FIELDS AND ELEMENTARY PARTICLES

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SEARCH FOR SUPERSYMMETRY AT THE LARGE HADRON COLLIDER

Search for supersymmetry is carried out in the framework of the Minimal Supersymmetric Standard Model (MSSM). Using the software programs SOFTSUSY and PROSPINO, the mass spectrum and the production cross-sections of superpartners are calculated. The results obtained are of importance for searching the new physics at the LHC.

K e y w o r d s: Minimal Supersymmetric Standard Model, mass spectrum, production cross sections of superpartners.

1. Introduction

Problems in high-energy physics associated with unifying all fundamental interactions in a single theory, the so-called Theory of everything [1], bring about a necessity of creating high-energy accelerators. On September 10, 2008, the Large Hadron Collider (LHC) – the largest experimental installation in the world – was officially started. The LHC can be useful not only in the study of the Higgs mechanism responsible for the violation of the electroweak interaction, but also in the verification of the theory of superstrings and D-branes, because the latter predicts the existence of such objects as

– superpartners,

– Kaluza–Klein particles,

– dark matter candidates, and

– microscopic black holes.

Our work aims at calculating the masses of superpartners at the LHC in the framework of supersymmetry theory. The latter is one of the most widespread theories beyond the Standard model (SM), because it allows a number of SM problems to be solved.

The SM of particle physics is rather a successful theory for the description of physical phenomena, which can be observed on modern colliders. However, the theorists are sure that the SM will not work at higher energy scales. Of course, the SM cannot be an ultimate theory at very high energies, because it has to be modified in order to include the gravitational interaction on Planck scales. This problem is called the hierarchy problem [2–4]. Even if the SM gives the best description of the subatomic world, it does not provide a complete picture of the Universe, since it does not imply the unification mechanism for the strong and electroweak interactions, on the one hand, and the gravitational interaction, on the other hand [1]. In addition, the radiation corrections to the mass of a Higgs boson give rise to large discrepancies between the experiment and the SM theory [5]. A considerable amount of the cold dark matter and the phenomenon of dark energy, which are observed in experiment [6], go beyond the scope of SM predictions.

Recent experimental data are bright markers of new physics beyond the SM. In particular,

(i) new measurements of the Higgs boson properties carried out by ATLAS and CMS Collaborations [7] point to the physics both in the SM framework and beyond it;
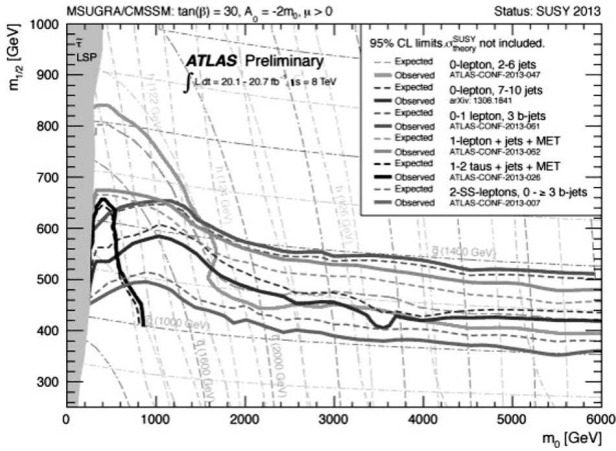
Fig. 1. Gaugino and scalar masses according to the scale of the Grand Unification Theory

(ii) there are problems with the stability of electroweak vacuum [8];

(iii) the total width of a recently discovered Higgs boson is 5.4 times larger than the corresponding SM value [9]; and

(iv) the production cross-sections of W^+W^- particles obtained on the LHC in the course of the proton-proton collisions at the energies $\sqrt{s} = 7$ and 8 TeV testify to a substantial deviation from the SM [10].

While searching for the supersymmetry, we calculated the production cross-sections of superpartners at the LHC at the energy $\sqrt{s} = 14$ TeV and determined the lower limits for the superpartner masses.

2. Calculations of Mass Spectra and Production Cross-Sections of Superpartners

Supersymmetry supplementing fermions with bosons and *vice versa* cannot be an exact symmetry in the Nature, because fermions and bosons must be degenerate with respect to the mass. In order to develop a realistic model of high-energy physics, the supersymmetry has to be broken. The issue concerning a supersymmetric interaction and the condition of its violation associated with the inclusion of soft

Table 1. **Two scenarios of MSSM model**

No.	m_0, GeV	$m_{1/2}$, GeV	A_0, GeV	$\tan\beta$	$\mathrm{sgn}(\mu)$
I	1400	800	−2800	30	+1
II	5000	600	−10000	30	+1

supersymmetry-breaking terms into the interaction potential is well consistent in the framework of the so-called Minimal Supersymmetric Standard Model [11].

The MSSM is defined by the superpotential

$$W = h^e_{ij} L_i H_1 \overline{E}_j + h^d_{ij} Q_i H_1 \overline{D}_j + h^u_{ij} Q_i H_2 \overline{U}_j + \mu H_1 H_2$$

and the potential of a soft supersymmetry breaking

$$V = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_{12}^2 \left(\epsilon_{ij} H_1^i H_2^j + \text{h.c.} \right) +$$
$$+ M_Q^2 \left[\tilde{t}_L^* \tilde{t}_L + \tilde{b}_L^* \tilde{b}_L \right] + M_U^2 \tilde{t}_R^* \tilde{t}_R +$$
$$+ M_D^2 \tilde{b}_R^* \tilde{b}_R + M_L^2 [\tilde{\nu}^* \tilde{\nu} + \tilde{\tau}_L^* \tilde{\tau}_L] +$$
$$+ M_E^2 \tilde{\tau}_R^* \tilde{\tau}_R + \frac{g}{\sqrt{2} m_W} \epsilon_{ij} \left[\frac{m_\tau A_\tau}{\cos\beta} H_1^i \tilde{l}_L^j \tilde{\tau}_R^* + \right.$$
$$+ \frac{m_b A_b}{\cos\beta} H_1^i \tilde{q}_L^j \tilde{b}_R^* - \frac{m_t A_t}{\sin\beta} H_2^i \tilde{q}^j t_R^* \right] +$$
$$+ \frac{1}{2} \left[M_3 \overline{\tilde{g}} \tilde{g} + M_2 \overline{\widetilde{W^a}} \widetilde{W}^a + M_1 \overline{\tilde{B}} \tilde{B} \right],$$

where L_i and Q_i are a slepton and a squark, respectively, $SU(2)_L$ doublets; $\overline{E}_j$ and $(\overline{D}_j, \overline{U}_j)$ are a selectron and a squark, respectively, $SU(2)_L$ singlets; and H_1 and H_2 are Higgs $SU(2)_L$ doublets.

The superpotential W and the potential V depend on more than 100 parameters. The number of the latter can be reduced to the following five owing to the theoretical reasoning and the experimental observations [12]:

$$m_0, \ m_{1/2}, \ A_0, \ \tan\beta, \ \mathrm{sgn}\,\mu,$$

where m_0 and $m_{1/2}$ are the masses of scalar and spinor, respectively, superpartners; A_0 is the parameter of the trilinear interaction, $\tan\beta$ is the ratio between the vacuum expectation values of two Higgs doublets, and $\mathrm{sgn}\,\mu$ is the sign of the Higgs mixing parameter.

The application of recent experimental data [13] obtained by the ATLAS Collaboration for the proton-proton collisions with the following final states: 1) 0 leptons + 2–6 jets, 2) 0 leptons + 7–10 jets, 3) 0 or 1 lepton + 3 b-quark jets, 4) 1 lepton + jets + MET (Missing transverse energy), 5) 1 or 2 tau-leptons + jets + MET, and 6) 2 same-sign leptons + 0 or more than 3 b-quark jets (see Fig. 1)–allowed us to consider two scenarios of the MSSM model (they are presented in Table 1) as such that exceed recent experimental observations made in six experiments shown in Fig. 1.

For the calculation of superpartner mass spectra, which are presented in Table 2, we used the software program SOFTSUSY [14]. The presented mass spectrum is confined, because the masses of quark superpartners are degenerate. In Table 2, the masses of first-generation left- and right-chiral squarks, $(\widetilde{u}_L, \widetilde{u}_R)$ and $(\widetilde{d}_L, \widetilde{d}_R)$, and the masses of gluino, $\widetilde{g}$, and neutralino, $\widetilde{\chi}_1^0$ (a candidate for the dark matter), are represented. The center-of-mass energy at the LHC is planned to achieve a value of 14 TeV, and the luminosity a value of 10^{35} cm^{-2}s^{-1} in 2015. Therefore, the probability to observe the processes of superpartner production and subsequent superpartner decay into quark jets + leptons + MET (e.g., neutralino χ_1^0) depicted in Fig. 2 will grow considerably.

Using the set of parameters from Table 1, it is possible to calculate the cross-sections of superpartner production with the help of the software program PROSPINO [15]. The corresponding results, which are listed in Table 3, were obtained for the transverse cross-sections with regard for the main terms $\sigma_{\mathrm{LO}}^{\mathrm{PROSPINO}}$ (LO means "leading order") for the squark-squark, squark-gluino, and gluino-gluino production, as well as the corresponding additional terms $\sigma_{\mathrm{NLO}}^{\mathrm{PROSPINO}}$ (NLO means "next-to-leading order"), which result from making allowance for the renormalization group terms. The calculations were carried out for the center-of-mass energy $\sqrt{s} = 14$ TeV.

Table 2. **Masses of superpartners, GeV**

No.	$m_{\widetilde{u}_L}$	$m_{\widetilde{u}_R}$	$m_{\widetilde{d}_L}$	$m_{\widetilde{d}_R}$	$m_{\widetilde{g}}$	$m_{\widetilde{\chi}_1^0}$
I	2188	2074	2120	2069	1838	344
II	5079	5081	5080	5079	1542	273

Table 3. **LO and NLO transverse cross-sections (in pb units) and K-factors for superpartners**

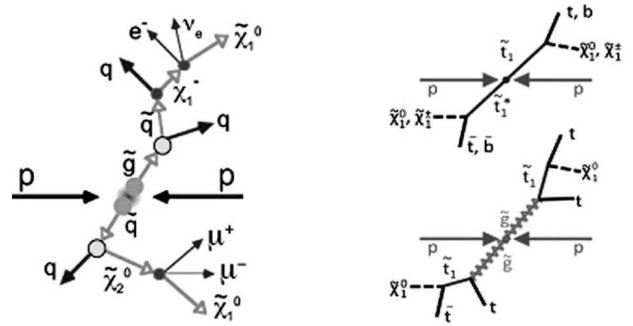| No.	channel	$\sigma_{\mathrm{LO}}^{\mathrm{PROSPINO}}$	$\sigma_{\mathrm{NLO}}^{\mathrm{PROSPINO}}$	K^{PROSPINO}
I	Squark-squark	0.446E-02	0.488E-02	1.096
	Squark-gluino	0.475E-02	0.810E-02	1.704
	Gluino-gluino	0.631E-03	0.204E-02	3.226
II	Squark-squark	0.374E-08	0.382E-08	1.022
	Squark-gluino	0.169E-04	0.481E-04	2.85
	Gluino-gluino	0.595E-02	0.137E-01	2.307

Fig. 2. Processes of superpartner production at the LHC: squark-gluino (left panel), squark-squark (right upper panel), and gluino-gluino (right bottom panel) processes

The K-factor is the ratio between the NLO and LO transverse cross-sections, $K = \sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$. While comparing the results of calculations for two scenarios, we can mark a substantial excess of the cross-sections in scenario I. This fact is associated with a large difference between the corresponding values of parameters m_0 and A_0 in both scenarios (see Table 1). Attention should also be paid to a large cross-section of gluino-gluino production in scenario II, since the mass of such a gluino amounts to 1542 GeV (Table 2), and the probability of its production considerably grows with respect to the gluino mass in scenario I. A large value of K-factor testifies to the necessity of more detailed calculations for the cross-sections, which would include additional (NLO) terms as LO ones in accordance with the QCD theories.

3. Conclusions

Search for the supersymmetry is an important step toward elucidating the deep contradictions of not only the theoretical, but also experimental character. This statement is testified by a number of recent experimental data, which are difficult to be explained if disregarding the new physics, including the supersymmetry. With the help of the computer simulation (SOFTSUSY, PROSPINO), leading western scientists [16] carry out a wide range of works in order to properly respond to the recent experimental data concerning the search for superpartners. The permanent updating of experimental data associated with the processing of large data arrays in the GRID database brings about the necessity of a new experimental simulation with the help of computer programs, which makes our work up-to-date and challenging, because

two new scenarios for the MSSM parameter space are taken into account in accordance with the last AT-LAS experiment. Since the superpartners are not so heavy as, e.g., Kaluza–Klein partners or microscopic black holes, the lower mass limit of which amounts to approximately 5–6 TeV [17], and the probability of the superpartner production is high enough, which is confirmed by the results of our calculations for scenario I, we hope for that they will be observed in the nearest future, when the energy and the luminosity at the LHC will be sufficient for that.

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ПОШУКИ СУПЕРСИМЕТРІЇ
НА ВЕЛИКОМУ АДРОННОМУ КОЛАЙДЕРІ

Р е з ю м е

Пошук суперсиметрії здійснюється в рамках Мінімальної Суперсиметричної Стандартної Моделі. За допомогою комп'ютерних програм SOFTSUSY і PROSPINO розраховані спектри мас і перерізи утворення суперчастинок. Такі результати є важливими для пошуків нової фізики на Великому адронному колайдері.