EXPERIMENTAL SEARCHES FOR THE EXTENDED HIGGS SECTOR AT THE LHC

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Higgs discovery is very important for SUSY searches for its simplest low energy manifestation. The most celebrated extension of the Standard Model - the Minimal Supersymmetric Standard Model (MSSM) is extended to contain three neutral and two charged scalar bosons. The mass of all MSSM Higgs bosons depends on the SUSY parameters. Using exclusion limit from the hard single lepton channel in the $(m_0, m_{1/2})$ plane for the mSUGRA/CMSSM model we calculated CP-even Higgs boson branching ratios and its production cross sections at the LHC as a function of the c.m. energy. With the help of computer program PYTHIA 8.2 we calculated limits on $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ and $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$ in the mass range of charged Higgs boson $m_{H^+} = 1500...3500$ GeV. In the mass range $m_{H^+} = 450...700$ GeV we compared the production cross section of charged Higgs boson with experimental data on the upper limits on $\sigma(pp \to tH^+)$ for $l + jets$ final states and found good agreement.

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1. INTRODUCTION

String theory as the theory, that unifies the different observed forces and particles within the framework of a comprehensive theory, in some sense requires gauge symmetry for its internal consistency. Many of the divergences associated with field theory are absent in string theory. Despite the lack of experimental proof, string theory is today one of the most perspective theories as it solves a number of problems:

- the gauge hierarchy problem;
- a coupling of gauge theories to gravity;
- predicts low energy supersymmetry.

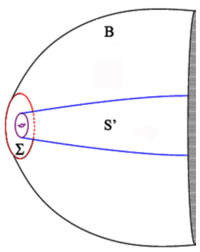

Fig.1. *Local model of a Calabi-Yau fourfold B*

String theory as incorporating gauge particles, matter and interactions among them describes the real world as the framework for including gravity, and deciding hierarchy problem [1]. Superstring theory that describes both bosons and fermions, requires ten dimensions. The geometry of superstring theory or, more precisely, the string vacuum corresponds to the space of the form $R^4 \times X$, where R^4 is Minkowski space and X is compact manifold (for example, Calabi-Yau manifold, B), which admits an elliptic fibration (Fig.1).

2. MSSM MODEL

To know which vacuum out of the set of vacua corresponds to our world, we will use experimental data. As unification energy scale, 10^{19} GeV, the way to achieve this is to include unified gauge theory in brane. The A-D-E type of elliptic fiber singularity corresponds to gauge theory, in particular, SU(5) GUT theory. Thus, the data of an SU(5) bundle over $R^4 \times S$ ($S \subset X$, contractible inside X) lead to the Standard Model gauge group. At high energy scale the Standard Model coupling constants come together at a distance of about 10^{-30} cm, assuming a supersymmetric completion (Minimal Supersymmetric Standard Model (MSSM)) of the Standard Model (Fig.2).

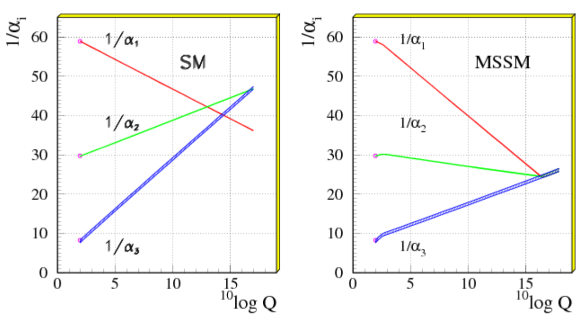

Fig.2. *Inverse gauge couplings α^{-1} in the Standard Model (left) and the MSSM model (right)*

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Yukawa couplings $c_{\alpha\beta\gamma}$ as triple interaction of three branes S_i, supported by Yukawa gauge groups G_i, correspond to triple intersection p_{ijk} with enhanced gauge group G_{ijk}

$$c_{\alpha\beta\gamma} = \phi^{\alpha}_{ij}(p_{ijk})\phi^{\beta}_{jk}(p_{ijk})\phi^{\gamma}_{ki}(p_{ijk}),$$

where ϕ^{α}_{ij} corresponds to zero modes of Dirac operator for matter fields on Σ_{ij} as the intersection of each pair of branes S_i, S_j. Matter content corresponding to Σ of Fig.1 is represented as curves of different colors in Fig.3 for SU(5) GUT [2]. Triple intersection of colored curves corresponds to Yukawa couplings according to dimensional reduction of the corresponding space-time: $\Sigma \subset S \subset B$.

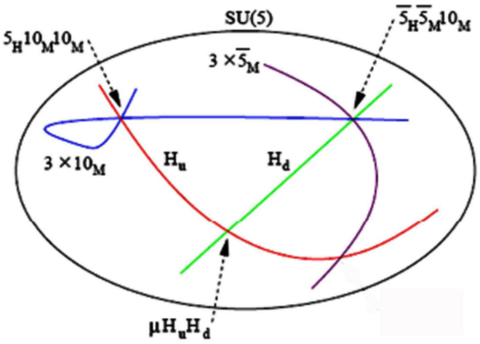

Fig.3. *Matter content (colored curves) and Yukawa couplings as intersection of curves*

The 1-loop RG (Renormalization Group) equations for the Standard Model gauge couplings g_1, g_2, g_3 are

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

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

where $t = ln(Q/Q_0)$, with Q the RG scale and Q_0 - input scale. The loop expansions for calculations of gauge couplings are necessary for describing physics near the electroweak scale. Yukawa couplings can induce masses for all Standard Model fermions. The gauge-invariant renormalizable superpotential with exact R-parity for the MSSM fields (up and down quarks and squarks, other quarks and squarks, electrons and selectrons leptons and sleptons and Higgs doublets) is the following [3]:

$$W_{MSSM} = y^u_{IJ} H_u Q_I U_J + y^d_{IJ} H_d Q_I D_J + y^e_{IJ} H_d L_I E_J + \mu H_u H_d \ .$$

Besides the supersymmetric interactions we need in SUSY breaking on the MSSM fields by soft SUSY-breaking terms:

$$\begin{aligned} L_{soft} = & -\tfrac{1}{2}\sum_{a=1}^{3} M_a tr \lambda_a \lambda_a + h.c. \\ & - m^2_{QIJ} \tilde{q}^+_I \tilde{q}_J - m^2_{UIJ} \tilde{u}^+_I \tilde{u}_J \\ & - m^2_{DIJ} \tilde{d}^+_I \tilde{d}_J - m^2_{LIJ} \tilde{l}^+_I \tilde{l}_J - m^2_{EIJ} \tilde{e}^+_I \tilde{e}_J \\ & - a_{UIJ} h_u \tilde{q}_I \tilde{u}_J - a_{DIJ} h_d \tilde{q}_I \tilde{d}_J - a_{EIJ} h_d \tilde{l}_I \tilde{e}_J \\ & - m^2_{H_u} |h_u|^2 - m^2_{H_d} |h_d|^2 - (b h_u h_d + h.c.) \ . \end{aligned}$$

Here M_a are complex gaugino masses, $m^2_{Q,U,D,L,E}$ are hermitian squark and slepton mass matrices, $a_{U,D,E}$ are general complex matrices of trilinear scalar couplings, $m^2_{H_u}$ and $m^2_{H_d}$ are real mass parameters for the up-type and down-type Higgs fields, and b is a complex mass mixing parameter for the Higgs scalars. Using scalar potential for the Higgs scalar fields

$$\begin{aligned} V = \ & (|\mu|^2 + m^2_{H_u})|h^0_u|^2 + (|\mu|^2 + m^2_{H_d})|h^0_d|^2 \\ & + (b h^0_u h^0_d + h.c.) \\ & + \tfrac{1}{8}(g^2 + g'^2)(|h^0_u|^2 - |h^0_d|^2)^2 \ , \end{aligned}$$

and due to the electroweak symmetry breaking in the MSSM at a scale

$$\upsilon^2 = \upsilon^2_u + \upsilon^2_d = (174 \text{ GeV})^2 = \frac{(246 \text{ GeV})^2}{2} \ ,$$

($h^0_u = \upsilon_u$, $h^0_d = \upsilon_d$) we receive the mass eigenvalues for five Higgs bosons:

$H^{\pm}$	charged Higgs boson pair;
A^0	CP-odd neutral Higgs boson;
H^0, h^0	CP-even neutral Higgs bosons :

$$m^2_{A^0} = \frac{2b}{\sin 2\beta} = 2|\mu|^2 + m^2_{H_u} + m^2_{H_d} \ ,$$

$$m^2_{h^0,H^0} = \tfrac{1}{2}\left(m^2_{A^0} + m^2_Z \mp \sqrt{(m^2_{A^0} - m^2_Z)^2 + 4 m^2_Z m^2_{A^0} \sin^2 2\beta}\right) \ ,$$

$$m^2_{H^{\pm}} = m^2_{A^0} + m^2_W \ .$$

3. SCENARIOS OF RECENT EXPERIMENTAL DATA AND SEARCHES FOR ADDITIONAL HIGGS STATES

As is known from the previous review, MSSM model predicts extended Higgs consisting of five Higgs bosons, two CP-even, one of which is a light Higgs state h, and H, a CP-odd A and two charged $H^{\pm}$ states. The Higgs discovery is very important for SUSY for its low energy manifestation. As an additional argument for this statement we can represent the dependence of the cross section for the gluon-gluon Higgs boson production H^0 on the energies at future colliders, calculated by application of computer program PYTHIA 8.2 [4]. As can be seen from Fig.4, the production cross section for additional Higgs state H^0 became larger at higher energies of colliders, that can be achieved in future.

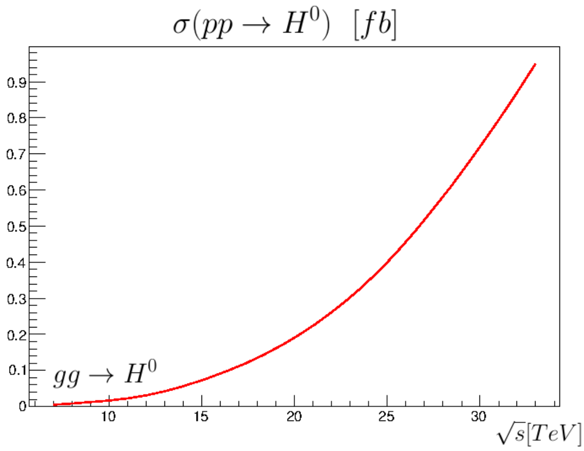

Fig.4. *The dependence of Higgs boson production cross section H^0 on the energies at future colliders*

The superpotential W of MSSM model depends on more than 100 parameters. The restriction of this parameter space, based on observational hints and theoretical considerations of Yukawa coupling constants, allows to consider the following five free parameters [5]: $m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}\mu$, where m_0 and $m_{1/2}$ are the masses of scalar and spinor superpartners, respectively; 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 [6] obtained by the ATLAS Collaboration for the proton-proton collisions allowed us to consider eight scenarios of the MSSM model, presented in Table, as such that exceed recent experimental observations shown in Fig.5.

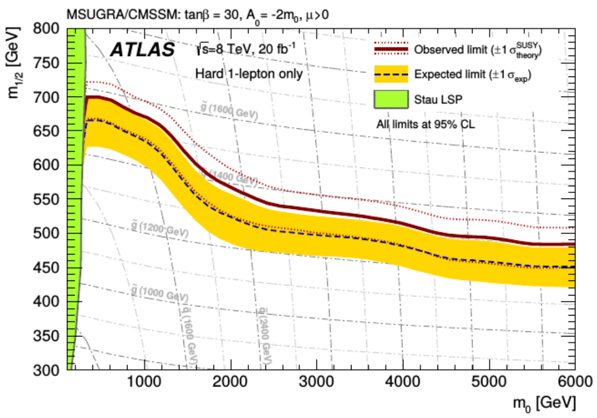

Fig.5. *95 % CL exclusion limit from the hard single-lepton channel in the $(m_0, m_{1/2}\ )$ plane for the mSUGRA/CMSSM model. The observed nominal limit is shown by a solid dark red line, with the dark red dotted lines indicating the $\pm 1\sigma$ variation on this limit due to the theoretical scale and PDF uncertainties on the signal cross section*

Eight scenarios of MSSM model

	m_0, GeV	$m_{1/2}$, GeV	A_0, GeV	tanβ	sgn(μ)
I	1000	750	-2000	30	+1
II	1800	700	-3600	30	+1
III	2000	750	-4000	30	+1
IV	2200	640	-4400	30	+1
V	3000	630	-6000	30	+1
VI	3200	630	-6400	30	+1
VII	4000	620	-8000	30	+1
VIII	4800	570	-9600	30	+1

Using the restricted parameter set of Table and by application of the computer program SDECAY [7], we presented the most significant branching ratios for H^0 decays: $H^0 \to b\bar{b}, H^0 \to \tau^+\tau^-, H^0 \to t\bar{t}$ (Fig.6).

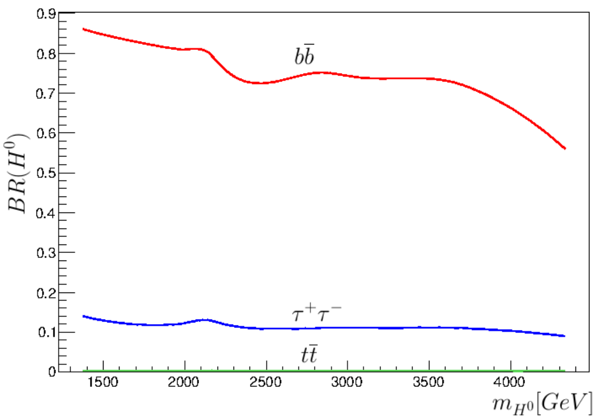

Fig.6. *The branching fractions of H^0 to $b\bar{b}$ (red), $\tau^+\tau^-$ (blue), $t\bar{t}$ (green)*

A search for a charged Higgs boson was performed with a data sample corresponding to an integrated luminosity of $19.7 \pm 0.5\, fb^{-1}$ collected with the CMS-detector in proton-proton collisions at $\sqrt{s} = 8\, TeV$ [8]. $H^+ \to \tau^+\nu_\tau$ and $H^+ \to t\bar{b}$ decay modes were considered in the search as the most probable decay channels of charged Higgs boson, produced most frequently via $t\bar{t}$ production. In the considered MSSM scenarios the charged Higgs boson preferentially decays to a τ lepton and corresponding neutrino, $H^+ \to \tau\nu_\tau$. A representative diagram for the decay mode of charged Higgs boson is shown in Fig.7.

Our purpose was to calculate the cross section times branching fraction $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ in the mass range m_H^+=1500...3600 GeV for proton-proton collisions at $\sqrt{s}$=14 TeV.

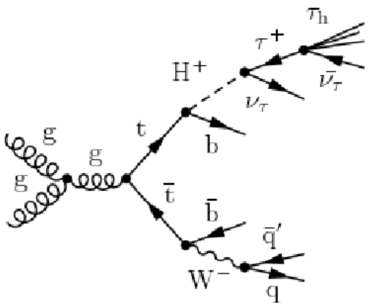

Fig. 7. *Production mode of the charged Higgs boson through $t\bar{t}$ production*

The results of calculations for charged Higgs boson by application of computer program PYTHIA 8.2 [4] are presented in Fig.8.

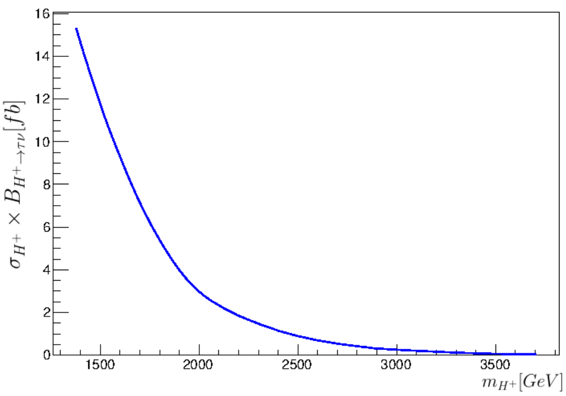

Fig. 8. *Dependence of $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ with m_{H^+}=1500...3600 GeV for the $H^+ \to \tau\nu_\tau$ search at $\sqrt{s}$=14 TeV*

In the mass range m$_{H^+}$=180...600 GeV, the analyses of the $\mu\tau_h$, l+jets, and ll' final states have sensitivity to both $H^+ \to \tau\nu_\tau$ and $H^+ \to t\bar{b}$ decays [9]. So, we provided results of calculation for $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$, presented in Fig.9.

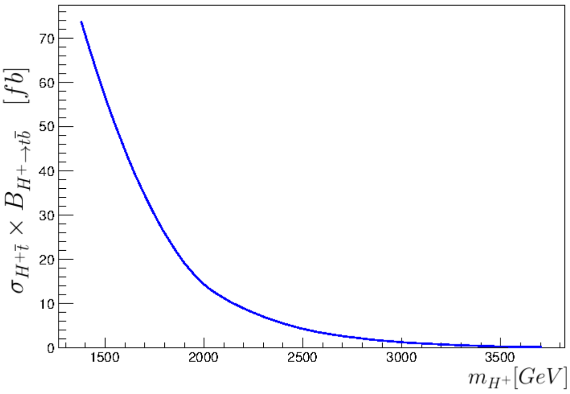

Fig. 9. *Dependence of $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$ with m_{H^+}=1500...3600 GeV for the $H^+ \to t\bar{b}$ search at $\sqrt{s}$=14 TeV*

For comparision of our results with experimental data in the low energy region, we have calculated the production cross section of charged Higgs boson at $\sqrt{s}$=8 TeV as a function of its mass with the help of computer program PYTHIA 8.2 [4]. As can be seen from the experimental data of [9], the character of production cross section dependence on the Higgs boson mass in the mass range m$_{H^+}$=450...730 GeV is almost the same, but the accordance is best in the higher mass range, see Fig.10.

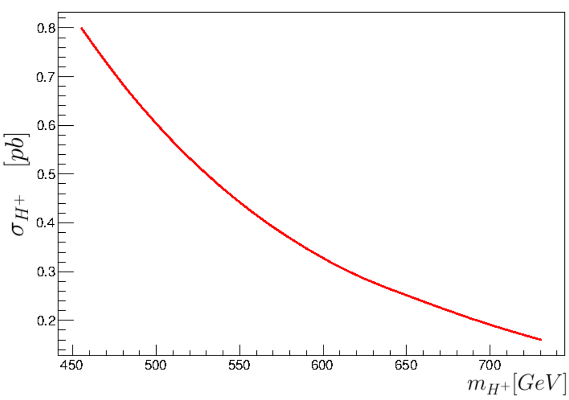

Fig. 10. *Production cross section of charged Higgs boson H^+ at $\sqrt{s}$ = 8 TeV*

4. CONCLUSIONS

The searches for additional sector of MSSM Higgs bosons are most preferred for the possible opening of SUSY at the LHC. Since Higgs boson production cross section significantly increases with increasing of energy at the LHC, such searches are relevant at $\sqrt{s}$=13 TeV in pp-collisions. Considering eight scenarios associated with searches for supersymmetry at the LHC, we calculated the branching ratios for the decays $H^0 \to b\bar{b}, H^0 \to \tau^+\tau^-, H^0 \to t\bar{t}$. Since decay modes $H^+ \to \tau^+\nu_\tau$ and $H^+ \to t\bar{b}$ are the most probable decay channels of charged Higgs boson, we have presented dependences of $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ and $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$ in the mass range of charged Higgs boson m_{H^+}=1500...3500 GeV at $\sqrt{s}$=14 TeV. From these results it follows that with the growth of the Higgs boson mass, the production cross section significantly fall. This fact is an additional stimulus for searches of MSSM additional Higgs states in the mass range up to 1 TeV, which indirectly proves the recently announced by ATLAS and CMS collaborations discovery of excess around 750 GeV in the two-photon spectrum with about 3σ [10].

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ЭКСПЕРИМЕНТАЛЬНЫЕ ПОИСКИ ДОПОЛНИТЕЛЬНОГО СЕКТОРА БОЗОНОВ ХИГГСА НА БАК

Т. В. Обиход

Открытие бозона Хиггса является важным для поисков суперсимметрии благодаря невысокому энергетическому порогу. Наиболее известным расширением Стандартной Модели является Минимальная Суперсимметричная Стандартная Модель (МССМ), содержащая три нейтральных и два заряженных скалярных бозона. Масса бозона Хиггса зависит от суперсимметричных параметров. Используя пространство параметров $(m_0, m_{1/2})$ mSUGRA/CMSSM модели для жёсткого однолептонного канала, мы посчитали ширины распадов для CP-чётного бозона Хиггса и вероятность его образования в БАК как функцию энергии в системе центра масс. С помощью компьютерной програмы PYTHIA 8.2 мы посчитали $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ и $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$ для заряженного бозона Хиггса в области масс m_{H^+}=1500...3500 ГэВ. В области масс m_{H^+}=450...700 ГэВ мы сравнили сечение образования для заряженного бозона Хиггса с экспериментальными данными на верхний предел на $\sigma(pp \to tH^+)$ для $l + jets$ конечных состояний и нашли хорошее согласие.

ЕКСПЕРИМЕНТАЛЬНІ ПОШУКИ ДОДАТКОВОГО СЕКТОРУ БОЗОНІВ ХІГГСА НА БАК

Т. В. Обіход

Відкриття бозона Хіггса є важливим для пошуків суперсиметрії завдяки низькому енергетичному порогу. Найбільш відомим розширенням Стандартної Моделі є Мінімальна Суперсиметрична Стандартна Модель (МССМ), що містить три нейтральних і два зарядженых скалярних бозона. Масса бозона Хіггса залежить від суперсиметричних параметрів. Використовуючи простір параметрів $(m_0, m_{1/2})$ mSUGRA/CMSSM моделі для жорсткого однолептонного каналу, ми розрахували ширини розпадів для CP-парного бозона Хіггса і переріз його утворення на БАК як функцію енергії в системі центру мас. За допомогою комп'ютерної програми PYTHIA 8.2 ми порахували $\sigma(pp \to tH^+)B(H^+ \to \tau^+\nu_\tau)$ та $\sigma(pp \to tH^+)B(H^+ \to t\bar{b})$ для зарядженого бозона Хіггса в діапазоні мас m_{H^+}=1500...3500 ГеВ. В діапазоні мас m_{H^+}=450...700 ГеВ ми порівняли переріз утворення зарядженого бозона Хіггса з експериментальними даними на верхню межу на $\sigma(pp \to tH^+)$ для $l + jets$ кінцевих станів і знайшли добре узгодження.