HIGH ENERGY PHYSICS AND TRIANGULATED CATEGORIES

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Superstring theory is applied to construct the Minimal Supersymmetric Standard Model (MSSM). The mass spectrum, partial widths, and production cross sections of superpartners are calculated. This approach gives specific predictions for superpartner searches at the LHC.

1. Introduction

The purpose of the present work is to construct the Minimal Supersymmetric Standard Model [1] from superstring theory [2]. This aim is achieved by using the notion of triangulated category [3]. Such approach allows one to determine the mass spectrum, partial widths, and production cross sections of superpartners. These predictions are important from experimental point of view as they are connected with searches for new physics at the LHC.

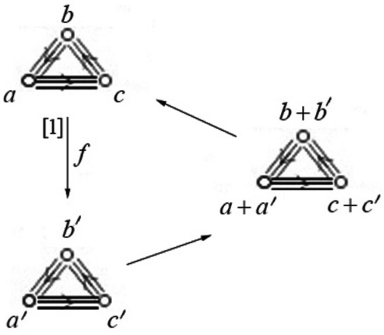

Fig. 1

2. Triangulated Category

Triangulated categories are the mathematical foundation of superstring theory. We consider the triangulated category of distinguished triangles over the Abelian category of McKay quivers [3]. Objects of this category are distinguished triangles (see Fig. 1) (numbers a, b, c and a', b', c' denote orbifold charges [4] characterizing McKay quivers); morphisms of this category are morphisms of distinguished triangles.

In this approach, D-branes are described by quivers (Fig. 2), and open superstrings are described by Ext^i groups determined by the diagram [3] (Fig. 3)

3. Particle Content

It was shown in [5] that the moduli space of an open superstring has the form

$$\mathrm{Ext}^0(Q,Q') = \mathbb{C}^{aa'+bb'+cc'},$$

$$\mathrm{Ext}^1(Q,Q') = \mathbb{C}^{3ab'+3bc'+3ca'}. \qquad (1)$$

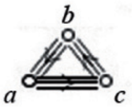

Fig. 2

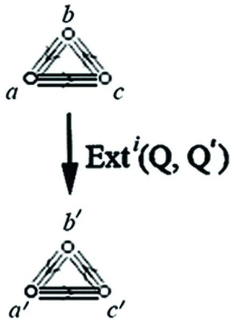

Fig. 3

Table 1. Mass spectrum of superpartners

	GeV		GeV		GeV
$\tilde{u}_R$	1187			$\tilde{g}$	1354
$\tilde{u}_L$	1232	$\tilde{\nu}_e$	391	$\tilde{\chi}_1^0$	249
$\tilde{d}_R$	1182	$\tilde{e}_R$	224	$\tilde{\chi}_2^0$	471
$\tilde{d}_L$	1235	$\tilde{e}_L$	398	$\tilde{\chi}_3^0$	727
$\tilde{c}_R$	1187			$\tilde{\chi}_4^0$	738
$\tilde{c}_L$	1232	$\tilde{\nu}_\mu$	391	$\tilde{\chi}_1^\pm$	470
$\tilde{s}_R$	1182	$\tilde{\mu}_R$	224	$\tilde{\chi}_2^\pm$	738
$\tilde{s}_L$	1235	$\tilde{\mu}_L$	398		
$\tilde{t}_1$	958			h^0	116
$\tilde{t}_2$	1155	$\tilde{\nu}_\tau$	379	A^0	671
$\tilde{b}_1$	1095	$\tilde{\tau}_1$	127	H^0	671
$\tilde{b}_2$	1148	$\tilde{\tau}_2$	408	$H^\pm$	676

Table 2. Partial widths of superpartners

	Channel	BR	Channel	BR
$\tilde{\nu}_e$	$\tilde{\chi}_1^0\nu_e$	1.000		
$\tilde{e}_L$	$\tilde{\chi}_1^0 e$	1.000		
$\tilde{\nu}_\mu$	$\tilde{\chi}_1^0\nu_\mu$	1.000		
$\tilde{\mu}_L$	$\tilde{\chi}_1^0\mu$	1.000		
$\tilde{\nu}_\tau$	$\tilde{\chi}_1^0\nu_\tau$	0.072	$\tilde{\tau}_1 W^+$	0.928
$\tilde{\tau}_2$	$\tilde{\chi}_1^0\tau$	0.107	$\tilde{\tau}_1 Z$	0.527
	$\tilde{\tau}_1 h^0$	0.365		
$\tilde{u}_R$	$\tilde{\chi}_1^0 u$	0.997	$\tilde{\chi}_4^0 u$	0.002
$\tilde{u}_L$	$\tilde{\chi}_1^0 u$	0.013	$\tilde{\chi}_1^+ d$	0.646
	$\tilde{\chi}_2^0 u$	0.320	$\tilde{\chi}_2^+ d$	0.012
	$\tilde{\chi}_4^0 u$	0.008		
$\tilde{d}_R$	$\tilde{\chi}_1^0 d$	0.997	$\tilde{\chi}_4^0 d$	0.002
$\tilde{d}_L$	$\tilde{\chi}_1^0 d$	0.016	$\tilde{\chi}_1^- u$	0.628
	$\tilde{\chi}_2^0 d$	0.317	$\tilde{\chi}_2^- u$	0.027
	$\tilde{\chi}_4^0 d$	0.011		
$\tilde{c}_R$	$\tilde{\chi}_1^0 c$	0.997	$\tilde{\chi}_4^0 c$	0.002
$\tilde{c}_L$	$\tilde{\chi}_1^0 c$	0.013	$\tilde{\chi}_1^+ s$	0.646
	$\tilde{\chi}_2^0 c$	0.320	$\tilde{\chi}_2^0 s$	0.012
	$\tilde{\chi}_4^0 c$	0.008		
$\tilde{s}_R$	$\tilde{\chi}_1^0 s$	0.997	$\tilde{\chi}_4^0 s$	0.002
$\tilde{s}_L$	$\tilde{\chi}_1^0 s$	0.016	$\tilde{\chi}_1^- c$	0.628
	$\tilde{\chi}_2^0 s$	0.317	$\tilde{\chi}_2^- c$	0.027
	$\tilde{\chi}_4^0 s$	0.011		
$\tilde{t}_1$	$\tilde{\chi}_1^0 t$	0.216	$\tilde{\chi}_4^0 t$	0.032
	$\tilde{\chi}_2^0 t$	0.105	$\tilde{\chi}_1^+ b$	0.249
	$\tilde{\chi}_3^0 t$	0.171	$\tilde{\chi}_2^+ b$	0.227

Substituting orbifold charges

$$a = b = c = a' = b' = c' = 4$$

in (1) and using the Langlands hypothesis [6], we obtain a realization of (1) in terms of $SU(5)$ multiplets

$$3 \times (24 + 5_H + \overline{5}_H + 5_M + \overline{5}_M + 10_M + \overline{10}_M)\ .$$

Table 3. Partial widths of superpartners

	Channel	BR	Channel	BR
$\tilde{t}_2$	$\tilde{\chi}_1^0 t$	0.025	$\tilde{\chi}_1^+ b$	0.247
	$\tilde{\chi}_2^0 t$	0.111	$\tilde{\chi}_2^+ b$	0.165
	$\tilde{\chi}_3^0 t$	0.114	$\tilde{t}_1 h^0$	0.045
	$\tilde{\chi}_4^0 t$	0.213	$\tilde{t}_1 Z$	0.080
$\tilde{b}_1$	$\tilde{\chi}_1^0 b$	0.055	$\tilde{\chi}_1^- t$	0.390
	$\tilde{\chi}_2^0 b$	0.220	$\tilde{\chi}_2^- t$	0.183
	$\tilde{\chi}_3^0 b$	0.063	$\tilde{t}_1 W^-$	0.047
	$\tilde{\chi}_4^0 b$	0.041		
$\tilde{b}_2$	$\tilde{\chi}_1^0 b$	0.023	$\tilde{\chi}_1^- t$	0.161
	$\tilde{\chi}_2^0 b$	0.091	$\tilde{\chi}_2^- t$	0.425
	$\tilde{\chi}_3^0 b$	0.079	$\tilde{t}_1 W^-$	0.125
	$\tilde{\chi}_4^0 b$	0.095		
$\tilde{g}$	$\tilde{d}_L d^*$	0.019	$\tilde{c}_L c^*$	0.020
	$\tilde{d}_L^* d$	0.019	$\tilde{c}_L^* c$	0.020
	$\tilde{d}_R d^*$	0.038	$\tilde{c}_R c^*$	0.036
	$\tilde{d}_R^* d$	0.038	$\tilde{c}_R^* c$	0.036
	$\tilde{u}_L u^*$	0.020	$\tilde{b}_1 b^*$	0.078
	$\tilde{u}_L^* u$	0.020	$\tilde{b}_1^* b$	0.078
	$\tilde{u}_R u^*$	0.036	$\tilde{b}_2 b^*$	0.054
	$\tilde{u}_R^* u$	0.036	$\tilde{b}_2^* b$	0.054
	$\tilde{s}_L s^*$	0.019	$\tilde{t}_1 t^*$	0.097
	$\tilde{s}_L^* s$	0.019	$\tilde{t}_1^* t$	0.097
	$\tilde{s}_R s^*$	0.038	$\tilde{t}_2 t^*$	0.043
	$\tilde{s}_R^* s$	0.038	$\tilde{t}_2^* t$	0.043

This result determines the particle content of the MSSM.

4. Superpotential

The gauge invariant MSSM superpotential takes the form

$$W_{SU(5)} = \lambda_{ij}^d \cdot \overline{5}_H \times \overline{5}_M^{(i)} \times 10_M^{(j)} +$$

$$+\lambda_{ij}^u \cdot 5_H \times 10_M^{(i)} \times 10_M^{(j)} + \mu \cdot 5_H \times \overline{5}_H, \qquad (2)$$

where 5_H and $\overline{5}_H$ are Higgs multiplets, $\overline{5}_M^{(i)}$ and $10_M^{(j)}$ are multiplets of quark and lepton superpartners, λ_{ij}^d, λ_{ij}^u are Yukawa coupling constants, and μ is the Higgs mixing parameter.

5. Mass Spectrum

The analysis of Yukawa coupling constants, based on observational hints and theoretical considerations, allows one to restrict the parameter space in (2) to five free parameters [7]:

$$m_0 = 0.01\ \text{GeV}, \quad m_{1/2} = 600\ \text{GeV},$$

Table 4. Partial widths of superpartners

	Channel	BR	Channel	BR
A^0	bb^*	0.858	$\tilde{\tau}_1^- \tilde{\tau}_2^+$	0.004
	$\tau^+\tau^-$	0.130	$\tilde{\tau}_1^+ \tilde{\tau}_2^-$	0.004
	tt^*	0.002		
H^0	bb^*	0.859	$\tilde{\tau}_1^- \tilde{\tau}_1^+$	0.003
	$\tau^+\tau^-$	0.130	$\tilde{\tau}_1^- \tilde{\tau}_2^+$	0.002
	tt^*	0.002	$\tilde{\tau}_1^+ \tilde{\tau}_2^-$	0.002
H^+	cb^*	0.001	tb^*	0.818
	$\tau^+\nu_\tau$	0.169	$\tilde{\tau}_1^+ \tilde{\nu}_\tau$	0.010
$\tilde{\chi}_1^0$	$\tilde{e}_R^- e^+$	0.032	$\tilde{\mu}_R^+ \mu^-$	0.032
	$\tilde{e}_R^+ e^-$	0.032	$\tilde{\tau}_1^- \tau^+$	0.436
	$\tilde{\mu}_R^- \mu^+$	0.032	$\tilde{\tau}_1^+ \tau^-$	0.436
$\tilde{\chi}_2^0$	$\tilde{\chi}_1^0 Z$	0.001	$\tilde{\tau}_2^- \tau^+$	0.037
	$\tilde{\chi}_1^0 h^0$	0.010	$\tilde{\tau}_2^+ \tau^-$	0.037
	$\tilde{e}_L^- e^+$	0.056	$\tilde{\nu}_e \nu_e^*$	0.064
	$\tilde{e}_L^+ e^-$	0.056	$\tilde{\nu}_e^* \nu_e$	0.064
	$\tilde{\mu}_L^- \mu^+$	0.056	$\tilde{\nu}_\mu \nu_\mu^*$	0.064
	$\tilde{\mu}_L^+ \mu^-$	0.056	$\tilde{\nu}_\mu^* \nu_\mu$	0.064
	$\tilde{\tau}_1^- \tau^+$	0.135	$\tilde{\nu}_\tau \nu_\tau^*$	0.081
	$\tilde{\tau}_1^+ \tau^-$	0.135	$\tilde{\nu}_\tau^* \nu_\tau$	0.081
$\tilde{\chi}_3^0$	$\tilde{\chi}_1^0 Z$	0.080	$\tilde{\chi}_2^0 h^0$	0.007
	$\tilde{\chi}_2^0 Z$	0.193	$\tilde{\tau}_1^- \tau^+$	0.088
	$\tilde{\chi}_1^+ W^-$	0.211	$\tilde{\tau}_1^+ \tau^-$	0.088
	$\tilde{\chi}_1^- W^+$	0.211	$\tilde{\tau}_2^- \tau^+$	0.051
	$\tilde{\chi}_1^0 h^0$	0.016	$\tilde{\tau}_2^+ \tau^-$	0.051

$$A_0 = 0, \quad \tan\beta = 35, \quad \mathrm{sgn}(\mu) = +1. \tag{3}$$

Using this restricted parameter set, it is possible to calculate the mass spectrum of superpartners by applying the computer program SOFTSUSY [8]. This MSSM spectrum is shown in Table 1.

6. Partial Widths

Using the parameter set (3), it is possible to calculate partial widths of superpartners by applying the computer program SDECAY [9]. These partial widths are shown in Tables 2–5.

7. Cross Sections

Using the parameter set (3), it is possible to calculate the production cross sections of superpartners by applying the computer program PYTHIA [10]. These cross sections at the center-of-mass energy $\sqrt{s} = 14$ TeV are shown in Table 6.

Table 5. Partial widths of superpartners

	Channel	BR	Channel	BR
$\tilde{\chi}_4^0$	$\tilde{\chi}_1^0 Z$	0.016	$\tilde{\mu}_R^- \mu^+$	0.001
	$\tilde{\chi}_2^0 Z$	0.009	$\tilde{\mu}_R^+ \mu^-$	0.001
	$\tilde{\chi}_1^+ W^-$	0.208	$\tilde{\tau}_1^- \tau^+$	0.061
	$\tilde{\chi}_1^- W^+$	0.208	$\tilde{\tau}_1^+ \tau^-$	0.061
	$\tilde{\chi}_1^0 h^0$	0.069	$\tilde{\tau}_2^- \tau^+$	0.058
	$\tilde{\chi}_2^0 h^0$	0.171	$\tilde{\tau}_2^+ \tau^-$	0.058
	$\tilde{e}_L^- e^+$	0.005	$\tilde{\nu}_e \nu_e^*$	0.009
	$\tilde{e}_L^+ e^-$	0.005	$\tilde{\nu}_e^* \nu_e$	0.009
	$\tilde{e}_R^- e^+$	0.001	$\tilde{\nu}_\mu \nu_\mu^*$	0.009
	$\tilde{e}_R^+ e^-$	0.001	$\tilde{\nu}_\mu^* \nu_\mu$	0.009
	$\tilde{\mu}_L^- \mu^+$	0.005	$\tilde{\nu}_\tau \nu_\tau^*$	0.010
	$\tilde{\mu}_L^+ \mu^-$	0.005	$\tilde{\nu}_\tau^* \nu_\tau$	0.010
$\tilde{\chi}_1^+$	$\tilde{\nu}_e e^+$	0.135	$\tilde{\mu}_L^+ \nu_\mu$	0.108
	$\tilde{\nu}_\mu \mu^+$	0.135	$\tilde{\tau}_1^+ \nu_\tau$	0.261
	$\tilde{\nu}_\tau \tau^+$	0.176	$\tilde{\tau}_2^+ \nu_\tau$	0.067
	$\tilde{e}_L^+ \nu_e$	0.108	$\tilde{\chi}_1^0 W^+$	0.010
$\tilde{\chi}_2^+$	$\tilde{\nu}_e e^+$	0.009	$\tilde{\tau}_2^+ \nu_\tau$	0.051
	$\tilde{\nu}_\mu \mu^+$	0.009	$\tilde{\chi}_1^+ Z$	0.206
	$\tilde{\nu}_\tau \tau^+$	0.105	$\tilde{\chi}_1^0 W^+$	0.079
	$\tilde{e}_L^+ \nu_e$	0.020	$\tilde{\chi}_2^0 W^+$	0.214
	$\tilde{\mu}_L^+ \nu_\mu$	0.020	$\tilde{\chi}_1^+ h^0$	0.183
	$\tilde{\tau}_1^+ \nu_\tau$	0.104		

Table 6. Cross sections of superpartners

Channel	Cross section
$gg \to \tilde{g}\tilde{g}$	$\sigma_{\tilde{g}\tilde{g}} = 0.307$pb
$gu \to \tilde{g}\tilde{u}$	$\sigma_{\tilde{g}\tilde{u}} = 0.891$pb
$du \to \tilde{d}\tilde{u}$	$\sigma_{\tilde{d}\tilde{u}} = 0.466$pb
$\overline{u}u \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\sigma_{\tilde{\chi}_1^+ \tilde{\chi}_1^-} = 0.157$pb
$\overline{d}u \to \tilde{\chi}_1^+ \tilde{\chi}_2^0$	$\sigma_{\tilde{\chi}_1^+ \tilde{\chi}_2^0} = 0.208$pb

8. Comparison with Experiments

The comparison of the predicted spectrum with experimental data obtained at the LEP and TEVATRON [11] (see Table 7) shows that the calculated masses exceed the lower limits on masses reached at colliders.

New searches for superpartners will be made at the LHC.

9. Conclusion

Let us compare our MSSM based on fundamental principles of triangulated categories with other MSSM presented in [12] (see Table 8).

Table 8 shows that, in scenarios α, β, γ, and δ, the lightest superpartners are neutralinos $\widetilde{\chi}_1^0(113)$, $\widetilde{\chi}_1^0(146)$, $\widetilde{\chi}_1^0(95)$, $\widetilde{\chi}_1^0(310)$, whereas, in scenarios ϵ, ς, and η, the

Table 7. Lower limits on masses reached at colliders

Particle		Condition	Lower limit	Source
$\tilde{\chi}_1^{\pm}$	gaugino	$M_{\tilde{\nu}} > 200$ GeV	103	LEP 2
		$M_{\tilde{\nu}} > M_{\tilde{\chi}^{\pm}}$	85	LEP 2
		any $M_{\tilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1$TeV	99	LEP 2
	GMSB		150	D0 isolated photons
	RPV	LL$\overline{E}$ worst case	87	LEP 2
		LQ$\overline{D}$ $m_0 > 500$ GeV	88	LEP 2
$\tilde{\chi}_1^0$	indirect	any tanβ, $M_{\tilde{\nu}} > 500$ GeV	39	LEP 2
		any tanβ, any m_0	36	LEP 2
		any tanβ, any m_0, SUGRA Higgs	59	LEP 2 combined
	GMSB		93	LEP 2 combined
	RPV	LL$\overline{E}$ worst case	23	LEP 2
$\tilde{e}_R$	$e\tilde{\chi}_1^0$	$\Delta M > 10$ GeV	99	LEP 2 combined
$\tilde{\mu}_R$	$\mu\tilde{\chi}_1^0$	$\Delta M > 10$ GeV	95	LEP 2 combined
$\tilde{\tau}_R$	$\tau\tilde{\chi}_1^0$	$M_{\tilde{\chi}_1^0} < 20$ GeV	80	LEP 2 combined
$\tilde{\nu}$			43	Z width
$\tilde{\mu}_R$, $\tilde{\tau}_R$		stable	86	LEP 2 combined
$\tilde{t}_1$	$c\tilde{\chi}_1^0$	any $\theta_{\text{mix}}, \Delta M > 10$ GeV	95	LEP 2 combined
		any $\theta_{\text{mix}}, M_{\tilde{\chi}_1^0} \sim \frac{1}{2} M_{\tilde{t}}$	115	CDF
		any θ_{mix}, and any ΔM	59	ALEPH
	$bl\tilde{\nu}$	any $\theta_{\text{mix}}, \Delta M > 7$ GeV	96	LEP 2 combined
$\tilde{g}$	any $M_{\tilde{q}}$		195	CDF jets+E_T
$\tilde{q}$	$M_{\tilde{q}} = M_{\tilde{g}}$		300	CDF jets+E_T

Table 8. Scenarios of MSSM

Model	α	β	γ	δ	ϵ	ζ	η	Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	293	370	247	750	440	1000	1000	$\tilde{g}$	711	880	619	1691	1026	2191	2191
m_0	206	225	328	500	20	100	20	e_L, μ_L	299	351	378	713	306	684	677
tan(μ)	10	10	20	10	15	231.5	23.7	e_R, μ_R	216	241	328	572	171	387	374
sin(μ)	+	+	+	+	+	+	+	ν_e, ν_μ	287	340	368	703	290	669	662
A_0	0	0	0	0	–25	–127	–25	τ_1	213	239	315	565	153	338	319
Masses	🟩	🟩	🟩	🟩	🟨	🟨	🟨	τ_2	300	352	378	712	309	677	670
h^0	115	117	115	122	119	124	124	ν_τ	287	340	365	700	288	660	653
H^0	267	328	241	1159	626	1293	1261	u_L, c_L	674	826	636	1604	935	1991	1998
A^0	265	325	240	1152	622	1285	1253	u_R, c_R	661	808	629	1550	902	1911	1908
$H^{\pm}$	278	337	255	1162	632	1296	1264	d_L, s_L	679	831	642	1606	938	1993	1990
χ_1^0	113	146	95	310	175	417	417	d_R, s_R	652	797	621	1544	899	1903	1900
χ_2^0	215	282	180	600	339	805	804	t_1	492	622	453	1219	710	1545	1553
χ_3^0	380	503	332	925	574	1192	1176	t_2	662	800	611	1486	900	1842	1840
χ_4^0	400	518	352	935	587	1200	1184	b_1	609	752	558	1456	852	1807	1804
$\chi_1^{\pm}$	215	283	180	601	340	807	806	b_2	641	785	603	1516	883	1851	1846
$\chi_2^{\pm}$	399	518	352	935	587	1200	1184								

lightest superpartners are gravitinos $\widetilde{G}(20)$, $\widetilde{G}(100)$, $\widetilde{G}(20)$.

In our MSSM, the lightest superpartner is a gravitino $\widetilde{G}(0.01)$, which is the preferable candidate for the gravitino dark matter in accordance with cosmological data [13].

High-energy physics is poised at the threshold of a new era. The Large Hadron Collider has now entered into operation with a center-of-mass energy of 7 TeV, and is already surpassing the previous accelerators in some of its probes of new physics beyond the Standard Model. This new physics known as the MSSM is the minimal supersymmetric extension of the Standard Model, in which particles are accompanied by superpartners with spins differing by 1/2. The squarks and gluinos of the MSSM are one example of such superpartners. Recently, the first searches for squarks and gluinos at the LHC in final states containing only jets and a large missing transverse momentum have been performed [14, 15]. Interest in these final states is motivated by the MSSM, in which squarks and gluinos can be produced in pairs $(\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g})$. When the production of squark pairs $\tilde{q}\tilde{q}$ is dominant, two jets are expected from decays $\tilde{q} \to q\tilde{\chi}_1^0$. When the production involves gluinos ($\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$), three jets are expected from decays $\tilde{g} \to qq^*\tilde{\chi}_1^0$. The analysis of these jets establishes the lower limits on squark and gluino masses:

$$m_{\tilde{q}} > 775 \text{ GeV}, \ m_{\tilde{g}} > 775 \text{ GeV}.$$

Last but not least, the categorical approach to the construction of the MSSM from superstring theory is our original clue toward the contemporary realization of Einstein's dream on the Theory of Everything.

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ФІЗИКА ВИСОКИХ ЕНЕРГІЙ І ТРИАНГУЛЬОВАНІ КАТЕГОРІЇ

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Резюме

Теорію суперструн застосовано до побудови Мінімальної суперсиметричної стандартної моделі. Виконано обчислення спектра мас, парціальних ширин і перерізів породження суперпартнерів. Цей підхід дає конкретні передбачення для пошуку суперпартнерів на LHC.