Search for Pair Production of Supersymmetric Top Quarks in Dilepton Events from pp[over-bar] Collisions at [sqrt]s=1.96 TeV

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Search for Pair Production of Supersymmetric Top Quarks in Dilepton Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the results of a search for pair production of the supersymmetric partner of the top quark (the top squark $\tilde{t}_1$) decaying to a b quark and a chargino $\tilde{\chi}_1^{\pm}$ with a subsequent $\tilde{\chi}_1^{\pm}$ decay into a neutralino $\tilde{\chi}_1^0$, lepton ℓ, and neutrino ν. Using a data sample corresponding to 2.7 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the CDF II detector, we reconstruct the mass of top squark candidate events and fit the observed mass spectrum to a combination of standard model processes and $\tilde{t}_1\bar{\tilde{t}}_1$ signal. We find no evidence for $\tilde{t}_1\bar{\tilde{t}}_1$ production and set 95% C.L. limits on the masses of the top squark and the neutralino for several values of the chargino mass and the branching ratio $\mathcal{B}(\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \ell^{\pm} \nu)$.

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Supersymmetry (SUSY) [1] is a plausible extension to the standard model (SM) of particle physics that naturally solves the hierarchy problem, predicts the unification of the gauge coupling constants, and provides a possible candidate for dark matter. In SUSY, a new spin-based symmetry turns a bosonic state into a fermionic state (and vice versa), postulating the existence of a superpartner for each of the known fundamental particles. To be reconciled with experimental data, SUSY must be broken, and thus supersymmetric particles are expected to be much heavier than their SM partners. An exception to this might come from the partner of the top quark t, the top squark, whose low-mass eigenstate $\tilde{t}_1$ may be lighter than the top quark due to the substantial top-Yukawa coupling [2]. This mass inequality $m_{\tilde{t}_1} \lesssim m_t$ is favored in supersymmetric electroweak baryogenesis scenarios [3].

In canonical SUSY models R parity is conserved, the lightest supersymmetric particle (LSP) is the neutralino $\tilde{\chi}_1^0$, and top squarks $\tilde{t}_1$ are expected to be pair produced via the strong interaction. The $\tilde{t}_1\bar{\tilde{t}}_1$ cross section depends primarily on the mass of the top squark $m_{\tilde{t}_1}$, and at the Tevatron is expected to be an order of magnitude smaller than that for top quarks of the same mass [4,5]. If the chargino $\tilde{\chi}_1^{\pm}$ is lighter than the $\tilde{t}_1$, the decay channel $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ becomes dominant. Subsequent chargino decays via $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \ell^{\pm} \nu$ result in experimental event signatures with two energetic, oppositely charged leptons, two jets from the bottom quarks, and a large imbalance in energy from the lack of detection of the neutrinos and neutralinos. This event signature is identical to the dilepton final state of top pair decays ($t\bar{t} \to W^+ b W^- \bar{b} \to \ell^+ \nu b \ell'^- \bar{\nu}' \bar{b}$). Therefore, an admixture of top squark events with the top dilepton events could impact measurements of the properties of the top quark, such as the mass value. This search was in part motivated by apparent inconsistencies in the top mass measurements between different top decay channels observed in the early CDF and D0 Run II data [6]. Previous searches for top squark decays $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ [7] did not exclude any region in the SUSY parameter space.

In this Letter we present the results of a search for pair production of scalar top quarks, each decaying as $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm} \to b\tilde{\chi}_1^0 \ell^{\pm} \nu$. We analyze a data set corresponding to 2.7 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions collected by the upgraded Collider Detector at Fermilab (CDF II) [8,9], and fit the data with the $\tilde{t}_1\bar{\tilde{t}}_1$ production hypothesis.

We identify and record events containing e or μ candidates with large transverse momenta ($p_T \geq 18$ GeV/c) using high-speed trigger electronics. The performance of the trigger and lepton identification (ID) algorithms is described elsewhere [10]. We identify final state quarks as jets of hadrons in the calorimeter. Jet reconstruction employs an iterative cone-based clustering algorithm that associates calorimeter energy deposits within a cone of $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. The energies of reconstructed jets and the missing transverse energy ($\not\!\!E_T$) [11] are corrected for detector nonuniformity and other effects [12]. Bottom quark candidates are identified (or "b tagged") through the presence within the jet cone of a displaced secondary vertex arising from the decay of a long-lived bottom hadron [13].

The first stage of the $\tilde{t}_1\bar{\tilde{t}}_1$ candidate event selection requires two leptons (e or μ) with $p_T > 20$ GeV/c, $|\eta| < 2.0(1.0)$ for $e(\mu)$, at least one of which is isolated [14], and $m_{\ell^+\ell'^-} > 20$ GeV/c^2. We also require two or more jets with $E_T > 12$ GeV within the region $|\eta| < 2.4$, and $\not\!\!E_T > 20$ GeV. For events with leptons compatible with originating from a Z boson in the mass window from 76 GeV/c^2 to 106 GeV/c^2, we apply a requirement on the missing transverse energy significance $\not\!\!E_T^{\mathrm{sig}} > 4\sqrt{\mathrm{GeV}}$ [15]. Selected events are divided into two categories based on whether any of the jets is identified as a b jet (b-tagged channel) or not (non-b-tagged channel). Further optimized event selection criteria are used in the last stage of the analysis.

The dominant SM process that contributes to the dilepton + jets + $\not\!\!E_T$ event signature is $t\bar{t}$ production. Other SM processes include Z/γ^* + jets, diboson, and W + jets production, where a real lepton comes from the W decay and one of the jets is misidentified as a second lepton. We use the PYTHIA v6.216 Monte Carlo (MC) event generator [16] to simulate $\tilde{t}_1\bar{\tilde{t}}_1$, $t\bar{t}$, and diboson processes. The $\tilde{t}_1\bar{\tilde{t}}_1$ signal is normalized according to the next-to-leading order (NLO) theoretical cross section obtained from PROSPINO2 [17] using the CTEQ6M [18] parton density functions (PDF). For $t\bar{t}$ we use the NLO theoretical cross section value of 7.3 pb [5], corresponding to the world average top mass of 172.5 GeV/c^2 [19], which is dominated by the measurements in the lepton +jets channel of $t\bar{t}$ decays. Diboson processes (WW, WZ, ZZ) are normalized to their NLO theoretical cross sections [20]. Z/γ^* events with associated jets are simulated with the ALPGEN v2.13 matrix element generator [21], interfaced to PYTHIA v6.325, and normalized to data in the Z-mass-peak region. The detector response in all MC samples is modeled by a GEANT-based CDF II detector simulation [22]. The W + jets background is modeled using data by measuring relative rates of jets being misidentified as charged leptons in inclusive jet data samples and applying them to data events with exactly one lepton plus jets. We validate the background modeling of dilepton events by comparing the predictions with observations using control samples that are independent of the signal sample. These include samples of events with low $\not\!\!E_T$, events with zero or one jet, and events with same-sign charged leptons.

To enhance the search sensitivity, we perform a kinematic reconstruction of events under the $\tilde{t}_1\bar{\tilde{t}}_1$ production and decay hypothesis. We use as inputs the measured four-momenta of the two leptons and of the two largest E_T jets, and the $\vec{\not\!\!E}_T$. Because of the unknown masses of the supersymmetric $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$, and because the two neutrinos and the two massive neutralinos escape detection, the kinematics of $\tilde{t}_1\bar{\tilde{t}}_1$ events is severely underconstrained. Therefore, we employ the following strategy. First, we use $m_{\tilde{\chi}_1^{\pm}}$ as a fixed parameter, and perform the reconstruction for different values of $m_{\tilde{\chi}_1^{\pm}}$. Second, we treat the $\tilde{\chi}_1^0\nu$ pair corresponding to each $\tilde{t}_1$ decay as one "massive particle." To compensate for nonresonant structure of the invariant mass of the $\tilde{\chi}_1^0\nu$ pair we assign to this "massive particle" a large width. Based on studies carried out on MC samples for a wide range of neutralino masses ($m_{\tilde{\chi}_1^0} \approx 46$–$90\ \text{GeV}/c^2$) we fix the values of $m_{\tilde{\chi}_1^0\nu}$ and $\Gamma_{\tilde{\chi}_1^0\nu}$ to 75 GeV/c^2 and 10 GeV/c^2, respectively. Third, to avoid the twofold ambiguity in assigning a b jet to a lepton, we always choose the combination that yields the smallest sum of invariant masses of a paired b jet and lepton. This approach identifies the correct pairing in ~90% of cases in the $\tilde{t}_1$ mass regime considered.

The system of kinematic equations consists of constraints imposed on the particle masses $m_{\tilde{\chi}_1^{\pm}}$, $m_{\tilde{\chi}_1^0\nu}$, $m_{\tilde{t}_1} = m_{\bar{\tilde{t}}_1}$, and the requirement of transverse momentum conservation: $\vec{\not\!\!E}_T = \vec{p}_T(\tilde{\chi}_1^0\nu)_1 + \vec{p}_T(\tilde{\chi}_1^0\nu)_2$. If the azimuthal directions ϕ_1 and ϕ_2 of the four-momenta of the $(\tilde{\chi}_1^0\nu)_1$ and $(\tilde{\chi}_1^0\nu)_2$ pairs are fixed, the event kinematics (with the exception of the singular points $\phi_1 - \phi_2 = k\pi$, where k is an integer) is constrained. There exist four solutions due to the twofold ambiguities in resolving the z components of the $(\tilde{\chi}_1^0\nu)_1$ and $(\tilde{\chi}_1^0\nu)_2$ four-momenta. We perform a scan of the entire parameter space of azimuthal angles wherein we repeat the reconstruction for different values of (ϕ_1, ϕ_2), avoiding the aforementioned singular points. The $\tilde{t}_1$ mass is reconstructed by minimizing the event χ^2, which takes the following form:

$$\chi^2 = \sum_{k=1,2}\left\{\frac{(m^{\text{fit}}_{(\tilde{\chi}_1^0\nu)_k} - m_{\tilde{\chi}_1^0\nu})^2}{\Gamma^2_{\tilde{\chi}_1^0\nu}} + \frac{(m^{\text{fit}}_{(\tilde{\chi}_1^0\nu\ell)_k} - m_{\tilde{\chi}_1^{\pm}})^2}{\Gamma^2_{\tilde{\chi}_1^{\pm}}} + \frac{(m^{\text{fit}}_{(\tilde{\chi}_1^0\nu\ell j)_k} - m^{rec}_{\tilde{t}_1})^2}{\Gamma^2_{\tilde{t}_1}}\right\} + \sum_{i=2\ell,2\text{jets}}\frac{(p^{\text{fit}}_{T,i} - p^{\text{meas}}_{T,i})}{\sigma^2_{p_{T,i}}}. \tag{1}$$

Here we assume $\Gamma_{\tilde{\chi}_1^{\pm}} \equiv 2\ \text{GeV}/c^2$ and $\Gamma_{\tilde{t}_1} \equiv 1.5\ \text{GeV}/c^2$, the k index represents the decay products from $\tilde{t}_1$ or $\bar{\tilde{t}}_1$, respectively, and the m^{fit} are the invariant masses of the final decay products from $\tilde{t}_1$ decays. We let the four-momenta of the leptons and the jets vary in the fit, and use the MINUIT package [23] to minimize the χ^2. At each step during the minimization procedure the $\vec{\not\!\!E}_T$ is recalculated according to the values of p_T^{fit} of the leptons and jets. The longitudinal components of $(\tilde{\chi}_1^0\nu)_1$ and $(\tilde{\chi}_1^0\nu)_2$ are free parameters in the fit with starting values initialized to the values corresponding to solutions of the system of kinematic equations. All four starting values are tried in the fit, but only the one that gives the lowest χ^2 is kept. The value $m^{\text{rec}}_{\tilde{t}_1}$ at which χ^2 is minimized yields the $\tilde{t}_1$ reconstructed mass for a given pair of the azimuthal angles (ϕ_1, ϕ_2). Finally, we integrate $m^{\text{rec}}_{\tilde{t}_1}(\phi_1, \phi_2)$ weighted by the goodness of fit term $e^{-\chi^2(\phi_1,\phi_2)}$ over ϕ_1 and ϕ_2 to obtain the $\tilde{t}_1$ reconstructed mass for each event. Running the reconstruction algorithm over simulated $\tilde{t}_1\bar{\tilde{t}}_1$ events yields a distribution with a peak near the generated $\tilde{t}_1$ mass, as shown in Fig. 1, and provides discrimination between a $\tilde{t}_1\bar{\tilde{t}}_1$ signal and SM backgrounds [24].

We perform an extended likelihood fit of the observed mass spectrum simultaneously in the b-tagged and the non-b-tagged channels. To quantify the level of agreement we employ a modified frequentist method, CL_s [25], based on a log-likelihood ratio test statistic, which involves computing p values under the hypothesis of the SM background only and the hypothesis of signal plus background. The systematic uncertainties for both signal and background, described below, enter the fit as Gaussian-constrained nuisance parameters. The uncertainties due to kinematic mismodeling are taken into account by allowing the reconstructed mass distributions to change according to the values of the nuisance parameters [26].

Imperfect knowledge of various experimental and theoretical parameters leads to systematic uncertainties that degrade our sensitivity to a $\tilde{t}_1\bar{\tilde{t}}_1$ signal. The dominant

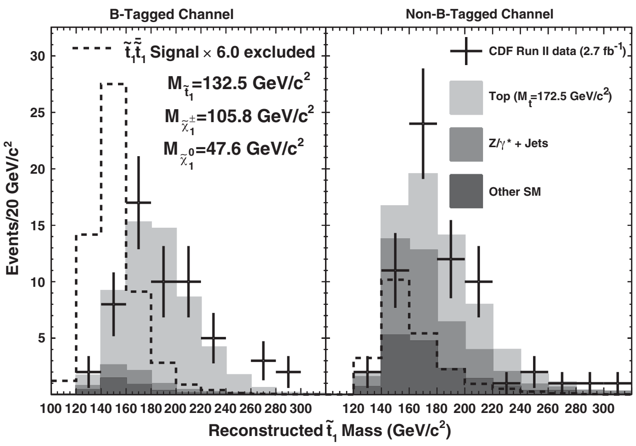

FIG. 1. The reconstructed $\tilde{t}_1$ mass distribution. The dashed line represents an example of the $\tilde{t}_1\bar{\tilde{t}}_1$ signal distribution.

systematic effect is due to the uncertainties in the NLO theoretical cross sections for $\tilde{t}_1\bar{\tilde{t}}_1$ and $t\bar{t}$ production. These uncertainties come from two sources: the renormalization and factorization scale (11% and 7% for $\tilde{t}_1\bar{\tilde{t}}_1$ and $t\bar{t}$, respectively) and PDFs (14% and 7%) [4,5]. We assume that the scale uncertainty is uncorrelated for $\tilde{t}_1\bar{\tilde{t}}_1$ and $t\bar{t}$ processes, while the PDF uncertainty is fully correlated. The theoretical uncertainty of the diboson cross sections is 10% [20], and assumed to be uncorrelated with other systematic uncertainties. The experimental uncertainties applied to MC-based background estimates include those due to jet energy scale (3%), b-tagging probability (5%), lepton ID and trigger efficiencies (1% per lepton), initial and final state radiation (2%), and the integrated luminosity (6%). The uncertainty on W + jets is dominated by the uncertainties in the rate to misidentify jets as leptons (30%), while the uncertainty on Z/γ^* + jets comes from MC mismodeling of the high-$\not{E}_T$ tail, jet multiplicity distribution, and Z/γ^*+ heavy-flavor contribution (16%).

Prior to looking at data in the signal sample we study the sensitivity of the search, taking into account all systematic effects, for various event selection criteria imposed separately for the b-tagged and the non-b-tagged channels. An algorithm based on biological evolution (a so-called genetic algorithm) [27] is employed to determine the most sensitive selection criteria. Requirements yielding poorer expected 95% C.L. limit are culled, while those improving the limit are bred together until reaching a plateau. This procedure optimizes the event selection criteria directly to produce the best expected 95% C.L. limit in the no-signal hypothesis.

In the b-tagged (non-b-tagged) channel the optimization procedure yields the following event selection criteria [28]: the leading jet E_T is required to be greater than 15 (20) GeV, and the subleading jet E_T must be greater than 12 (20) GeV. In both channels we require $\not{E}_T > 20$ GeV, while this requirement is tightened to 50 GeV in the non-b-tagged channel if there is a lepton or jet within an azimuthal angle of 20° from the $\vec{\not{E}}_T$ direction. Because of the fact that the $\tilde{t}_1$ is a scalar particle, and the top quark is a fermion, the angular distributions of their final decay products are very distinct. Therefore we implement an additional topological cut in both the b-tagged and non-b-tagged channels to suppress $t\bar{t}$ events:

$$\sum p_T < \left(\frac{\Delta\phi_{jj} \times \Delta\phi_{\ell\ell}}{\pi^2} \times 325 + 215\right) \text{GeV}/c, \qquad (2)$$

where $\sum p_T$ is the scalar sum of transverse momenta of the leptons, jets and the $\not{E}_T$, the $\Delta\phi_{jj}$ and $\Delta\phi_{\ell\ell}$ are the azimuthal angles between the jets and leptons, respectively, and the numerical values are the result of the optimization procedure. This requirement rejects about 50% of $t\bar{t}$ events and only about 10% of $\tilde{t}_1\bar{\tilde{t}}_1$ events.

After applying these event selection requirements we obtain the numbers of predicted and observed events listed in Table I. The data distributions of the reconstructed $\tilde{t}_1$ mass in both channels are shown in Fig. 1, together with the expectations from SM processes and an example of $\tilde{t}_1\bar{\tilde{t}}_1$ signal. The data are consistent with the SM alone and there is no evidence of $\tilde{t}_1\bar{\tilde{t}}_1$ production. We use these results to calculate the 95% C.L. exclusion limits in the $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{t}_1}$ plane for several values of the branching ratio $\mathcal{B}(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu)$ and $m_{\tilde{\chi}_1^\pm}$, assuming equal branching ratios into different lepton flavors and $\mathcal{B}(\tilde{t}_1 \to \tilde{\chi}_1^\pm b) = 100\%$. The limits for two different values of chargino mass are presented in Fig. 2. For a given branching ratio of the pair of top squarks decaying into leptons, equal to $\mathcal{B}^2(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu)$, we exclude the top squark and neutralino masses below the respective curve shown in the plot. The values $\mathcal{B}^2(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu)$ are expected to range from almost 100%, corresponding to the scenario with light sleptons and sneutrinos ($m_{\tilde{\ell}}, m_{\tilde{\nu}} \gtrsim m_{\tilde{t}_1}$), where the leptonic decay of the chargino goes mostly through virtual sleptons and sneutrinos, down to 11%, where sleptons and sneutrinos are heavy ($m_{\tilde{\ell}}, m_{\tilde{\nu}} \gg m_W$) and the chargino decay through a virtual W is dominant. For the scenario corresponding to the case in which the masses of the chargino and neutralino are near the current lower LEP exclusion limits, $m_{\tilde{\chi}_1^\pm} = 105.8$ GeV$/c^2$, $m_{\tilde{\chi}_1^0} = 47.6$ GeV$/c^2$ [29], we exclude a top squark with masses between 128 and 135 GeV$/c^2$ at 95% C.L. independent of the value of $\mathcal{B}^2(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu)$. The limits obtained are applicable to any R parity conserving SUSY scenario where the neutralino is the LSP and the $\tilde{t}_1$ decays exclusively into $\tilde{\chi}_1^\pm b$, and are the first lower limits on $\tilde{t}_1$ mass in this mode.

In conclusion, we have presented the results of a search for pair production of supersymmetric top quarks decaying

TABLE I. The expected event yields from SM processes with the total uncertainties and the observed numbers of events in the signal region.

	Events per 2.7 fb^{-1} in the signal region.					
	Top	Z/γ^* + jets	Diboson	W + jets	Total	Data
b tag	49.0 ± 6.9	4.0 ± 0.4	0.5 ± 0.1	2.8 ± 0.9	56.4 ± 7.2	57
no tag	25.2 ± 3.3	25.0 ± 5.6	6.0 ± 1.3	9.8 ± 2.9	65.9 ± 9.8	65

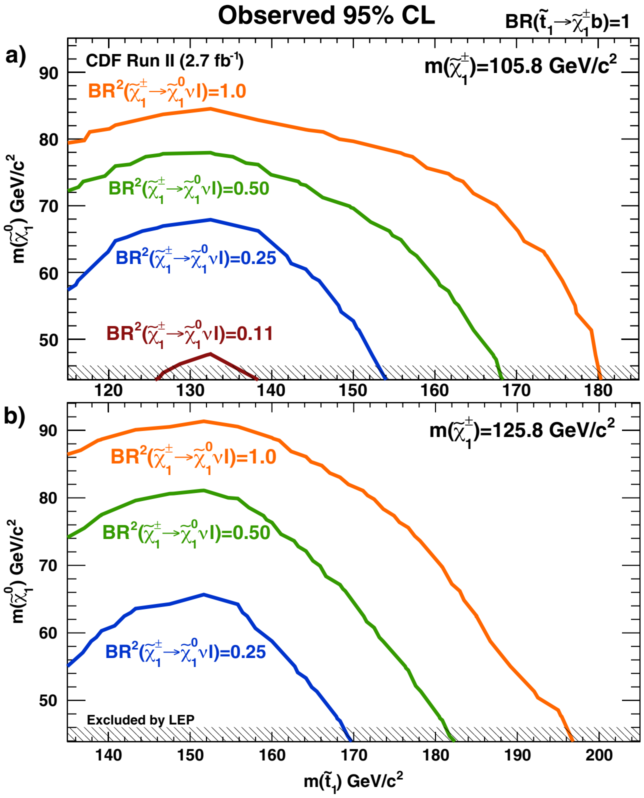

FIG. 2 (color online). The observed 95% C.L. exclusion regions in the $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1}$ mass plane for several values of $\mathcal{B}(\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \ell^{\pm} \nu)$ and $m_{\tilde{\chi}_1^{\pm}}$. The excluded region corresponds to the area below the lines. Universality of e, μ, and τ in the $\tilde{\chi}_1^{\pm}$ decays is assumed.

via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 \ell^{\pm} \nu$ using a data sample corresponding to 2.7 fb^{-1} of integrated luminosity in 1.96 TeV $p\bar{p}$ collisions. Our fit to the observed $m_{\tilde{t}_1}^{\text{rec}}$ distribution reveals no evidence for $\tilde{t}_1\bar{\tilde{t}}_1$ production, and we place the world's first limits on the masses of $\tilde{t}_1$ and $\tilde{\chi}_1^0$ for several values of $m_{\tilde{\chi}_1^{\pm}}$ and branching ratio of $\mathcal{B}(\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \ell^{\pm} \nu)$ in this mode.

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[29] LEP SUSY Working Group (ALEPH, DELPHI, L3, and OPAL experiments), notes No. LEPSUSYWG/01-03.1, No. LEPSUSYWG/02-06.2.