NLO CORRECTIONS TO THE PAIR PRODUCTION OF SUPERSYMMETRIC PARTICLES

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The analysis of recent experimental data received from LHC (CMS) restricts the range of MSSM parameters. Using computer programs SOFTSUSY, SDECAY the mass spectrum and partial width of superpatners are calculated. With the help of computer program PROSPINO the calculations of the next-to-leading order (NLO) corrections to the production cross sections of superpartners are made. With the help of computer program PYTHIA the NLO corrections on differential distributions of p_T and η for squarks and gluino are represented.

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1. INTRODUCTION

Supersymmetry played a most important role in the development of theoretical physics and strongly influenced on experimental particle physics.

Supersymmetry first appeared in the context of string theory as the symmetry of two-dimensional world sheet theory [1]. Later it was realized that it could be relevant to elementary particle physics through the four-dimensional quantum field theory.

Why particle physicist consider supersymmetric theories? There are several famous reasons:

- the vanishing or extreme smallness of the cosmological constant;
- the hierarchy problem;
- dark matter candidate;
- gauge-coupling unification.

The simplest action that can be written down for fermions, scalar fields and non-propagating complex auxiliary field consists of kinetic energy terms [2]:

$$L_{free} = -\partial^\mu \phi^{*i} \partial_\mu \phi_i + i\psi^{+i}\overline{\sigma}^\mu \partial_\mu \psi_i + F^{*i} F_i \ ,$$

$$S = \int d^4x L_{free} \, .$$

The renormalizable interactions for these fields, that are invariant under supersymmetric transformations are the following

$$L_{int} = \left(-\frac{1}{2} W^{ij} \psi_i \psi_j + W^i F_i \right) + c.c. \, ,$$

where $W^{i,j}, W^i$ are polynomials in the scalar fields ϕ_i, ϕ^{*i} with degrees 1 and 2 respectively. It is possible to write

$$W^{ij} = \frac{\delta^2}{\delta\phi_i \delta\phi_j} W \, ,$$

where

$$W = L^i \phi_i + \frac{1}{2} M^{ij} \phi_i \phi_j + \frac{1}{6} y^{ijk} \phi_i \phi_j \phi_k$$

is the superpotential. Here L^i are parameters, which affect the scalar potential part of the Lagrangian, M^{ij} is a symmetric mass matrix for the fermion fields, and y^{ijk} is a Yukawa coupling of a scalar ϕ_k and two fermions $\psi_i \psi_j$ that must be totally symmetric under interchange of i, j, k. The Minimal Supersymmetric Standard Model (MSSM) superpotential has the form

$$W_{MSSM} = \overline{u} y_u Q H_u - \overline{d} y_d Q H_d - \overline{e} y_e L H_d + \mu H_u H_d .$$

The fields $H_u, H_d, Q, L, \overline{u}, \overline{d}, \overline{e}$ are chiral superfields corresponding to the chiral supermultiplets. y_u, y_d, y_e are Yukawa coupling parameters

$$y_u \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}, y_d \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix},$$

$$y_e \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau \end{pmatrix}.$$

The μ term is the supersymmetric version of the Higgs boson mass. The models of spontaneous symmetry breaking should be soft (of positive mass dimension) in order to be able to naturally maintain a hierarchy between the electroweak scale and the Planck (or any other very large) mass scale. In the Lagrangian of a general theory the possible soft supersymmetry-breaking terms are

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$$
\begin{aligned}
L_{soft} &= \\
&= -\left(\frac{1}{2}M_a\lambda^a\lambda^a + \frac{1}{6}a^{ijk}\phi_i\phi_j\phi_k + +\frac{1}{2}b^{ij}\phi_i\phi_j + t^i\phi_i\right) \\
&+ c.c. - (m^2)^i_j\phi^{j*}\phi_i, \qquad (1)
\end{aligned}
$$

where M_a are gaugino masses, $(m^2)^i_j$ and b^{ij} are scalar squared-mass terms, a^{ijk} and t^i are couplings - scalar and "tadpole".

The advantage of the MSSM is the unification of gauge couplings. The 1-loop RG equations for the gauge couplings g_1, g_2, g_3 are

$$\beta_{g_a} \equiv \frac{d}{dt}g_a = \frac{1}{16\pi^2}b_a g_a^3,$$

$$(b_1, b_2, b_3) = \begin{cases} (41/10, -19/6, -7) & \text{Standard Model} \\ (33/5, 1, -3) & \text{MSSM} \end{cases}$$

where $t = \ln(Q/Q_0)$, with Q the Renorm group (RG) scale. The quantities $\alpha = g_a^2/4\pi$ run linearly with RG scale at one-loop order:

$$\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi} \quad (a = 1, 2, 3)$$

and can unify at a scale $M_U \sim 2\times 10^{16}$ GeV. As this unification is not perfect, however, this small difference can be corrected due to the application of the RG analysis for MSSM model. The form of the renormalization group equations with the parameters appearing in the superpotential is the following

$$
\begin{aligned}
\beta_{y^{ijk}} &\equiv \frac{d}{dt}y^{ijk} = \gamma^i_n y^{njk} + \gamma^j_n y^{ink} + \gamma^k_n y^{ijn}, \\
\beta_{M^{ij}} &\equiv \frac{d}{dt}M^{ij} = \gamma^i_n M^{nj} + \gamma^j_n M^{in}, \qquad (2) \\
\beta_{L^i} &\equiv \frac{d}{dt}L^i = \gamma^i_n L^n,
\end{aligned}
$$

where the γ^i_j are anomalous dimension matrices associated with the superfields. At 1-loop order

$$\gamma^i_j = \frac{1}{16\pi^2}\left[\frac{1}{2}y^{imn}y^*_{jmn} - 2g_a^2 C_a(i)\delta^i_j\right],$$

where $C_a(i)$ are the quadratic Casimir group theory invariants for the superfield Φ_i , defined in terms of the Lie algebra generators T^a by

$$(T^aT^a)^j_i = C_a(i)\delta^j_i$$

with gauge couplings g_a. For the MSSM supermultiplets

$$C_3(i) = \begin{cases} 4/3 & \text{for } \Phi_i = Q, \overline{u}, \overline{d}, \\ 0 & \text{for } \Phi_i = L, \overline{e}, H_u, H_d, \end{cases}$$

$$C_2(i) = \begin{cases} 3/4 & \text{for } \Phi_i = Q, L, H_u, H_d, \\ 0 & \text{for } \Phi_i = \overline{u}, \overline{d}, \overline{e}, \end{cases}$$

$C_1(i) = \{\ 3Y_i^2/5$ for each Φ_i with weak hypercharge Y_i.

The one-loop renormalization of gauge couplings has the form

$$\beta_{g_a} = \frac{d}{dt}g_a = \frac{1}{16\pi^2}g_a^3\left[\sum_i I_a(i) - 3C_a(G)\right],$$

where $C_a(G)$ is the quadratic Casimir invariant of the group, $I_a(i)$ is the Dynkin index of the chiral supermultiplet ϕ_i . Putting RG equations for γ^i_j at the 1-loop order into (2), we can receive the expressions of the running superpotential parameters

$$
\begin{aligned}
\beta_{y_t} &\equiv \frac{d}{dt}y_t = \frac{y_t}{16\pi^2}\left[6y_t^*y_t + y_b^*y_b - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right], \\
\beta_{y_b} &\equiv \frac{d}{dt}y_b = \frac{y_b}{16\pi^2}\left[6y_b^*y_b + y_t^*y_t + y_\tau^*y_\tau - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right], \\
\beta_{y_\tau} &\equiv \frac{d}{dt}y_\tau = \frac{y_\tau}{16\pi^2}\left[4y_\tau^*y_\tau + 3y_b^*y_b - 3g_2^2 - \frac{9}{5}g_1^2\right], \\
\beta_\mu &\equiv \frac{d}{dt}\mu = \frac{\mu}{16\pi^2}\left[3y_t^*y_t + 3y_b^*y_b + y_\tau^*y_\tau - 3g_2^2 - \frac{3}{5}g_1^2\right].
\end{aligned}
$$

The 1-loop renormalization group equations for the gaugino mass parameters in the MSSM are determined by

$$\beta_{M_a} \equiv \frac{d}{dt}M_a = \frac{1}{8\pi^2}b_a g_a^2 M_a \quad (b_a = 33/5, 1, -3)$$

for $a = 1, 2, 3$. Near the scale $Q = M_U = 2\times 10^{16}$ GeV gaugino masses unify with the value $m_{1/2}$

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} = \frac{m_{1/2}}{g_U^2}.$$

Our goal is to learn GUT theory at the GUT scale and seeing which models are consistent with the experimental data. At hadron colliders, sparticles can be produced in pairs from parton collisions of QCD strength:

$$
\begin{aligned}
gg &\to \widetilde{g}\widetilde{g}, \\
gq &\to \widetilde{g}\widetilde{q}_i, \\
q\overline{q} &\to \widetilde{g}\widetilde{g}, \\
qq &\to \widetilde{q}_i\widetilde{q}_j.
\end{aligned}
$$

The total hadronic cross-sections are obtained by integrating the parton cross-sections over the parton distributions f_i in the proton/antiproton:

$$\sigma(ij \to \widetilde{q}, \widetilde{g}) = \int dx_1 dx_2 f_i(x_1) f_j(x_2)\sigma^B(ij \to \widetilde{q}, \widetilde{g}; s = x_1x_2S),$$

where the total centre-of-mass energy of the collider is denoted by $\sqrt{s}$. Lowest-order (LO) partonic cross-sections are the following [3]:

$$
\begin{aligned}
\sigma^B(q_iq_j \to \widetilde{q}\widetilde{q}) &= \frac{\pi\widehat{\alpha}_s^2}{s}\left[\beta_{\widetilde{q}}\left(-\frac{4}{9} - \frac{4m_-^4}{9(m_{\widetilde{g}}^2 s + m_-^4)}\right) + \right. \\
&\left. + \left(-\frac{4}{9} - \frac{8m_-^2}{9s}\right)L_1\right] + \\
&+ \delta_{ij}\frac{\pi\widehat{\alpha}_s^2}{s}\left[\frac{8m_{\widetilde{g}}^2}{27(s + 2m_-^2)}L_1\right], \\
\sigma^B(q\overline{q} \to \widetilde{g}\widetilde{g}) &= \frac{\pi\alpha_s^2}{s}\beta_{\widetilde{g}}\left(\frac{8}{9} + \frac{16m_{\widetilde{g}}^2}{9s}\right) + \\
&+ \frac{\pi\alpha_s\widehat{\alpha}_s}{s}\left[\beta_{\widetilde{g}}\left(-\frac{4}{3} - \frac{8m_-^2}{3s}\right) + \right. \\
&\left. + \left(\frac{8m_{\widetilde{g}}^2}{3s} + \frac{8m_-^4}{3s^2}\right)L_2\right] + \\
&+ \frac{\pi\widehat{\alpha}_s^2}{s}\left[\beta_{\widetilde{g}}\left(\frac{32}{27} + \frac{32m_-^4}{27(m_{\widetilde{q}}^2 s + m_-^4)}\right) + \right. \\
&\left. + \left(-\frac{64m_-^2}{27s} - \frac{8m_{\widetilde{g}}^2}{27(s - 2m_-^2)}\right)L_2\right],
\end{aligned}
$$

$$\sigma^B(gg \to \widetilde{g}\widetilde{g}) = \frac{\pi\alpha_s^2}{s}\left[\beta_{\widetilde{g}}\left(-3 - \frac{51m_{\widetilde{g}}^2}{4s}\right) + \right.$$
$$\left. + \left(-\frac{9}{4} - \frac{9m_{\widetilde{g}}^2}{s} + \frac{9m_{\widetilde{g}}^4}{s^2}\right)\log\left(\frac{1-\beta_{\widetilde{g}}}{1+\beta_{\widetilde{g}}}\right)\right],$$
$$\sigma^B(qg \to \widetilde{q}\widetilde{g}) = \frac{\pi\alpha_s\widehat{\alpha}_s}{s}\left[\frac{\kappa}{s}\left(-\frac{7}{9} - \frac{32m_-^2}{9s}\right) + \right.$$
$$+ \left(-\frac{8m_-^2}{9s} + \frac{2m_{\widetilde{q}}^2 m_-^2}{s^2} + \frac{8m_-^4}{9s^2}\right)L_3 +$$
$$\left. + \left(-1 - \frac{2m_-^2}{s} + \frac{2m_{\widetilde{q}}^2 m_-^2}{s^2}\right)L_4\right]$$

with

$$L_1 = \log\left(\frac{s + 2m_-^2 - s\beta_{\widetilde{q}}}{s + 2m_-^2 + s\beta_{\widetilde{q}}}\right), \quad L_2 = \log\left(\frac{s - 2m_-^2 - s\beta_{\widetilde{g}}}{s - 2m_-^2 + s\beta_{\widetilde{g}}}\right),$$

$$L_3 = \log\left(\frac{s - m_-^2 - \kappa}{s - m_-^2 + \kappa}\right), \quad L_4 = \log\left(\frac{s + m_-^2 - \kappa}{s + m_-^2 + \kappa}\right),$$

$$\beta_{\widetilde{q}} = \sqrt{1 - \frac{4m_{\widetilde{q}}^2}{s}}, \quad \beta_{\widetilde{g}} = \sqrt{1 - \frac{4m_{\widetilde{g}}^2}{s}},$$

$$m_-^2 = m_{\widetilde{g}}^2 - m_{\widetilde{q}}^2, \qquad \kappa = \sqrt{(s - m_{\widetilde{g}}^2 - m_{\widetilde{q}}^2)^2 - 4m_{\widetilde{g}}^2 m_{\widetilde{q}}^2},$$

$$\alpha_s = \frac{g_s^2}{4\pi}, \qquad \widehat{\alpha}_s = \frac{\widehat{g}_s^2}{4\pi}.$$

The momenta of the two partons in the initial states are denoted by k_1 and $k_2, s = (k_1 + k_2)^2$ - kinematical invariant, g_s - Yukawa couplings.

Squarks and gluinos can be produced at the LHC, if their masses are in the accessible range. The LO cross sections and NLO corrections in SUSY-QCD can be calculated with the computer program PROSPINO [4]. The next-to-leading order (NLO) strong supersymmetric Quantum chromodynamics (SUSY-QCD) corrections increase the cross-sections for the various production processes with respect to the leading-order (LO) predictions and reduce the dependence on the renormalization and factorization scale significantly [5, 6].

According to the experimental data [7] with the observed and exclusion limits in the $(m_0, m_{1/2})$ plane for $\tan\beta = 10$ and $A_0 = 0$, calculated with SUSY in final states with missing transverse energy and 0,1,2,or ≥ 3 b-quark jets in 7 TeV pp collisions we can consider two sets of input parameters for SUSY at the LHC in Table 1

Table 1. *The input parameters for two mSUGRA scenarios*

	m_0, GeV	$m_{1/2}$, GeV	A_0, GeV	$\tan\beta$	sgn(μ)
I	800	650	0	10	+1
II	1300	425	0	10	+1

For calculation the mass spectra was used SOFTSUSY program [8]. The masses are listed in Table 2.

Table 2. *The masses of superparticles (GeV)*

	$m_{\widetilde{u}_L}$	$m_{\widetilde{u}_R}$	$m_{\widetilde{d}_L}$	$m_{\widetilde{d}_R}$	$m_{\widetilde{g}}$	$m_{\widetilde{\chi}_1^0}$
I	1546	1504	1548	1500	1498	272
II	1552	1538	1554	1536	1053	176

With the help of computer program SDECAY [9] we can calculate branching ratios (BR) for superparticles. In Table 3 we will show the decays of the produced squarks with the shortest 'cascade', $\widetilde{q} \to q\widetilde{\chi}_1^0$

Table 3. *The branching ratios for the decay $\widetilde{q} \to q\widetilde{\chi}_1^0$ for the two scenarios*

	$\widetilde{u}_L \to u\widetilde{\chi}_1^0$	$\widetilde{u}_R \to u\widetilde{\chi}_1^0$	$\widetilde{d}_L \to d\widetilde{\chi}_1^0$	$\widetilde{d}_R \to d\widetilde{\chi}_1^0$
I	0.012	0.997	0.015	0.997
II	0.003	0.095	0.005	0.026

It can be seen that BR is larger for the first scenario I and BR for $\widetilde{q}_L$ is quite small. Using the parameter set of Table 1 it is possible to calculate production cross sections of superpartners by application of the computer program PROSPINO. These cross sections at the center-of-mass energy $\sqrt{s} = 14$ TeV are shown in Table 4.

Table 4. *LO and NLO cross sections (pb) and K-factors for superpartners*

	channel	$\sigma_{\rm LO}^{\rm Prospino}$	$\sigma_{\rm NLO}^{\rm Prospino}$	$K^{\rm Prospino}$
I	squark-squark	0.397E-01	0.469E-01	1.1788
	squark-gluino	0.434E-01	0.678E-01	1.5616
	gluino-gluino	0.462E-02	0.127E-01	2.7549
II	squark-squark	0.406E-01	0.511E-01	1.2601
	squark-gluino	0.163	0.264	1.6130
	gluino-gluino	0.988E-01	0.230	2.3269

The computations of NLO cross sections for SUSY particles at hadron collider are made with some simplifications. The NLO corrections are always summed over the subchannels assumming a common mass for all squarks. The K-factor, i.e. the ratio between the NLO and LO cross section $K = \frac{\sigma_{NLO}}{\sigma_{LO}}$ is determined for the total cross section, with all subchannels summed up. With the help of computer program PYTHIA [10] we can represent NLO corrections on differential distributions. Fig.1 displays this distribution, normalized with the appropriate cross section.

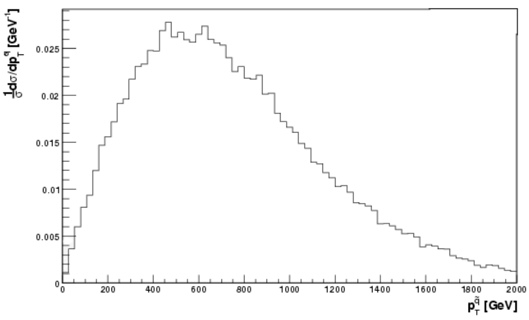

Fig.1. *Normalized $p_T^{\widetilde{q}}$ distribution for the first scenario with the center-of-mass energy of 14 TeV*

For both scenarios we also calculated the NLO results and received several distributions of inclusive quantities: the transverse momentum p_T , the pseudorapidity η for both squarks and gluino (Figs. 2 - 9).

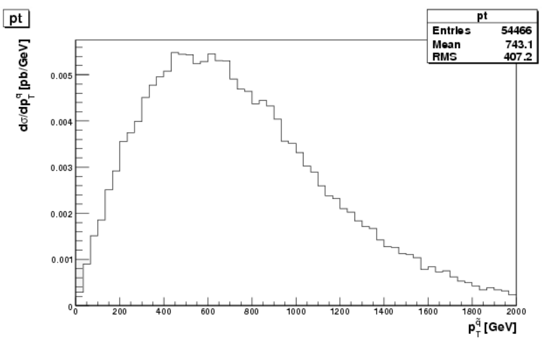

Fig.2. *p_T distribution with NLO corrections for squarks (first scenario)*

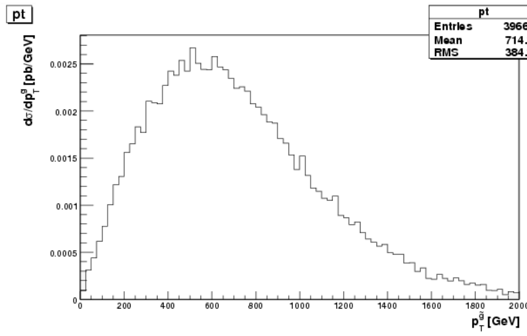

Fig.3. *p_T distribution with NLO corrections for gluino (first scenario)*

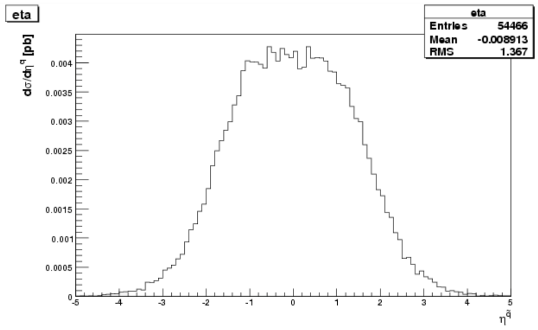

Fig.4. *η distribution with NLO corrections for squarks (first scenario)*

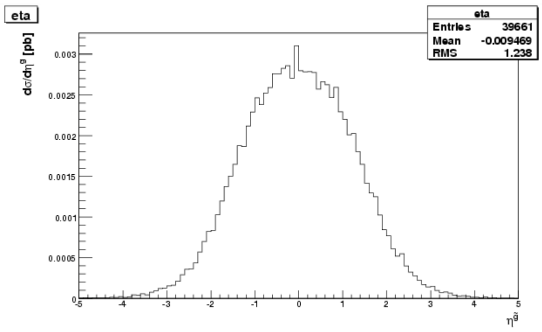

Fig.5. *η distribution with NLO corrections for gluino (first scenario)*

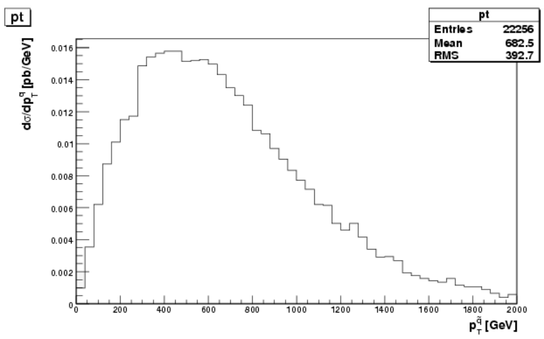

Fig.6. *p_T distribution with NLO corrections for squarks (second scenario)*

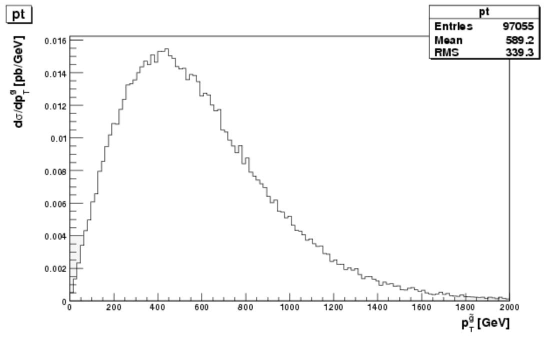

Fig.7. *p_T distribution with NLO corrections for gluino (second scenario)*

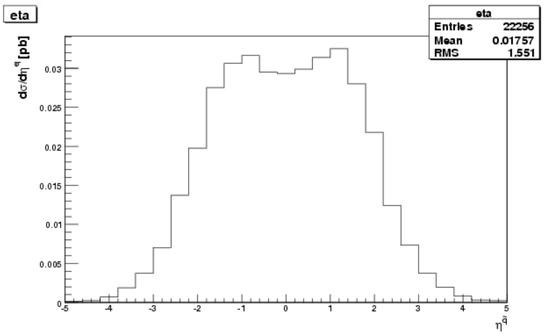

Fig.8. *η distribution with NLO corrections for squarks (second scenario)*

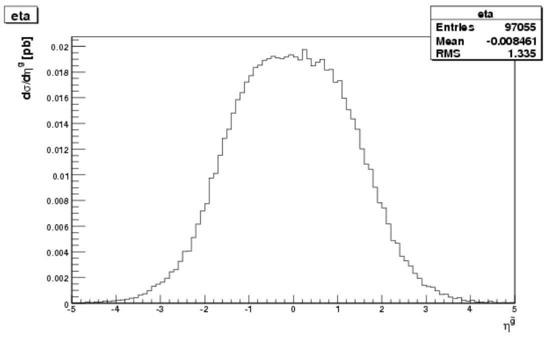

Fig.9. *η distribution with NLO corrections for gluino (second scenario)*

6. CONCLUSIONS

Supersymmetry is probably the best motivated scenario today for physics beyond the SM and has been the object of intense searches at high-energy collider. We have used different analysis methods for clarification of the experimental strategies in searches for SUSY at the LHC. For the interpretation of the experimental data precise theoretical predictions are of great importance. The present paper contributes to this effort by providing NLO corrections to the pair production of squarks and gluinos of the first two generations in a Monte Carlo programs. Current and future LHC data for searching physics beyond the Standard Model requires theoretical prediction for observables, including distributions and cross sections with kinematical cuts. The results presented in this paper provide a diffrential description of supersymmetric particle production and decay, and should form the theoretical basis for experiments at the LHC in future.

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NLO КОРРЕКЦИИ К ОБРАЗОВАНИЮ ПАРЫ СУПЕРСИММЕТРИЧНЫХ ЧАСТИЦ

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Анализ последних экспериментальных данных, полученных из БАК (КМС), ограничил пространство МССМ параметров. С помощью компьютерных программ SOFTSUSY, SDECAY посчитаны спектры масс и ширины распадов суперчастиц. Проведены расчеты next-to-leading order (NLO) поправок к поперечному сечению образования суперчастиц с помощью компьютерной программы PROSPINO. Представлены NLO поправки к дифференциальному сечению распределения по p_T и η для скварков и глюино.

NLO КОРРЕКЦІЇ ДО УТВОРЕННЯ ПАРЫ СУПЕРСИМЕТРИЧНИХ ЧАСТИНОК

Т.В. Обіход, А.О. Вербицький

Аналіз останніх експериментальних даних отриманих на ВАК (КМС) звузив простір МССМ параметрів. За допомогою комп'ютерних програм SOFTSUSY, SDECAY розраховано спектри мас і ширини розпадів суперчастинок. Проведено розрахунки next-to-leading order (NLO) поправок до поперечного перерізу утворення суперчастінок за допомогою комп'ютерної програми PROSPINO. Представлено NLO поправки до диференційного перерізу розподілу по p_T і η для скварків і глюіно.