Searches for New-Physics Effects in the D0 Experiment: Latest Results

FERMILAB-CONF-09-839-E-PPD

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Received March 21, 2008; in final form, November 7, 2008

Abstract—Latest results obtained in searches for particles and phenomena beyond the Standard Model (new-physics effects) in the D0 experiment at the Tevatron accelerator (FNAL, USA) on the basis of statistics corresponding to the integrated luminosity of about 1 fb^{-1} are surveyed.

PACS numbers: 4.50.Cd, 12.10.Dm, 12.60.Cn, 12.60.Jv, 12.60.Rc
DOI: 10.1134/S1063778809040152

1. INTRODUCTION

The Standard Model [1] has demonstrated its viability throughout many years of investigations, satisfactorily describing processes and phenomena observed in particle physics. Yet, it is not free from significant drawbacks, which trigger searches for Standard Model extensions that could provide answers to unresolved problems, including those of hierarchy, dark-matter phenomenon, and gauge-coupling unification. All of them call for an explanation.

Before the commissioning of the Large Hadron Collider (LHC, CERN), the Tevatron accelerator (FNAL, USA), its c.m. energy of colliding beams being 1.96 TeV, has provided the most appropriate ground for new-physics searches. In the D0 experiment, extensive investigations, including searches for supersymmetric partners of quarks, gluons, and gauge and Higgs bosons; searches for leptoquarks; searches for additional spatial dimensions and effects associated with them; searches for new heavy gauge bosons; and searches for excited states of leptons have been performed along these lines. The latest results obtained on the basis of statistics corresponding to the integrated luminosity of about 1 fb^{-1} are examined in the present article.

2. SUPERSYMMETRY

Sypersymmetric theories postulate the existence of symmetry between boson and fermion states and predicts the presence of supersymmetric partners for the Standard Model particles, the partners differing only in spin values (bosons correspond to fermions, and vice versa). The concept of R parity, which is a multiplicative quantum number equal to $+1$ for the Standard Model particles and -1 for their supersymmetric partners, is introduced in the theory, R-parity conservation being postulated in minimal supersymmetric extensions of the Standard Model (Minimal Supersymmetric Standard Model or MSSM). (Yet, there are supersymmetric models in which R parity is not conserved.) The conservation of R parity has two important implications: supersymmetric particles arise in pairs, and the lightest of the supersymmetric particles is stable (this provides a natural solution to the dark-matter problem). No experimental proof of the existence of supersymmetric particles has been found so far, which suggests their high mass and, hence, a large mass difference between the Standard Model particles and their supersymmetric partners. This in turn means that supersymmetry (SUSY) is a broken symmetry. Several mechanisms of SUSY breaking have been proposed. In this connection, the model of minimal supergravity (mSUGRA), where SUSY breaking is due to interaction with gravity, is of particular interest for the present discussion. This model is characterized by five main parameters: m_0 and $m_{1/2}$, which are universal masses for the scalar and gauge supersymmetric partners on the Grand Unification scale; A_0, which is a universal trilinear coupling constant on the Grand Unification scale; tanβ, which is the ratio of the vacuum expectation values of the Higgs fields; and sign(μ), which is the sign of the higgsino mass parameter.

2.1. Searches for Supersymmetric Partners Quarkов and Gluons

In SUSY-inspired models, ordinary particles and the lightest supersymmetric particle (LSP), which are stable, are produced in the final state of the decays of supersymmetric partners of quarkов (squarks) and

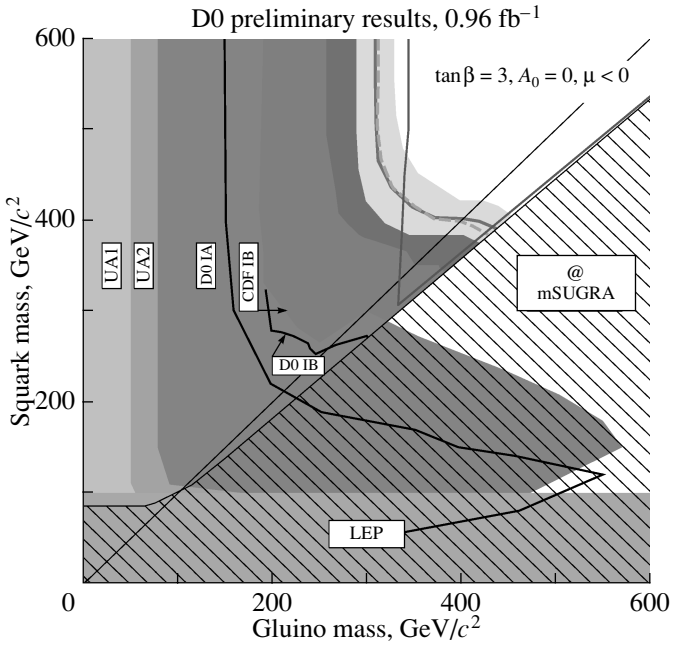

Fig. 1. Region excluded by the present analysis in the plane of squark and gluino masses. The expected upper limit (in the absence of a signal) is shown by the dashed line. The results of earlier experiments are shown for the sake of comparison.

gluons (gluinos). In mSUGRA, these are the lightest of the neutralinos ($\tilde{\chi}_1^0$), supersymmetric partners neutral gauge and Higgs bosons. The LSP is coupled to matter only via weak interaction. Therefore, it escapes detection, contributing to the missing energy.

Double squark and gluino production is expected to be dominant at hadron colliders. If the squark mass is smaller than the gluino mass (small values of the parameter m_0), the double production of squarks will be dominant. Product squarks then decay to an ordinary quark and an LSP ($\tilde{q} \to q\tilde{\chi}_1^0$), thereby forming a final state featuring two acoplanar jets and a large missing transverse energy (so-called dijet topology). If the gluino mass is less than the squark mass (large values of the parameter m_0), then double gluino production will be dominant. Product gluinos undergo decay through the channel $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, and this leads to final states featuring four or more jets and a large missing transverse energy (gluino topology). In the intermediate case of commensurate squark and gluino masses, a significant contribution of double squark–gluino production is possible, which would lead to final states involving three or more jets and a large missing transverse energy (three-jet topology).

In the D0 experiment, searches for squarks and gluinos were performed within all of the aforementioned three topologies on the basis of statistics corresponding to the integrated luminosity of 0.96 fb^{-1} [2]. The background here is dominated by processes involving W and Z bosons and processes featuring t-quark production and decay [$Z \to \nu\bar{\nu} +$ jets and $W \to l\nu +$ jets, $t\bar{t}$, $WW/WZ/ZZ$], as well processes featuring single t-quark production.

The ALPGEN [3] and PYTHIA [4] generators with the CTEQ6L1 set of structure functions [5] were used to simulate Standard Model background processes. The CompHEP code [6] was employed to simulate processes involving single t-quark production.

The results of an analysis of all three topologies are given in Table 1, where the numbers of events that remained after the application of all selections and cuts [2] are presented along with the expected numbers of events of the simulated Standard Model backgrounds.

Table 1 shows that the numbers of events in the data of the experiment being discussed correspond to Standard Model productions; therefore, we can conclude that the statistical data sample presented

Table 1. Numbers of events for various topologies after the application of all selections and cuts: observed data and expected Standard Model backgrounds

Topology	Data	Background
"dijet"	5	7.47 ± 1.06 (stat.)$^{+1.32}_{-1.02}$ (syst.)
"three-jets"	6	6.10 ± 0.37 (stat.)$^{+1.26}_{-1.16}$ (syst.)
"gluino"	34	33.35 ± 0.81 (stat.)$^{+5.56}_{-4.92}$ (syst.)

Table 2. Numbers of events for various topologies after the application of all selections and cuts: observed data, expected Standard Model backgrounds, and mSUGRA results

Topology	data	Background	mSUGRA
ee + track	0	0.76 ± 0.67 (stat.)	3.45 ± 0.01 (stat.)
$e\mu$ + track	0	$0.94^{+0.40}_{-0.13}$ (stat.)	2.80 ± 0.11 (stat.)
$\mu\mu$ + track	2	$0.32^{+0.73}_{-0.03}$ (stat.)	1.83 ± 0.10 (stat.)
Likely charged $\mu\mu$	1	1.1 ± 0.4 (stat.)	4.0 ± 0.4 (stat.)

here exhibits no evidence of double squark and gluino production within the topologies under consideration. Upper limits on the cross sections for squark and gluino production versus their masses were calculated for all three of these topologies (at the mSUGRA parameter values of $A_0 = 0$, $\tan\beta = 3$, and $\mathrm{sign}(\mu) < 0$); also, lower limits on their masses were obtained at a confidence level of 95%:

$$m_{\tilde{q}} > 375\ \mathrm{GeV}/c^2, \quad (\text{“dijet”}, m_0 = 25\ \mathrm{GeV}/c^2); \tag{1}$$

$$m_{\tilde{q}} = m_{\tilde{g}} > 383\ \mathrm{GeV}/c^2, \quad (\text{“three-jets”});$$

$$m_{\tilde{g}} > 289\ \mathrm{GeV}/c^2, \quad (\text{“gluino”}, m_0 = 500\ \mathrm{GeV}/c^2).$$

The corresponding limits obtained in the CDF experiment on the basis of a somewhat vaster statistics ($1.4\,\mathrm{fb}^{-1}$) and for a somewhat different choice of mSUGRA parameters ($A_0 = 0$, $\tan\beta = 5$, and $\mathrm{sign}(\mu) < 0$) [7] are 375, 380, and 280 GeV/c^2, respectively.

In the plane spanned by the squark and gluino masses, Fig. 1 shows regions excluded by the above analysis. The respective results obtained previously in several experiments are also displayed here for the sake of comparison.

2.2. Searches of Supersymmetric Partners of Gauge Bosons

Searches for supersymmetric partners of gauge bosons were performed in channels characterized by the presence of three final-state leptons and a large missing energy. Processes involving the double production of charged ($\tilde{\chi}_1^{\pm}$) and neutral ($\tilde{\chi}_2^0$) supersymmetric partners, which subsequently decay to leptons and LSP through intermediate gauge bosons and sleptons ($p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to lll\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$), are the most probable processes involving supersymmetric particles and leading to this topology at hadron colliders. In the D0 experiment, an identification of the particle type was required only for two leptons in order to improve the detection efficiency for such processes; that is, final states featuring ee, $\mu\mu$, and $e\mu$+ isolated track in the central tracker and a large missing energy were considered [8, 9]. The primary statistical sample for all three channels corresponded to the integrated luminosity of $1.1\ \mathrm{fb}^{-1}$.

The case where the intermediate-slepton mass is somewhat smaller than the $\tilde{\chi}_2^0$ mass is also of interest. The transverse momentum of the third lepton in the final state may then be quite low, and so will accordingly be the detection efficiency for such a lepton. In this case, the topology featuring two likely charged leptons and a large missing energy is used in searches for supersymmetric particles. In the D0 experiment, this topology was studied on the basis of statistics corresponding to the integrated luminosity of $0.9\ \mathrm{fb}^{-1}$ [10].‘

Here, processes involving W and Z bosons (for example, $Z/\gamma \to ll$, $W + \gamma \to l\nu + \gamma$, and $WW \to ll\nu\nu$) and various QCD processes are dominant Standard Model background processes. For the topology involving two likely charged muons, the background is dominated by QCD processes. The PYTHIA generator [4] was used to estimate the contribution of such backgrounds. Generated events were passed through the code for completely simulating the detector response. The background from QCD processes was estimated directly on the basis of live data.

Table 2 presents the numbers of events for all four of the above topologies after the application of all trigger conditions, selections, and cuts [10]. Estimates for the numbers of background events and estimates for the number of events involving supersymmetric-particle production that are expected within mSUGRA are also given. The model parameters used to obtain the corresponding values in Table 2 for the ll + track topologies are the following: $A_0 = 0$, $\tan\beta = 3$, $\mathrm{sign}(\mu) < 0$, $m_0 = 98\ \mathrm{GeV}/c^2$, $m_{1/2} = 192\ \mathrm{GeV}/c^2$, $m_{\tilde{\chi}_1^{\pm}} = 125\ \mathrm{GeV}/c^2$, $m_{\tilde{\chi}_2^0} = 127\ \mathrm{GeV}/c^2$, and $m_{\tilde{l}} = 129\ \mathrm{GeV}/c^2$. For the topology featuring two likely charged muons, the parameters of the mSUGRA model were changed somewhat in order to meet the condition $m_{\tilde{l}} \leq m_{\tilde{\chi}_2^0}$: $m_0 = 68\ \mathrm{GeV}/c^2$, $m_{1/2} = 170\ \mathrm{GeV}/c^2$, $m_{\tilde{\chi}_1^{\pm}} =$

104.3 GeV/c^2, $m_{\tilde{\chi}_2^0} = 108.2$ GeV/c^2, and $m_{\tilde{l}} =$ 100.6 GeV/c^2. In either case, the parameters of the model were chosen in those regions of the model where the probability of the production of final states involving three leptons is enhanced. No statistically significant deviations of the observed numbers of events from Standard Model predictions and, accordingly, no indication of the production of supersymmetric partners of gauge bosons have been revealed.

In order to obtain an upper limit on the cross section for the process in which the production of supersymmetric particles was followed by their decay to three leptons, the results of all four analyses were combined. Figure 2 shows the resulting upper limit as a function of the $\tilde{\chi}_1^{\pm}$ mass for three scenarios of the mSUGRA model. In the large-m_0 scenario, sleptons have quite a high mass, so that W/Z exchange in dominant, in which case the branching ratio for decay to three leptons is relatively small. On the contrary, the $3l$-max scenario is operative under the assumption of relatively light sleptons ($m_{\tilde{l}}$ is only slightly in excess of $m_{\tilde{\chi}_2^0}$). In this case, the branching ratio for decay into three leptons is maximal. In the heavy-quark scenario, which is the last of the three scenarios considered here, the cross section for the production of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pairs is maximized.

A new lower limit on the $\tilde{\chi}_1^{\pm}$ mass was obtained within the $3l$-max scenario: $m_{\tilde{\chi}_1^{\pm}} > 141$ GeV/c^2.

2.3. GMSB SUSY

Speaking of SUSY breaking, we have so far considered only one presumed, gravitational (mSUGRA model), mechanism of this symmetry breaking. However, different mechanisms are also possible. For one, we can consider that which is realized in the model of gauge-mediated SUSY breaking (GMSB) and which is due to interaction with extra gauge fields. In this model, one introduces chiral supermultiplets (so-called messengers) relating supersymmetric particles to the source of SUSY breaking. In the GMSB model, the gravitino plays the role of the LSP, while heavier supersymmetric particles ultimately decay to a gravitino and a photon. In models conserving R parity, the supersymmetric partners of the gauge bosons are produced in pairs ($\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$), so that a pair of energetic photons and a large missing energy carried away by an LSP must be present in the final state.

The minimal GMSB model, in which the energy scale of SUSY breaking, Λ, is the main parameter, was considered in analyzing data from [11]. The remaining model parameters are the number of messengers, $N_m = 1$; their mass, $M_m = 2\Lambda$; $\tan\beta = 15$, and $\mathrm{sign}(\mu) > 0$.

Table 3. Estimated number of events from Standard Model backgrounds, expected numbers of events involving the production of supersymmetric particles for two values of the parameter Λ, and observed number of events for the missing transverse energies $E_T^{(\mathrm{miss})}$ in excess of 30 and 60 GeV after the application of all selections and cuts

$E_T^{(\mathrm{miss})}$, GeV	Background	Λ, TeV		Data
		75	90	
>30	10.8 ± 1.1	28.3 ± 1.0	8.7 ± 0.3	16
>60	1.6 ± 0.4	18.1 ± 0.8	6.4 ± 0.3	3

Supersymmetric particles were sought in the statistical data sample corresponding to the integrated luminosity of 1.1 fb^{-1}. Events involving two high-energy photons and a large missing energy in the final state were selected. In that case, $W/Z + \gamma\gamma \to l\nu/\nu\nu + \gamma\gamma$, $W\gamma$, $W +$ jets, $t\bar{t}$, $Z/\gamma \to ee$, direct photon emission, and the background from QCD processes were dominant Standard Model background processes. The contribution of the majority of these processes to ultimate distributions was estimated directly on the basis of live data; the contribution of the processes $W/Z + \gamma\gamma \to l\nu/\nu\nu + \gamma\gamma$ was estimated by means of simulations with the aid of the CompHEP [6] and MADGRAPH [12] codes.

The results of this analysis are briefly summarized in Table 3. No statistically significant excess of the number of events in live data over that which is expected on the basis of simulations for the number of events from Standard Model backgrounds was found. Since, for all values of the missing energy, the number of observed events is in good agreement with Standard Model predictions, we can conclude that the above analysis did not reveal any piece of evidence of the presence of GMSB SUSY effects (production of supersymmetric particles). An upper limit on the cross section for the production of supersymmetric particles within the GMSB SUSY model as a function of the parameter Λ (as well as a function of the χ_2^0 and $\chi_1^{\pm}$ masses) was determined; the result is shown in Fig. 3. The respective lower limit on the parameter Λ is 92 TeV. The lower limits on the χ_1^0 and $\chi_1^{\pm}$ masses are, respectively, 126 and 231 GeV/c^2 (at a 95% CL).

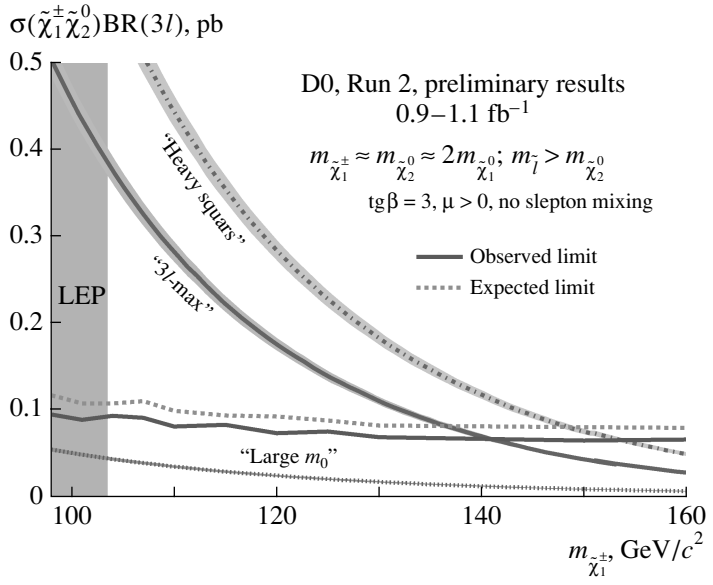

Fig. 2. Upper limit on the product $\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)Br(3l)$ as a function of the $\tilde{\chi}_1^{\pm}$ mass along with its values expected for three scenarios of the mSUGRA model (for the explanation, see main body of the text).

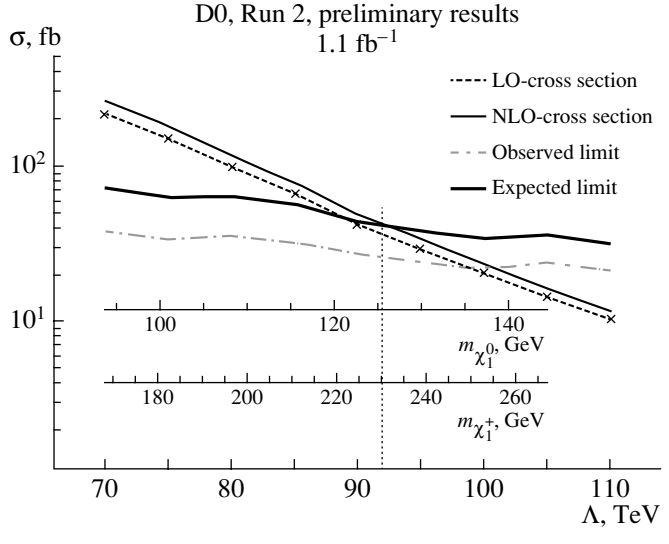

Fig. 3. Upper limit on the cross section for the production of supersymmetric particles as a function of the parameter Λ within the GMSB SUSY model (for explanations, see main body of the text).

3. SEARCHES FOR LEPTOQUARKS

The existence of leptoquarks—that is, scalar and vector bosons having a fractional electric charge (an integral multiple of 1/3), carrying both lepton and quark quantum numbers, and decaying to a lepton and a quark—is predicted in many extensions of the Standard Model, such as Grand Unified Theories (GUT), technicolor, and various theories assuming a composite structure of quarks. It is believed that leptoquarks may decay only to leptons and quarks of corresponding generations; therefore, one distinguishes between the leptoquarks of the first, second, and third generations. Double production is a dominant process that leads to leptoquark production at hadron colliders. The cross section for the production of a leptoquark pair depends on the leptoquark mass, but it is independent of leptoquark coupling to the corresponding lepton and quark.

Searches for the double production of second-generation scalar leptoquarks in the process $p\bar{p} \to$

$LQ_2L\bar{Q}_2 \to \mu\nu qq$ were performed in the D0 experiment on the basis of statistics corresponding to the integrated luminosity of 1.05 fb^{-1} [13]. If we denote by $\beta = \text{Br}(LQ_2 \to \mu q)$ the $LQ_2 \to \mu q$ branching ratio, then $\text{Br}(LQ_2 \to \nu q) = 1 - \beta$ and $\text{Br}(LQ_2L\bar{Q}_2 \to \mu\nu qq) = 2\beta(1-\beta)$. The choice of $\beta = 0.5$ maximizes the corresponding decay branching ratio $\text{Br}(LQ_2L\bar{Q}_2 \to \mu\nu qq) = 0.5$.

The presence in the final state of a high-energy muon, two jets of high transverse energy, and a large missing energy carried away by a neutrino is a signature of double leptoquark production. Here, $W+$ jets $\to \mu\nu +$ jets, $Z+$ jets $\to \mu\mu +$ jets, and $t\bar{t}$, as well as the background from QCD processes involving jet production, are dominant background processes. The contribution of the bulk of background processes was estimated by means of a simulation with the aid of the PYTHIA [4] and ALPGEN [3] codes. The contribution of the background from QCD processes was estimated on the basis of live data.

Six events were observed after the application of all trigger conditions, selections, and cuts [13], the expected number of events from background processes being $6.4 \pm 0.7(\text{stat.}) \pm 0.8(\text{syst.})$. Thus, one can state that the above analysis did not reveal any peace of evidence of the double production of second-generation leptoquarks in the channel $p\bar{p} \to LQ_2L\bar{Q}_2 \to \mu\nu qq$. An upper limit on the cross section for the production of second-generation leptoquarks as a function of the leptoquark mass was determined. The result is shown in Fig. 4. The corresponding lower limit on the mass of the second-generation scalar leptoquark is 214 GeV/c^2 ($\beta = 0.5$; the confidence level is 95%). The preceding result obtained for the lower limit on the mass of the second-generation scalar leptoquark in the CDF experiment was 208 GeV/c^2 ($\beta = 0.5$; combined statistics for the $\mu\mu qq$, $\mu\nu qq$, and $\nu\nu qq$ channels) [14].

4. SEARCHES FOR RANDALL–SUNDRUM

The Randall–Sundrum (RS) model [15] proposes a possible solution to one of the most important problems of the Standard Model, that of an enormous distinction between the Planck scale ($M_{\text{Pl}} \sim 10^{16}$ TeV), at which gravity becomes commensurate in strength with remaining interactions, and the scale of electroweak-symmetry breaking ($M_{\text{ew}} \sim 1$ TeV). This is achieved by considering five-dimensional anti-de Sitter spacetime (AdS_5) featuring only one extra dimension and a curved metric $ds^2 = \exp(-2kR|\phi|)\eta_{\mu\nu}dx^\mu dx^\nu - R^2 d\phi^2$, where $0 \le |\phi| \le 3\pi$ is a coordinate along the radius R, which is the only extra dimension; k is the curvature of AdS_5; x^μ are coordinates in $(3+1)$-dimensional spacetime; and $\eta_{\mu\nu}$ is the metric tensor of Minkowski space. One can then consider two $(3+1)$ branes separated in the coordinate ϕ: the Planck brane at $\phi = 0$ and the Standard Model brane at $\phi = \pi$. All Standard Model fields live in the corresponding branes, while gravity can propagate in the extra dimension. Gravity originating from the Planck brane then proves to be exponentially suppressed in the Standard Model brane because of the curvature factor k.

As was indicated above, gravitons are the only particles that propagate in the extra dimension. In the Standard Model, they manifest themselves in the form of Kaluza–Klein excitations; the zero-point excitation ($G^{(0)}$) remains massless and undergoes virtually no interaction with the Standard Model fields, while the first excitation ($G^{(1)}$) is massive and may decay to a fermion–antifermion pair (P wave) or to two photons (S wave; the graviton spin is 2). Thus, the probability of decay to $\gamma\gamma$ is twice as high as the probability of decay to $f\bar{f}$.

The mass of the first excited state of the graviton, M_1, and its dimensionless coupling to the Standard Model fields, $k/\bar{M}_{\text{Pl}}$ ($\bar{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$), which determines both the cross section for the production of gravitons ($\sim(k/\bar{M}_{\text{Pl}})^2$) and their width, are basic parameters of the theory. Theoretically preferred intervals for M_1 and $k/\bar{M}_{\text{Pl}}$ lie, respectively, between a few hundred GeV units and a few TeV units and between 0.01 and 0.1.

In the D0 experiment, searches for RS gravitons were performed on the basis of statistics corresponding to the integrated luminosity of about 1.1 fb^{-1} [16]. The hypothesized two-electron and two-photon decay modes were studied. In doing this, events featuring two high-energy electromagnetic clusters of invariant mass above 50 GeV/c^2 were selected. Drell–Yan processes leading to the production of e^+e^- pairs and the direct production of $\gamma\gamma$ pairs are dominant background processes there. The contribution of such processes was simulated by means of the PYTHIA code [4], whereupon a complete simulation of detector operation was performed. Processes in which the type of one or both electromagnetic objects was misidentified were yet another background source (so-called instrumental background). The contribution of the instrumental background was estimated directly on the basis of live data.

This analysis did not reveal any excess of events in relation to the expected number of background events. The resulting data are in good agreement with Standard Model predictions. Lower limits on M_1 were determined for various values of the coupling constant $k/\bar{M}_{\text{Pl}}$. At $k/\bar{M}_{\text{Pl}} = 0.01$, the lower limit on the mass of the first excited state of the RS graviton is

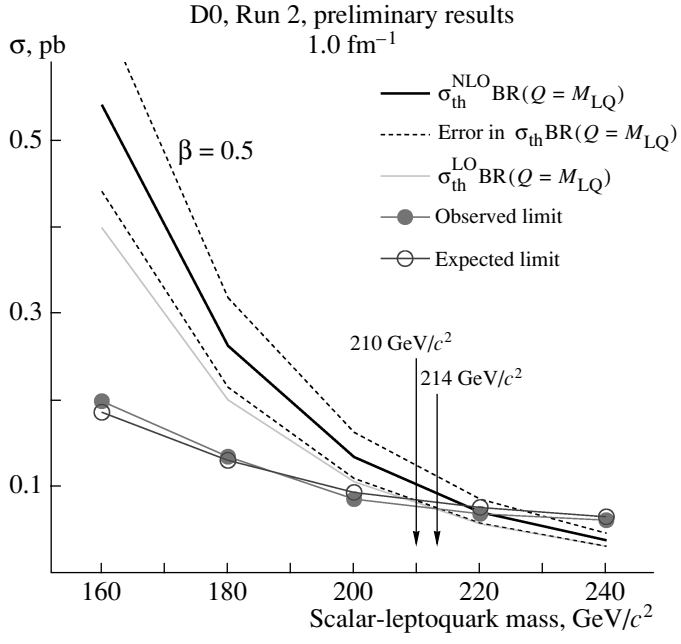

Fig. 4. Upper limit on the cross section for the double production of second-generation scalar leptoquarks (at a 95% C.L.) as a function of the leptoquark mass along with theoretical predictions in the leading and next-to-leading orders of perturbative QCD (LO and NLO).

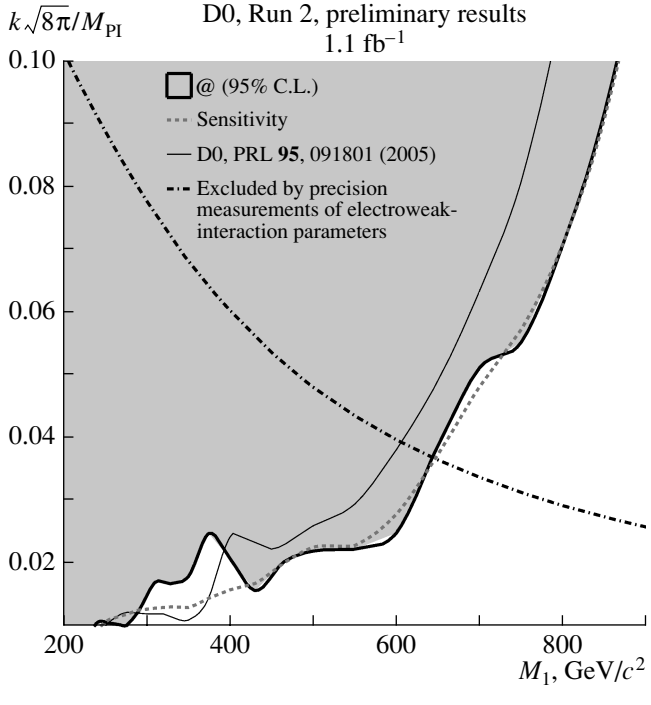

Fig. 5. Upper limit on the quantity $k/\bar{M}_{Pl}$ as function of the RS-graviton mass M_1 (at a 95% C.L.) along with the previous result of the D0 experiment.

$M_1 \geq 240$ GeV/c^2, while, at $k/\bar{M}_{Pl} = 0.1$, it is $M_1 \geq 865$ GeV/c^2 at a 95% C.L. In the plane spanned by the parameters M_1 and $k/\bar{M}_{Pl}$, Fig. 5 shows the region excluded by the above analysis at a 95% C.L. The last result of the CDF experiment for the lower limit on M_1 (it was obtained on the basis of statistics corresponding to 1.3 fb^{-1}) is $M_1 \geq 889$ GeV/c^2 at $k/\bar{M}_{Pl} = 0.1$ [17].

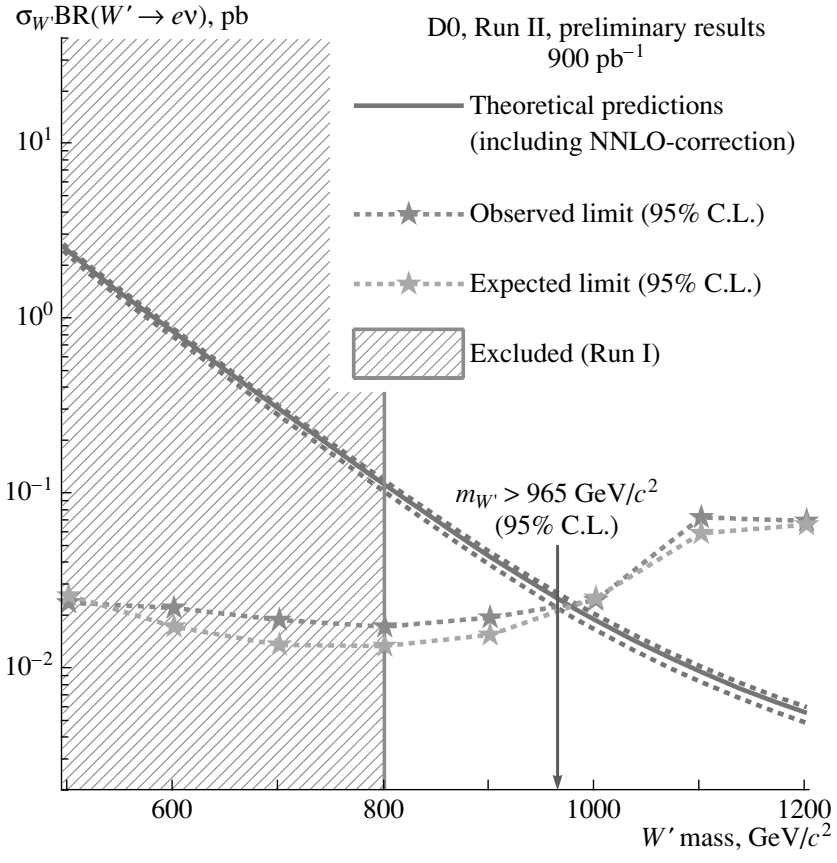

Fig. 6. Upper limit on the product $\sigma_{W'} Br(W' \to e\nu)$ as a function of the W' mass and lower limit on this mass at a 95% C.L.

5. SEARCH FOR HEAVY GAUGE BOSONS

Heavy gauge bosons (W', Z') arise in various extensions of the Standard Model, such as technicolor, left–right symmetric models, Grand Unified Theories, and some SUSY models. In general, a new gauge group can be characterized by a new mixing angle ξ, new fermionic coupling constants g', and new mixing matrices U'.

In the D0 experiment, searches for a heavy charged gauge boson in the process $W' \to e\nu$ [18] were performed on the basis of statistics corresponding to the integrated luminosity of 0.9 fb^{-1}. In doing this, it was assumed that mixing is absent and that the quantities g' and U' are identical to their counterparts in the Standard Model. Under such conditions, the width of a heavy boson is dependent on its mass $m_{W'}$ and can be calculated by means of the expression

$$\Gamma_{W'} = \frac{4}{3}\frac{m_{W'}}{m_W}\Gamma_W. \qquad (2)$$

The reason behind the appearance of the factor of 4/3 is that, at a rather high value of the mass $m_{W'}$, decays to third-generation quarks—for example, $W' \to t\bar{b}$—become possible.

Processes involving ordinary W and Z bosons, such as $W \to e\nu X, W \to \tau\nu X \to e\nu X, Z \to \tau\tau X \to e\nu X$, $WW \to e\nu X$, $ZZ \to ee\nu\nu$, $WZ \to e\nu X$, and $t\bar{t} \to e\nu X$, are dominant background processes here. It is also necessary to take into account the process $Z \to ee$, in which one of the electrons was lost or erroneously reconstructed (this may lead to a large missing mass), and the background of QCD processes, where one of the jets was misidentified as an electron. The contribution of all these processes (with the exception of QCD) was simulated with the aid of the PYTHIA code [4], while the contribution of QCD processes to the background was determined directly from live data.

An analysis revealed no excess of events above Standard Model predictions. New limits on the product $\sigma_{W'}\mathrm{BR}(W' \to e\nu)$ as a function of $m_{W'}$ were obtained (see Fig. 6), and a new limit on the mass of the heavy charged gauge boson was set: $m_{W'} >$ 965 GeV/c^2 at a 95% C.L. The preceding constraint obtained for this mass in the CDF experiment [19] was $m_{W'} > 788$ GeV/c^2.

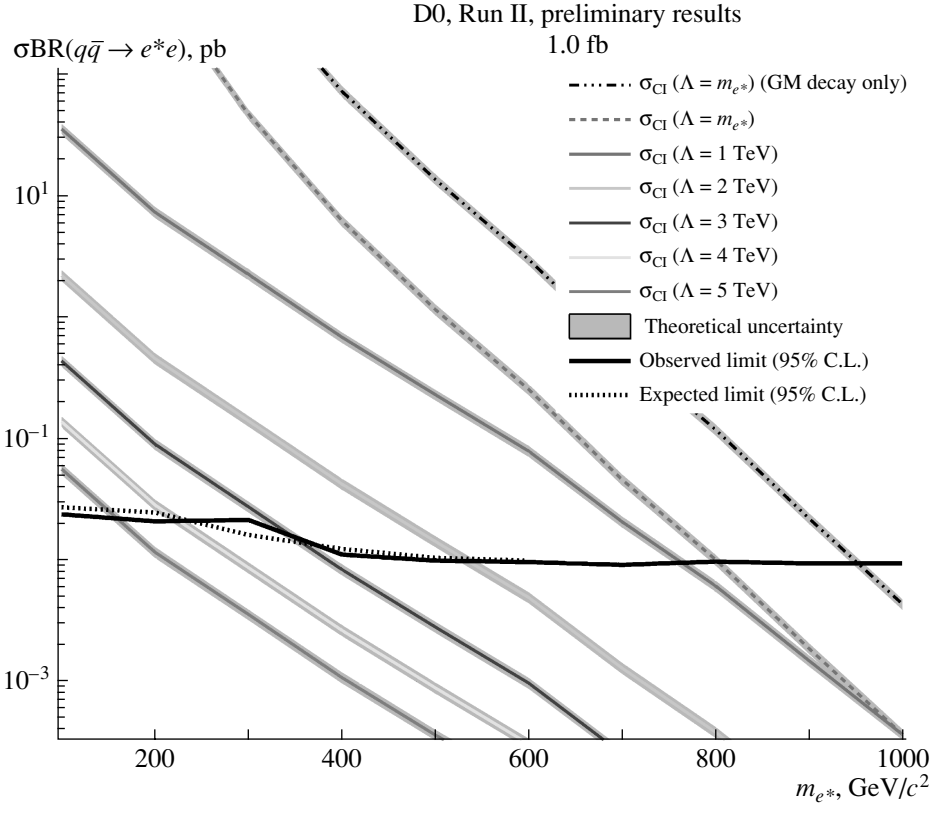

Fig. 7. Upper limit on cross section for the production of an excited electron state as a function of the electron mass at a 95% C.L along with theoretical predictions at various values of the parameter Λ (for explanations, see main body of the text).

6. SEARCHES FOR EXCITED STATES OF QUARKS AND LEPTONS

Some theoretical models try to explain the existence of three fermion generations by considering quarks and leptons as objects consisting of more fundamental particles, so-called preons whose spin is 0 or 1/2. Such models must contain excited states of quarks and leptons, and preon exchange in them leads to so-called contact interactions (CI) between quarks and leptons [20, 21].

Contact interactions can be described with the aid of the four-fermion Lagrangian

$$L_{\mathrm{CI}} = \frac{g^2}{2\Lambda^2} j^\mu j_\mu, \tag{3}$$

where j_μ is the fermion current

$$j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}^*_L \gamma_\mu f^*_L + \eta''_L \bar{f}^*_L \gamma_\mu f_L + \mathrm{h.c.} + (L \to R) \tag{4}$$

and the parameter Λ characterizes the scale of contact interactions. Ordinary fermions and their excited states are denoted by f and f^*, respectively; g^2 is usually chosen to be 4π; and the coefficients η are set to unity for left-handed and to zero for right-handed currents.

In the D0 experiment, searches for excited electrons in the process $p\bar{p} \to e^*e \to ee\gamma$, where $e^* \to e\gamma$ [22], were performed on the basis of statistics corresponding to a luminosity of about 1 fb^{-1}. In doing this, it was assumed that the excited state of an electron is produced owing to contact interactions and that the decay $e^* \to e\gamma$ is induced primarily by electroweak interaction, but the contribution of contact interactions was also taken into account.

In that case, the process $Z/\gamma^* \to ee$ involving the emission of an extra photon is the main background source. Less significant contributions to the background may come from the processes $Z/\gamma^* \to \tau\tau$, WW, WZ, and ZZ, as well as from the processes $W \to e\nu$ and $t\bar{t}$. The contribution of these background processes was simulated with the aid of the PYTHIA code [4]. Processes involving two or more jets and photons may also be a source of background if the jets were misidentified as electrons (QCD background). The contribution from such processes was estimated directly on the basis of live data.

An analysis along these lines revealed that the experimental distributions in question comply well with the Standard Model. In particular, no statistically significant excess of the number of events above that which was expected from Standard Model

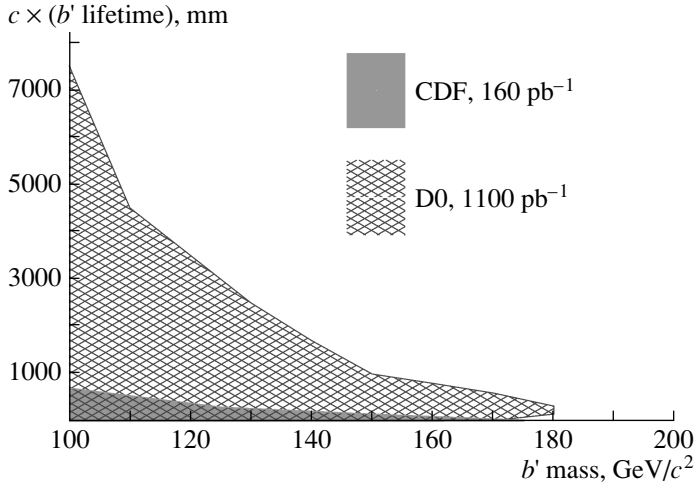

Fig. 8. Region excluded by the present analysis in the plane spanned by the parameters b' $c\tau$ and $M(b')$ at a 95% confidence level. Also presented here for the sake of comparison the corresponding result obtained in the CDF experiment on the basis of a smaller statistical sample.

background processes was found. An upper limit on the cross section for the production of excited electrons that is followed by decay to an electron and a photon was obtained as a function of the excited-electron mass (see Fig. 7). The respective constraint on the excited-electron mass is $m_{e^*} > 756$ GeV/c^2 at $\Lambda = 1$ TeV or $m_{e^*} > 796$ GeV/c^2 at $\Lambda = m_{e^*}$ (at a 95% C.L.).

7. SEARCHES FOR LONG-LIVED PARTICLES DECAYING TO Z BOSONS

Searches for long-lived particles that may travel a few tens of centimeters from their production vertex are an interesting problem, but it has not yet received adequate experimental study. In the context of new physics, such particles appear in various theories: such as the GMSB model, models involving an extended Higgs sector, and models where the number of quark generations is greater than three.

In the D0 experiment, searches for such particles decaying to final states containing a Z boson were performed on the basis of statistics corresponding to the integrated luminosity of 1.1 fb^{-1} [23]. In those searches, it was assumed that Z decays to a e^+e^- pair. Since, in the case of the production and decay of a long-lived particle, the secondary vertex may be at a large distance from the primary vertex, ordinary methods of vertex identification and reconstruction are inefficient here. In particular, secondary vertices for electromagnetic (EM) objects, including electrons and photons, in the calorimeter were reconstructed in the analysis under discussion by means of a dedicated EM-pointing algorithm, whose operation was tested by applying it to reference $Z \to e^+e^-$ events.

The radius of the secondary vertex was defined as a positive one if the scalar product of the transverse momentum of a pair of EM objects and the point-to-point vector from the primary to the secondary vertex was positive and as a negative one in the opposite case. It is obvious that, for secondary vertices associated with real physics decays, the radius must be positive within the measurement errors. Since this radius is zero for the primary vertex, the distribution of this quantity for events that do not have remote secondary vertices must be symmetric about zero (because of measurement errors). At the same time, the presence of secondary vertices at a large distance from the primary vertex must lead to an asymmetry of this distribution (excess of events in the positive region).

The respective analysis did not show any statistically significant excess of events featuring positive values of the radius of the secondary vertex, and this gives sufficient grounds to conclude that there is no experimental evidence of the existence of long-lived particles. It should also be noted that, within a theoretical model involving four quark generations, an analysis made it possible to exclude a region in the plane of the parameters $c \times (b'$ lifetime) and b' mass (see Fig. 8), where b' is the hypothesized long-lived four-generation quark.

8. CONCLUSIONS

Despite all of its problems and limitations, the Standard Model works astonishingly well, and the results of the latest experiments at the Tevatron have only confirmed this. So far, no data suggesting a hint of new physics have been obtained either in the D0

or in the CDF experiment, even though the hunt for new phenomena has been covering a very broad range of lines of research (only a few of them has been listed in the present survey). Yet, it should be recalled that the results discussed above were obtained on the basis of statistics corresponding to an integrated luminosity of about 1 fb^{-1}, but statistics accumulated in experiments at the Tevatron to date corresponds to an integrated luminosity in excess of 3 fb^{-1}. Moreover, it is planned that statistics corresponding to an integrated luminosity of 8 fb^{-1} or even more will have been accumulated before the completion of the accelerator operation. An eight- to tenfold increase in statistics may probably lead to the discovery of new-physics effects even at the Tevatron. In addition, the commissioning of the Large Hadron Collider will enormously increase our potential in this respect.

Much more detailed information about work already done and work under way to seek new physics in the D0 and CDF experiments can be found on the websites of the two experiments in question [24, 25].

ACKNOWLEDGMENTS

I am grateful to S.P. Denisov, D.S. Denisov, and heads of the New Phenomena Group in the D0 experiment (P. Verdier and T. Adams) for their help in the preparation of this article.

This work was supported in part by the Russian Foundation for Basic Research (project no. 08-02-00607).

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Translated by A. Isaakyan