An Inclusive Search for Anomalous Production of High-p_T Like-Sign Lepton Pairs in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for anomalous production of events with at least two charged, isolated, like-sign leptons with $p_T > 11$ GeV/c using a 107 pb^{-1} sample of 1.8 TeV $p\overline{p}$ collisions inside the CDF detector. We define a signal region containing low background from Standard Model processes. To avoid bias, we fix the final cuts before examining the event yield in the signal region using control regions to test the Monte Carlo predictions. We observe no events in the signal region, consistent with an expectation of $0.63^{+0.84}_{-0.07}$ events. We present 95% confidence limits on new physics processes in both a signature-based context as well as within a low $\tan\beta$ mSUGRA model.

Numerous attempts to resolve theoretical problems with the Standard Model (SM) require the existence of new particles with masses at the electroweak scale, $\sim$100 GeV/c^2 [1]. A productive method for searching for new particles at this scale has been to search for lepton production at $p\overline{p}$ colliders with high momentum transverse to the beam axis (p_T). Such searches led to the discovery of the W and Z bosons at the $Sp\overline{p}S$ and to the discovery of the t quark at the Tevatron [2]. Recently, searches for anomalous high-p_T lepton production have been used to constrain supersymmetric extensions to the SM. For example, production of charginos and neutralinos were constrained by searches for events with three high-p_T leptons [3–5]. Limits on gluino production were likewise placed by searching for events with two like-sign charged leptons, two jets, and energy imbalance, $\not\!\!E_T$, due to escaping particles such as neutralinos and neutrinos [6]. These analyses achieved the necessary suppression of background processes by requiring three or more reconstructed objects in the final state and constraints on their kinematical properties.

In this Letter we present the results of a search for new particles with masses at the electroweak scale using a minimal number of required objects or kinematics. Specifically, we search for two like-sign, isolated, charged leptons in the final state, each with $p_T > 11$ GeV/c, but do not require any other objects or $\not\!\!E_T$. We define a signal region with less than one event expected from SM background but broad acceptance for typical models of new particle production. To avoid bias, we fix the final cuts before examining the event yield in the signal region.

We examine 107 pb^{-1} of data collected by the Collider Detector at Fermilab (CDF) during the 1992-95 data run of the Fermilab Tevatron. The CDF detector [7] is an azimuthally and forward-backward symmetric solenoidal detector designed to study $p\overline{p}$ reactions at the Fermilab Tevatron. The central tracking chamber (CTC) measures the trajectories of charged particles traversing a uniform 1.4 T magnetic field with a resolution of $\delta p_T/p_T^2 = 8 \times 10^{-4}$ (GeV/c)$^{-1}$. Outside the solenoid, a lead/scintillator central electromagnetic sampling calorimeter detects electromagnetic showers with an energy resolution of $13.5\%/\sqrt{E \sin\theta} \oplus 1.5\%$. Steel/scintillator hadronic calorimeters directly behind the electromagnetic calorimeters measure the hadronic component of deposited energy. Drift chambers located behind the steel detect penetrating muons with momenta above 3 GeV/c.

We begin with a sample of 457,478 loosely selected dilepton events. We select candidate events similarly to the previous CDF trilepton searches [3,4]. We identify charged leptons as electrons or muons with $p_T > 11$ GeV/c using the "strict" selection criteria of those analyses. As in the previous analyses, we remove events consistent with conversions ($\gamma \to e^+e^-$), cosmic rays, or a J/ψ or Z resonance. We require $|z_{vertex}| < 60$ cm and $|z_{lepton} - z_{vertex}| <$ 5 cm for each lepton, where z is measured along the beam line, to ensure that both leptons came from the same primary collision and are well measured. We identify the two highest p_T same-sign leptons as a like-sign dilepton pair. To reduce the background from back-to-back jet events which are both misidentified as leptons, we require the lepton pair to have a vector sum transverse momentum of $p_T^{\ell\ell} > 20$ GeV/c. To remove low mass events in which both leptons result from jets misidentified as leptons we impose invariant mass of $M_{\ell\ell} > 10$ GeV/c^2.

One notable difference from the previous analyses is a modification to the lepton isolation variable (ISO). ISO is originally defined as the scalar sum of the E_T measured in each calorimeter cell, $\sum E_T$, added in quadrature to the scalar sum of the p_T measured in the CTC, $\sum P_T$, within a cone $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \leq 0.4$ of each lepton candidate. The energy of the lepton candidate is removed from the ISO sum by subtracting the p_T of the lepton candidate track, p_T^{cand}, and the calorimeter E_T of the lepton candidate, E_T^{cand}, from $\sum P_T$ and $\sum E_T$, respectively.

$$ISO_{\Delta R \leq 0.4} = \sqrt{(\sum E_T - E_T^{cand})^2 + (\sum p_T - p_T^{cand})^2} \qquad (1)$$

Fig. 1 shows distributions of $ISO_{\Delta R \leq 0.4}$ for the high and low-p_T leptons in a control sample of 194 opposite-sign dilepton events selected with the same lepton ID requirements as the LS dilepton pairs except the ISO cut, which is not applied to either lepton. E_T^{cand} is the scalar sum of the E_T in the calorimeter cell to which we extrapolate the lepton candidate track (the "seed" cell) and the two cells adjacent to either side of the seed cell in η to account for lateral energy leakage between cells.

$$E_T^{cand} = E_T^{seed} + E_T^{leakage} \qquad (2)$$

In this analysis we have changed $E_T^{leakage}$ so that the electron or muon is excised from $\sum E_T$ more effectively by modeling the energy leakage between cells in greater detail. In addition to the usual cut at $ISO_{\Delta R \leq 0.4} < 2$ GeV we have added a cut on an identically defined ISO cone with radius of 0.7, $ISO_{\Delta R \leq 0.7} < 7$ GeV. Fig. 1 shows lepton signal efficiency for leptons selected from 1255 $Z \rightarrow e^+e^-$ and 1389 $Z \rightarrow \mu^+\mu^-$ events as a function of jet background selected from jet control samples with 20 and 50 GeV thresholds on the jet E_T. These changes reduce background from jets being misidentified as leptons by a factor of two while retaining the same efficiency for leptons [8].

Diboson production, WZ and ZZ, where "Z" denotes a mixture of the Z and γ^*, produces an irreducible source of SM background. Although the Z mass cut removes most of these events, some survive because the Z is off-shell or we fail to find one of the leptons from the Z. We model this background using the Monte Carlo programs PYTHIA [9] and MCFM [10] which include contribution from off-shell Z/γ^*. The two processes contribute 0.25 ± 0.09 and 0.07 ± 0.02 events, respectively, to the signal region. The only other significant background is W+jets and Z+jets production where one of the jets is misidentified as a lepton. Because the rate of lepton misidentification is beyond the scope of our Monte Carlo programs and simulations, we anchor this calculation in the data. First, we demonstrate that PYTHIA correctly models the observed rate of isolated tracks as a function of p_T in $Z \to \ell^+\ell^-$ events, excluding the two tracks from the legs of the Z. Second, we use several control samples to measure the probability that an isolated track passes all lepton identification requirements: $(2.5 \pm 0.7)\%$ with no measurable p_T dependence. Third, we multiply the PYTHIA prediction for W or Z with an underlying isolated track by this factor to estimate backgrounds to be 0.30 ± 0.08 and 0.03 ± 0.01 events, respectively [11]. Using ISAJET [12] we estimate the small contribution, $0.008^{+0.006}_{-0.004}$, from $t\bar{t}$, $b\bar{b}$ and $c\bar{c}$. Finally, we set an upper limit to the contribution from events in which both lepton candidates are jets misidentified as leptons, $0.0^{+0.83}_{-0.0}$, using event yields outside the signal region. We find negligible background due to charge misassignment by using Z events and track curvature studies [11].

Different kinematical regions, some of which are shown in Fig. 2, have sensitivity to different background sources. For example, the significant backgrounds separated by type in region A of Fig. 2, with $6 <$ Lepton 2 $p_T < 11$ GeV/c and $p_T^{\ell\ell} > 20$ GeV/c, are detailed in Table I. The consistency of these control regions indicates the reliability of our lepton misidentification rates. With all the nominal cuts but the Z mass window inverted, we predict 0.11 ± 0.03 events and see zero. If, instead of requiring like-sign, we require an opposite-sign pair and an additional isolated $p_T > 3$ GeV/c track we predict 68 ± 9 events and observe 62, thereby testing our modeling of the effect of lost Drell-Yan leptons.

Background type	Background	SM expected	Data
2 leptons	WZ,ZZ,$t\bar{t}$	0.033±0.001	0
1 lepton and 1 misidentified jet	Drell-Yan, W+jets, $b\bar{b}$, $c\bar{c}$	3.5±0.1±0.9	3
2 misidentified jets	QCD	2.5±0.5±1.5	1

TABLE I. A comparison of SM background predicted from the Monte Carlo (except for QCD, estimated from event yields in adjacent data control regions) to events selected in the data in the control region: $6 <$ Lepton 2 $p_T < 11$ GeV/c and Dilepton Pair $p_T > 20$ GeV/c. Errors are ±statistical±systematic.

In the signal region we predict $0.63^{+0.84}_{-0.07}$ events and observe zero. Hence our analysis provides no indication of physics beyond the SM and we proceed to set limits on new physics using the standard CDF technique [13]. Following the methodology of previous analyses, the sources of systematic uncertainty include trigger efficiency, luminosity, lepton identification, structure function choice, and Q^2 variations [4], which ultimately have little effect on the quoted limits.

Because we perform this search without considering any one particular model for new physics, we evaluate the result as a general limit on particle production leading to our like-sign dilepton signature. We generate WZ pairs with PYTHIA using standard couplings and spins. However, we allow the masses of the W-like and Z-like particles to vary. We find that efficiencies (after forcing the bosons to decay leptonically) range from 3% to 8% as the W-like and Z-like masses vary from 100 to 300 GeV. These values are about three times higher than if three leptons had been required, demonstrating the usefulness of this technique. Exclusion limits on the cross section times branching ratio (including the 16% systematic uncertainty) are shown in Fig. 3.

In addition to such signature-based limits we derive a limit within the framework of a specific supersymmetric extension to the SM, mSUGRA, a supergravity-inspired extension to the Minimal Supersymmetric Standard Model. We take representative parameters $\tan\beta = 3$, $\mu < 0$ and $A = 0$, but allow m_0 and $m_{1/2}$ to vary and use PYTHIA to calculate event yields. The simulation allows all particles to decay according to their calculated branching ratios so that charged leptons may be produced at any stage of cascade sparticle and particle decays. Within the context of this model we improve our expected sensitivity by lowering the $p_T^{\ell\ell}$ cut from 20 to 10 GeV/c. In this mSUGRA model like-sign dilepton events are primarily produced by the decay $\chi_1^{\pm}\chi_2^0 \rightarrow \ell^{\pm}\ell^{\pm}\ell^{\mp}\chi^0\chi^0\nu$. However, this analysis is sensitive as well to like-sign dileptons produced in the sequential decays of squarks and gluinos and even to production of charginos with gluinos. Here the efficiency (which now includes the branching ratio to leptons imposed by the model) ranges from 0.02% to 0.12%. We calculate exclusion limits on the cross section versus m_0 and $m_{1/2}$, including the 17% systematic uncertainty. We use the available next-to-leading order corrections (20%–40%) to the cross sections [14,15]. Using predicted cross sections for mSUGRA as a function of these parameters, we construct an excluded region in $m_0 - m_{1/2}$ space, as shown in Fig. 4. Previous exclusions, based on missing energy in multijet events [16], have already covered all of this space, but with an entirely different technique.

We have shown in feasibility studies that the like-sign dilepton signature considered here and the previously published trilepton signatures [3,4] can be significantly complementary, depending on the physics process considered. For the Run II data, it will be possible to analyze the data simultaneously from both perspectives and obtain a sensitivity to mSUGRA space greater than either analysis alone.

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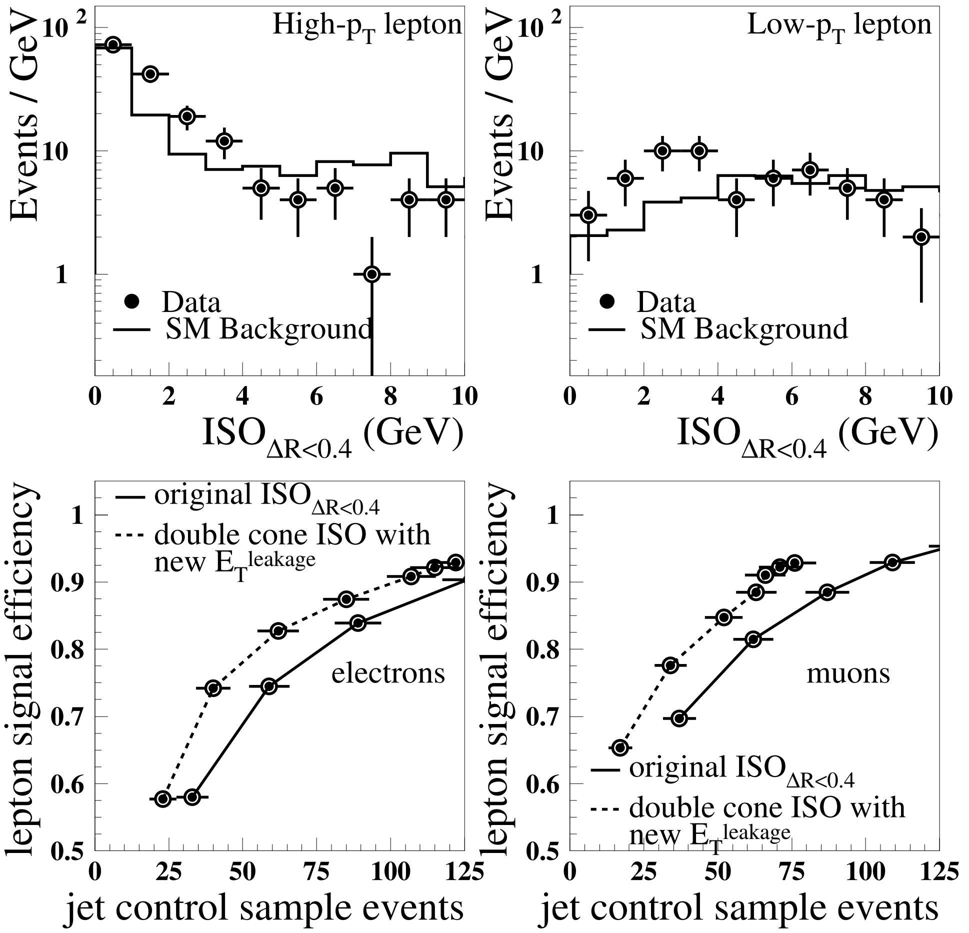

FIG. 1. Distributions of the new ISO variable. (a) and (b) show the energy spectrum in the $ISO_{\Delta R \leq 0.4}$ cone for the high and low-p_T leptons in the OS dilepton pair control sample. (c) and (d) show lepton signal efficiency as a function of selected number of jet control sample events for the original and new double cone ISO with a redefined $E_T^{leakage}$. Each point on the curves represents a fixed cut on the energy in the ISO cone. Errors are statistical only.

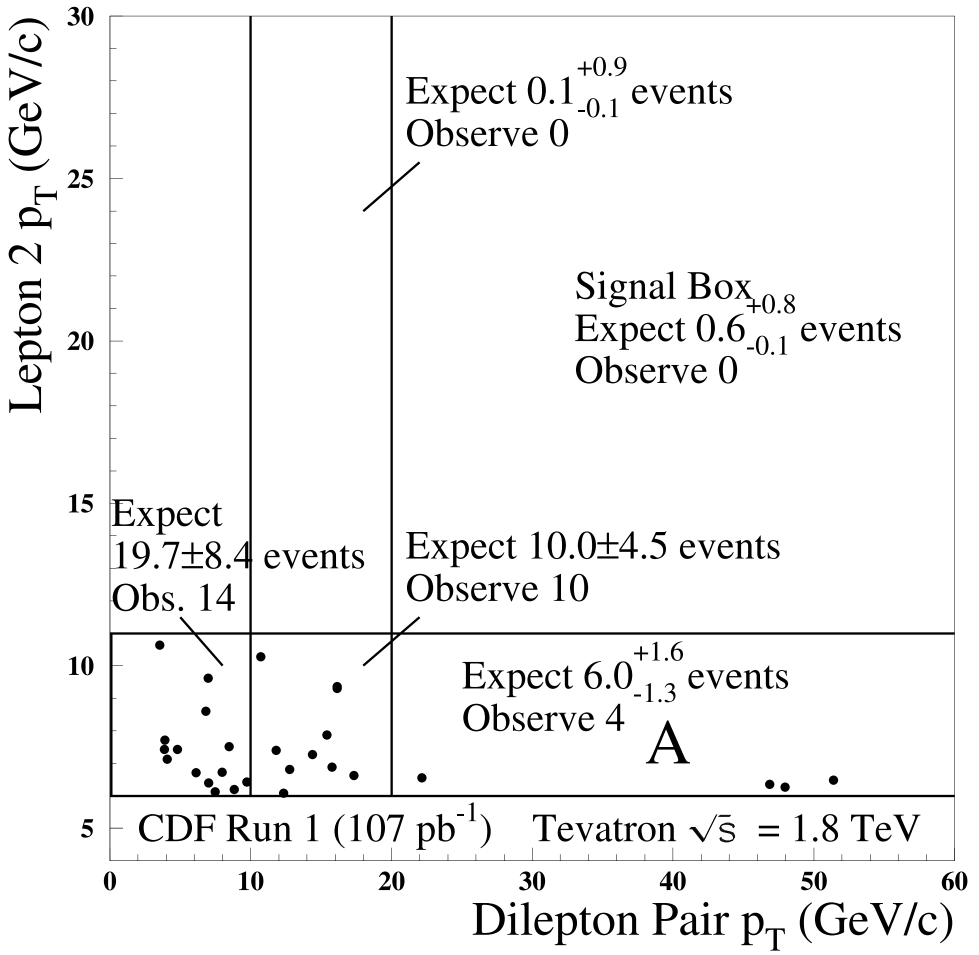

FIG. 2. Predicted and observed events in kinematical regions adjacent to the signal region. The SM background prediction and events observed in region A are considered in greater detail in Table I. Errors include statistical and systematic.

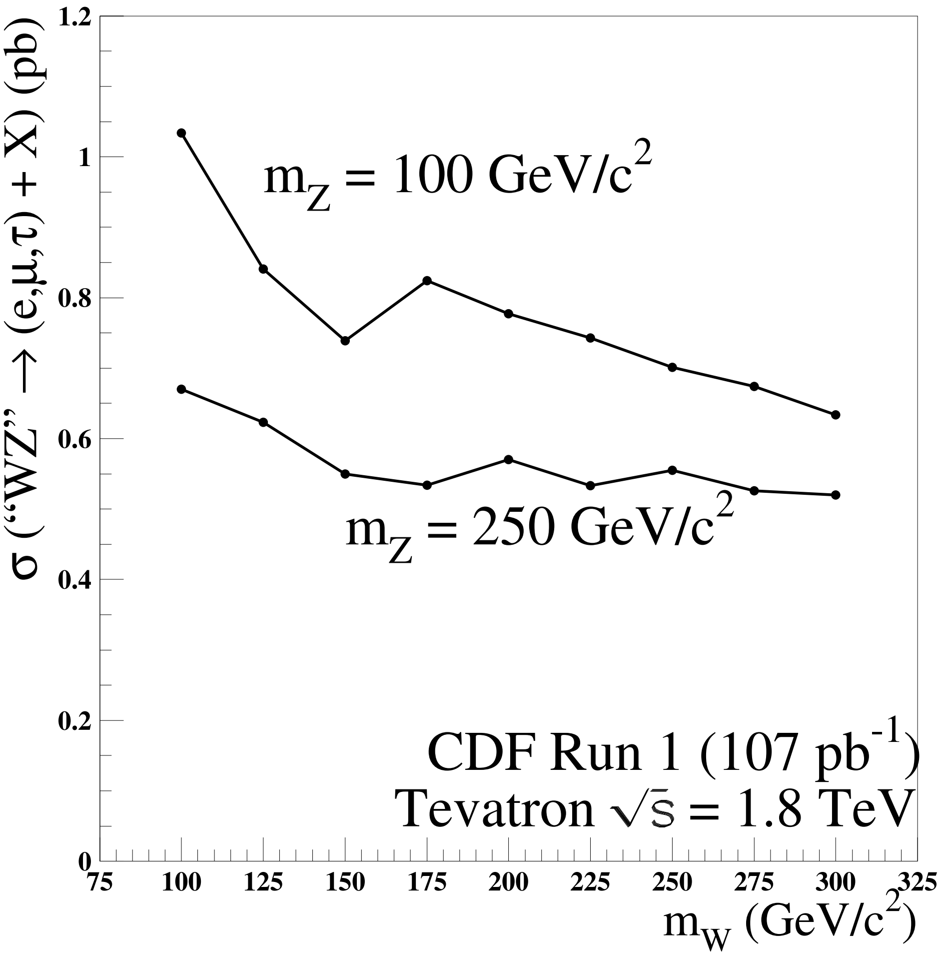

FIG. 3. The 95% confidence limit on the cross section for "WZ-like" production as a function of the W-like particle mass, for two values of the mass of the Z-like particle.

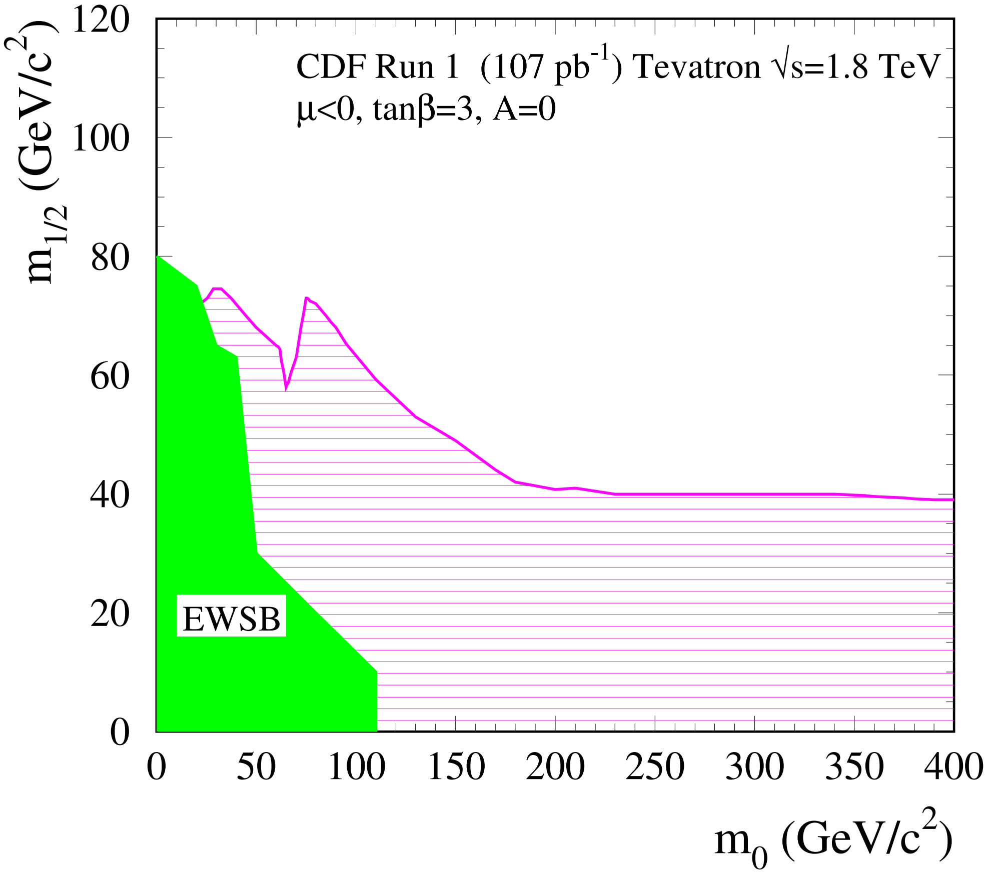

FIG. 4. The 95% confidence limit on the parameters m_0 and $m_{1/2}$ in the mSUGRA framework for $\tan\beta = 3$, $\mu < 0$ and $A = 0$ (hatched region). The solid region labeled "EWSB" is theoretically forbidden as it leads to unphysical sparticle mass predictions. The feature near 75 GeV/c^2 is an artifact of the sneutrino sector of the mSUGRA model.