}$ eV $< m_{3/2} < \sim 10^3$ eV, which entails $10^7$ GeV $< \Lambda < \sim 10^{10}$ GeV. Condensation scales in this range are obtained for hidden gauge groups like SU(3) and SU(4) with light hidden matter fields.

The gaugino masses depend on the gauge kinetic function ($f$), as follows

$$m_{1/2} = m_{3/2} \left( \frac{\partial_z f}{2 \Re f} \right) \left( \frac{\partial_z G}{\partial_{zz} G} \right),$$

(1)

where $z$ represents the hidden sector (moduli) fields in the model, and the gaugino mass universality at the Planck scale is insured by a gauge-group independent choice for $f$. The usual expressions for $f$ give $m_{1/2} \sim m_{3/2}$. This undesirable result in the light gravitino scenario can be avoided by considering the non-minimal choice $f \sim e^{-A z^q}$, where $A, q$ are constants. Assuming the standard no-scale expression $G = -3 \ln(z + z^*)$, one can then readily show that

$$m_{1/2} \sim \left( \frac{m_{3/2}}{M} \right)^{1 - \frac{2}{3} q} M.$$  

(2)

The phenomenological requirement of $m_{1/2} \sim 10^2$ GeV then implies $\frac{2}{3} \geq q \geq \frac{1}{2}$ for $10^{-5}$ eV $\lesssim m_{3/2} \lesssim 10^3$ eV. Note that $q = \frac{2}{3}$ gives the relation $m_{3/2} \sim m_{1/2}^2/M \sim 10^{-5}$ eV, which was obtained very early on in Ref. [14] from the perspective of hierarchical supersymmetry breaking in extended N=8 supergravity. The recent theoretical impetus for supersymmetric M-theory in 11 dimensions may also lend support to this result, as N=1 in D=11 corresponds to N=8 in D=4.

Enforcing the constraints from radiative electroweak symmetry breaking in the usual manner we obtain the low-energy supersymmetric spectrum in terms of two parameters: $\tan \beta$ and $m_{1/2}$ (as well as the sign of $\mu$ and our choice of $m_t = 175$ GeV). Enforcing also $B_0 = 0$ allows one to solve for $\tan \beta$ in terms of $m_{1/2}$, giving our one-parameter model. (The sign of $\mu$ gets also determined in this process.) In practice allowing $B_0$ to ‘float’ does not qualitatively change the model predictions, although it dulls them somewhat. These one- and two-parameter supergravity models have been effectively considered before [15, 16] without explicit mention of what the gravitino mass was. The restriction $m_{3/2} \ll m_{1/2}$ does not alter the spectra, but it changes the experimental signals that must now always contain hard photons from $\chi_1^0$ decay. To be consistent with our soft-supersymmetry-breaking assumptions at the Planck
scale, we have started the renormalization-group evolution at that scale (as in the case of string models). As is well known, unification of the gauge couplings in this type of scenario requires the introduction of intermediate-scale particles, which we have implemented as described in Refs. [15, 16].

The question may arise of why of all possible unified supergravity models described in terms of four parameters \((m_{1/2}, m_0, A_0, \tan \beta)\) should one pay particular attention to our one-parameter model. To gain some insight into this question we have generated 10,000 different random four-parameter sets of this kind, and in each case determined the low-energy spectrum, in particular the \(\chi^0_1\) and \(\tilde{e}_{R,L}\) masses. The known kinematics of the \(ee\gamma\gamma\) event in the light gravitino scenario allow one to delineate an allowed region in the \((m_{\tilde{e}}, m_{\chi^0_1})\) plane [3]. Figure 1 shows the distribution of models in this space, with the preferred region delineated by the polygon. For clarity, in the figure we restrict the choices of \(\xi_0 = m_0/m_{1/2}\) to the integer values shown (i.e., \(0 \rightarrow 5\)), with the other three parameters allowed to vary at random. (The branches for \(\tilde{e}_R\) and \(\tilde{e}_L\) are only distinguishable for \(\xi_0 = 0, 1\).) This figure illustrates the fraction of the generic supergravity parameter space that is consistent with the kinematics of the CDF event. Moreover, our model prediction of \(\xi_0 = 0\) clearly falls within the allowed region for both \(\tilde{e}_R\) and \(\tilde{e}_L\), whereas \(\xi_0 \geq 1\) is not allowed.

We now turn to the phenomenological consequences of our one-parameter model. The spectrum as a function of the lightest neutralino mass is given in Fig. 2 for the lighter particles (sleptons, lightest higgs, lighter neutralinos and charginos) and in Fig. 3 for the heavier particles (gluino, squarks, heavy higgses, heavier neutralinos and charginos). In addition we have the result \(\tan \beta \approx 8 - 10\). These figures show that the lightest neutralino (which is mostly bino) is always the next-to-lightest supersymmetric particle (NSLP), followed by the right-handed sleptons (\(\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1\)), the lighter neutralino/chargino (\(\chi^0_2, \chi^\pm_1\)), the sneutrino (\(\tilde{\nu}\)), and the left-handed sleptons (\(\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_2\)). (The order of the second and third elements is reversed for very light neutralino masses.) Note the splitting between the selectron/smuon masses and the stau mass due to the non-negligible value of the \(\lambda_\tau\) Yukawa coupling. The lightest higgs boson crosses all sparticle lines with \(m_h = (100 - 120)\) GeV. Also notable is that the average squark mass is slightly below the gluino mass and the lightest top-squark (\(\tilde{t}_1\)) is somewhat lighter than these. The dominant decay of the lightest neutralino is via \(\chi^0_1 \rightarrow \gamma\tilde{G}\), which will proceed without suppression in the experimentally preferred range \(m_{\chi^0_1} \approx (38 - 95)\) GeV, requiring only \(m_{3/2} \lesssim 250\) eV for it to likely occur within the CDF (or any other such) detector.

In Fig. 4 we show the correlated values of the lightest neutralino mass versus the selectron (or smuon) mass. The lightest chargino mass (which obeys \(m_{\chi^\pm_1} \approx m_{\chi^0_2}\)) is also shown in the figure. As the figure shows, the experimentally preferred region (polygon) overlaps our model predictions significantly for both \(\tilde{e}_R\) and \(\tilde{e}_L\). Moreover, the cross section for pair-production of such particles at the Tevatron, as indicated for a few points in the figure, shows that indeed only a few events should have been produced in 0.1 fb\(^{-1}\) of data so far. Note also that in the (preferred) case of \(\tilde{e}_R\), the real constraint on our one-parameter spectrum is on the selectron mass, the constraint
on the neutralino mass follows automatically. Our model is thus consistent with the kinematics and dynamics of the CDF event.

LEP 1 constraints on our model are satisfied by construction. Because the allowed region implies $m_{\tilde{e}} > 80$ GeV and $m_{\chi_1^\pm} \approx m_{\chi_2^0} > 70$ GeV (see Fig. 1), LEP 1.5 ($\sqrt{s} = (130 - 136)$ GeV) was only sensitive to $\chi_1^0\chi_1^0$ production. A recent analysis by the OPAL Collaboration [17] of acoplanar photon pairs at LEP 1.5 puts a 95%CL upper limit on such cross section of 2 pb. We find $\sigma(e^+e^- \rightarrow \chi_1^0\chi_1^0) < 1.6$ pb, and thus LEP 1.5 imposes no new constraints on our model. Constraints from the Tevatron are harder to determine. The lower bound on the selectron masses from Fig. 1 implies $m_{\tilde{g}} > 365$ GeV, $m_{\tilde{q}} > 350$ GeV, $m_{\tilde{t}_1} > 235$ GeV (see Fig. 1), all of which automatically satisfy present Tevatron limits. However, neutralino/chargino production via $p\bar{p} \rightarrow \chi_1^+\chi_1^-, \chi_2^0\chi_1^{\pm}$ have larger rates leading to $\gamma\gamma+n\ell+m_j+E_T$ signals that might have been detected. ($\chi_1^0\chi_2^0$ production is also kinematically accessible but negligible because of the dominant gaugino nature of $\chi_1^0\chi_2^0$.) Ref. [6] estimates that the apparent non-observation of such processes at the Tevatron with 100 pb$^{-1}$ of data requires $m_{\chi_1^\pm} > 125$ GeV. Taken at face value, this constraint would eliminate the lighter half of the allowed parameter space, marked by the central point on the $\tilde{\ell}_R$ curve in Fig. 3, and single out $\tilde{e}_R$ as the only possible explanation for the event (i.e., $m_{\chi_1^\pm} > 125$ GeV implies $m_{\tilde{e}_L} > 155$ GeV).

The presumed lower bound on the chargino mass from Tevatron searches makes $\tilde{\ell}^+\tilde{\ell}^-, \chi_1^+\chi_1^-, \chi_2^0\chi_2^0$, and higgs production at LEP160 or 190 kinematically disallowed. The only accessible channel is $e^+e^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\gamma G\bar{G}$, which for our bino-like neutralino proceeds dominantly via $t$-channel $\tilde{e}_R$ exchange. The cross sections for this process at LEP 160 and 190 are shown in Fig. 4 as a function of $m_{\chi_1^0}$. It is not clear what sensitivity will LEP160 have for such signal with the expected 10 pb$^{-1}$ of data. At LEP190 with 500 pb$^{-1}$ of data, a detailed study [6] shows that it should be able to probe all of the preferred range: $m_{\chi_1^0} \approx (38 - 95)$ GeV.

Any light gravitino scenario can be distinguished from the neutralino LSP scenario, for instance, by the nature of the photon spectrum in, e.g., $e^+e^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\gamma G\bar{G}$ versus $e^+e^- \rightarrow \chi_2^0\chi_2^0 \rightarrow \gamma\gamma \chi_1^0\chi_1^0$ [18]. Our supergravity light gravitino model can be further distinguished from the gauge-mediated models by the differing predicted spectra, although the gauge-mediated ones depend on the unknown nature of their ‘messenger sector’.

Concerning the cosmological aspects of our model, as is well known, for $m_{3/2} \sim 1$ KeV the relic gravitinos constitute a form of ‘warm’ dark matter with a behavior similar to that of cold dark matter. The non-thermal gravitinos from $\chi_1^0$ decay do not disturb big bang nucleosynthesis, and may constitute a form of hot dark matter [18], although with small abundance. Other forms of dark matter, such as metastable hidden sector matter fields (cryptons) [19] and a cosmological constant [20], may need to be considered as well.

If the CDF event is really of supersymmetric origin, because of its peculiar properties it would not only establish the existence of supersymmetry but also provide
strong clues as to the origin of supersymmetry breaking. Our no-scale supergravity model with a light gravitino has strong roots in strings, even in the modern era of extended supergravity and M-theory [21].

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Figure 1: Calculated distribution of selectron ($\tilde{e}$) and lightest neutralino ($\chi^0_1$) masses (in GeV) in generic supergravity models for fixed values of the ratio $\xi_0 = m_0/m_{1/2} = 0, 1, 2, 3, 4, 5$; and varying values of $\{m_{1/2}, \tan \beta, A_0\}$. The area within the polygon is consistent with the kinematics of the CDF $ee\gamma\gamma$ event. The branches for $\tilde{e}_R$ and $\tilde{e}_L$ are only distinguishable for $\xi_0 = 0, 1$. Our model predicts $\xi_0 = 0$. 
Figure 2: The lighter members of the spectrum of our one-parameter model versus the lightest neutralino mass. The vertical dashed lines delimit the experimentally preferred region. All masses in GeV.
Figure 3: The heavier members of the spectrum of our one-parameter model versus
the lightest neutralino mass. The vertical dashed lines delimit the experimentally
preferred region. All masses in GeV.
Figure 4: The correlated predictions for the lightest neutralino mass ($m_{\chi^0_1}$) versus the selectron (or smuon) mass ($m_{\tilde{e},\tilde{\mu}}$) in our one-parameter model. The corresponding values of the lightest chargino mass ($m_{\chi^\pm_1}$) are shown on the right axis. (All masses in GeV.) The area within the polygon is consistent with the kinematics of the CDF $ee\gamma\gamma$ event. The values at the marked points along the lines indicate the cross section for the corresponding slepton pair-production at the Tevatron. Also shown are the cross sections for $e^+e^- \rightarrow \chi^0_1\chi^0_1 \rightarrow \gamma\gamma + E_T$ production at LEP160 and 190, as a function of $m_{\chi^0_1}$. 