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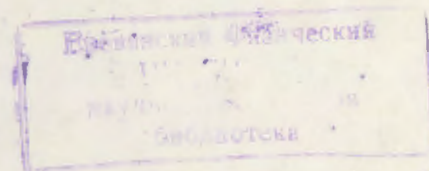
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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ  
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HIGGS-BOSON ASSOCIATED PRODUCTION  
IN  $\Upsilon$ -COLLISIONS



ЦНИИатоминформ  
ЕРЕВАН - 1989

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Հիգսի բոզոնների շնչառելի ծնունդը ՇՐ-բախուժներում

Ուսումնասիրված է ծանր քվարկ-հակաքվարկ զույգով Հիգսի բոզոնների համատեղ ծնման մեխանիզմը ՇՐ-բախուժներում: Ցույց է տրված, որ ծնման կտրվածքը թույլ է տալիս ունենալ մինչև 1000 դեպք տարվա ցնդողը Հիգսի բոզոնների ծնման նախատեսված ՄԻԿ վրա և LEP + LHC էներգիաների և լուսատվույթյան դեպքում: Ծնված Հիգսի մասնիկները կարող են մեծ լայնակի իմպուլսներ ունենալ, որը հնարավորություն է տալիս առանձնանալ ուժեղ ֆոնային գործընթացներից:

Երևանի ֆիզիկայի ինստիտուտ

Երևան 1989

In connection with ep-colliders being constructed and planned (HERA,  $\sqrt{S_0} = 314$  GeV; LEP+LHC,  $\sqrt{S_0} = 1.4 + 1.8$  TeV; UNK + electron linear beam,  $\sqrt{S_0} = 1.1 + 4.9$  TeV), a thorough analysis of the feasibility to study the new physics with these machines has been carrying on in the recent years [1-5]. As known, the merits of the ep-colliders consist in larger background conditions to study the new physics (as opposed to the pp- and p $\bar{p}$ -colliders where hadron backgrounds are very great).

The ep-colliders make it possible to create  $\gamma$ p-colliders on real photons practically without losses for luminosities and  $\sqrt{S_0}$ . The creation of  $\gamma$ p-colliders and problems that can be studied with these machines are investigated in detail in Ref. [6]. In the present paper we have considered the possibility to search for the Higgs bosons on the  $\gamma$ p-colliders. We have suggested a mechanism of production of Higgs scalar and pseudoscalar bosons in  $\gamma$ p-collisions when H $^0$ - and P $^0$ -bosons are produced in association with a heavy quark pair.

$$\gamma P \rightarrow F \bar{F} H^0(P^0) X \quad (1)$$

where  $F, \bar{F}$  are hadrons containing heavy quarks  $Q, \bar{Q}$  (a similar mechanism for  $pp$ - and  $p\bar{p}$ -collisions was studied in Refs [7-10]). The mechanism under study is interesting due to the fact that the Higgs bosons are produced in association with easily detectable heavy quarks, which will undoubtedly help to identify  $H^0(P^0)$ -bosons, since the studied reaction has interesting final states. So, if  $2m_f \leq m_h \leq 2m_t$  (running ahead, we note that the studied mechanism is interesting and gives noticeable cross sections for produced  $H^0(P^0)$ -bosons of medium masses  $10 \text{ GeV} \leq m_h \leq 100 \text{ GeV}$ , i.e. for the existing restrictions on a t-quark mass  $m_t \geq 50 \text{ GeV}$  [11,12] the best decay mode for Higgs bosons in our case will be  $H^0(P^0) \rightarrow b\bar{b}$ ), and  $Q$  is t-quark, then in the final state of the reaction we may have, say, events with four c-quarks and eight charged fast leptons resulting from semileptonic decays of heavy quarks. Besides, in this mechanism the Higgs bosons are produced with large transverse momenta, which will help to escape from the possible background processes.

The amplitude of the studied process (1) at a quark-gluon level in the lowest order of the perturbation theory is of the form (see Fig.1):

$$A = m(g_e Q) (G\sqrt{2})^{1/2} \left(\frac{\lambda_{ij}^a}{2}\right) \epsilon_\mu^a(K_2) e_\nu(K_1)$$

$$\times \bar{Q}_j(K_4) \left[ C \frac{\hat{K}_4 + \hat{K}_5 + m}{(K_4 + K_5)^2 - m^2} \gamma_\nu \frac{\hat{K}_2 - \hat{K}_3 + m}{(K_2 - K_3)^2 - m^2} \gamma_\mu + \left( \begin{matrix} \mu \leftrightarrow \nu \\ K_1 \leftrightarrow K_2 \end{matrix} \right) \right. \\ \left. + \gamma_\nu \frac{\hat{K}_4 - \hat{K}_1 + m}{(K_4 - K_1)^2 - m^2} C \cdot \frac{\hat{K}_2 - \hat{K}_3 + m}{(K_2 - K_3)^2 - m^2} \gamma_\mu + \left( \begin{matrix} \mu \leftrightarrow \nu \\ K_1 \leftrightarrow K_2 \end{matrix} \right) \right. \\ \left. + \gamma_\nu \frac{\hat{K}_4 - \hat{K}_1 + m}{(K_4 - K_1)^2 - m^2} \gamma_\mu \frac{-\hat{K}_3 - \hat{K}_5 + m}{(K_3 + K_5)^2 - m^2} C + \left( \begin{matrix} \mu \leftrightarrow \nu \\ K_1 \leftrightarrow K_2 \end{matrix} \right) \right] Q_i(-K_3), \quad (2)$$

where  $g = \sqrt{4\pi\alpha_s}$ ,  $\alpha_s = 12\pi/21 \ln(S/\Lambda_{QCD}^2)$ ,  $S = (K_1 + K_2)^2$ ,  $\Lambda_{QCD} \approx 0.2 \text{ GeV}$ ;  $m$  and  $Q$  are a mass and a charge of the heavy quark;  $i, j = 1, 2, 3$  are color indices of the quarks,  $a = 1 \dots 8$  is gluon color index,  $\lambda_{ij}^a$  are Gell-Mann matrices of SU(3) group;  $\epsilon_\mu^a(K_2)$ ,  $e_\nu(K_1)$  are polarization matrices for gluon and photon, respectively, and notations for momenta are given in Fig.1.  $C=1$  for  $H^0$ -bosons where the relations of minimal standard model are preserved,  $C = y\gamma_5$  for pseudoscalar  $P^0$ -boson production (such bosons arise, e.g. in models of electro-weak interaction with two doublets of Higgs bosons, at SUSY with two doublets of Higgs bosons), and  $y = v_2/v_1$  where  $v_1$  and  $v_2$  are vacuum expectation values for two Higgs doublets. In what follows we everywhere take  $y=1$  for numerical calculations; note, however, that the experimental restriction  $y \leq 40$  [13] points out that the cross section of pseudoscalar boson production may increase by a large factor,  $y^2$ .

After standard calculations we obtain expressions for the total  $\sigma$  and differential cross sections  $d\sigma/dx_n$  and  $d\sigma/dx_1$  by energy and transverse momentum of produced Higgs bosons.

Here  $x_H = 2E_H/\sqrt{S_0}$ ,  $x_1 = 2K_1/\sqrt{S_0}$ , and  $E_H$  and  $K_1$  are energy and transverse momentum of  $H^0(P^0)$ -boson (we do not give expressions for cross sections because the obtained results are cumbersome). In our calculations we used both the scaling function of gluon distribution  $xG(x) = \beta(1-x)^5$  and the one with scale-breaking taking from Ref. [8] (see formula (2.14) of this work; here  $x$  is a fraction of momentum carried away by the gluon from the proton).

Fig. 2 shows the total cross section as a function of colliding beams energy  $\sqrt{S_0}$  ( $S_0 = (K_1 + p_2)^2$ , where  $K_1$  and  $p_2$  are momenta of photon and proton beams, respectively,  $K_2 \approx x p_2$ ) for various values of masses of  $H^0(P^0)$ -bosons and t-quark. One can see that the cross section of the studied reaction attains, say,  $\sim 3 \cdot 10^{-36} \text{ cm}^2$  at  $m_H = 10 \text{ GeV}$ ,  $m_t = 160 \text{ GeV}$  and  $\sqrt{S_0} = 4.9 \text{ TeV}$ . This will provide from 30 to 3000 events yearly for scalar particle production, at the planned luminosities  $\mathcal{L} \approx 10^{31} \div 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ . We'd like to note strong dependence of the obtained results on gluon distribution function. Thus, for  $m_H = 10 \text{ GeV}$ ,  $m_t = 160 \text{ GeV}$  and at  $\sqrt{S_0} = 3.5 \text{ TeV}$  the non-scaling cross section is by a factor of 4 larger than the scaling one. Fig. 2 also illustrates that the  $H^0$ -boson production cross section is essentially larger than the  $P^0$ -boson one, and only with increasing  $m_H$  this difference somewhat decreases (remind, that we took  $y=1$  everywhere).

Fig. 3 presents the cross section as a function of  $m$  - heavy quark mass (everywhere below, under  $Q$  we imply the t-quark, since the contribution to the cross section of reaction (1) from the b-quarks is small and achieves  $\sim 10^{-38} \text{ cm}^2$  at the

best) at various values of  $m_H$  and  $\sqrt{S_0}$ . For each pair of values of  $m_H$  and  $\sqrt{S_0}$  we have a most advantageous region of production of Higgs particles by t-quark mass. So, for  $m_H = 20 \text{ GeV}$  and  $\sqrt{S_0} = 3.5 \text{ TeV}$  a largest cross section of  $H^0$ -boson production is achieved in the mass range  $m_t \approx 160 \div 200 \text{ GeV}$ , being  $\sigma \approx 7 \cdot 10^{-37} \text{ cm}^2$ , which for planned luminosities yields from 70 to 700 events yearly. In case we have  $\sqrt{S_0} = 1.1 \text{ TeV}$  and  $m_H = 10 \text{ GeV}$ , a cross section is  $\sim 5 \cdot 10^{-37} \text{ cm}^2$  for  $m_t = 80 \div 100 \text{ GeV}$ . At HERA energies ( $\sqrt{S_0} = 314 \text{ GeV}$ ) the cross section of the studied reaction lies within  $\sim 10^{-37} \div 10^{-39} \text{ cm}^2$  for Higgs boson production with  $m_H \leq 50 \text{ GeV}$ . So, for  $m_H = 10 \text{ GeV}$  and  $m_t = 40 \text{ GeV}$  we'll have 100 events yearly at luminosities  $\mathcal{L} \approx 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ .

Figs. 4 and 5 present differential cross sections  $d\sigma/dx_H$  versus the energy of produced Higgs bosons,  $x_H$ , for various values of  $m_H$  and  $m_t$  at  $\sqrt{S_0} = 1.1 \text{ TeV}$ . One can see that when  $m_t \gg m_H$ , we have a peak in differential distribution in the region of small  $x_H$  which is pronounced more distinctly for  $H^0$ -bosons. At  $m_t \approx m_H$  the peaks shift toward larger  $x_H$  and differential cross sections for  $H^0$  and  $P^0$ -bosons become comparable. The similar picture can be observed for  $\sqrt{S_0} = 2.4, 3.5$  and  $4.9 \text{ TeV}$ , so we do not present these plots. We'd like to emphasize weak dependence of  $d\sigma/dx_H$  on gluon distribution function (Figs. 4, 5).

We have also considered differential cross section  $d\sigma/dx_1$  with respect to Higgs boson transverse momentum  $x_1$ . It turned out that in the studied mechanism  $H^0(P^0)$ -bosons are produced with large transverse momenta, and the differential cross

section over  $\alpha_1$  has an original behavior. So, as shown in Fig.6, the differential cross section has a sharp peak at  $\alpha_1 \approx 0.15$  for  $\sqrt{s_0} = 1.1$  TeV,  $m_H = 20$  GeV and  $m_t = 160$  GeV, which corresponds to  $K_1 \approx 75$  GeV.

As the difference between Higgs boson and heavy quark masses decreases, the peak over  $\alpha_1$  is shifting to the right, which is indicative of produced Higgs bosons with even large transverse momenta. So, at  $\sqrt{s_0} = 1.1$  GeV,  $m_H = 50$  GeV and  $m_t = 160$  GeV we have  $K_1 \approx 80$  GeV (cf. Figs. 6 and 8). The differential cross section over  $\alpha_1$  practically does not change its behavior with increasing  $\sqrt{s_0}$  (see Fig.8 wherein curves for  $\sqrt{s_0} = 4.9$  TeV are presented). Figs. 6-8 show that in scalar and pseudoscalar bosons peak regions over  $\alpha_1$  practically coincide.

One can see that the studied mechanism of Higgs boson production in  $\gamma p$ -collisions yields noticeable cross sections only for particles with masses  $m_H \approx 2m_t$ , i.e. for  $H^0(P^0)$ -bosons the  $H^0(P^0) \rightarrow b\bar{b}$  decay is dominant. In this case the major background processes for the mechanism of  $H^0(P^0)$ -boson production suggested in this work are QCD-processes with pair production of b- and t-quarks:

$$\gamma g \rightarrow b + \bar{b} + t + \bar{t} \quad (3)$$

Estimating these backgrounds solely on the basis of interaction constants, we obtain that their cross sections are of the same order as the signal from the Higgs particle production is (in  $p\bar{p}(pp)$ -collisions for a similar mechanism the background processes are two orders higher than the signal [14]). To

suppress the backgrounds (for instance, using the corresponding cutoffs over transverse momenta and invariant masses of  $b\bar{b}$ ,  $t\bar{t}$  pairs) and for more reliable identification of the major signal, a more detailed study of process (3) is needed, this to be done by us elsewhere.

In conclusion, we'd like to note once again that the considered mechanism is of interest to search for Higgs particles of medium masses (especially noticeable cross sections come out for production of particles with  $m_H \lesssim 80$  GeV) on planned ep-colliders [3]. For luminosities feasible on them ( $\mathcal{L} \sim 10^{31} \div 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ) there are produced, say, as many as 350  $H^0$ -bosons for  $\sqrt{s_0} = 2.4$  TeV,  $m_H = 20$  GeV and  $m_t = 80$  GeV, or up to 200 events for  $\sqrt{s_0} = 3.5$  TeV,  $m_H = 50$  GeV and  $m_t = 120$  GeV.

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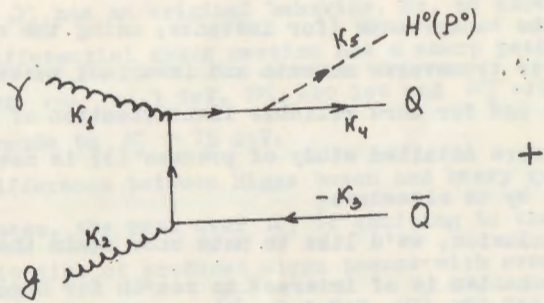


Fig.1

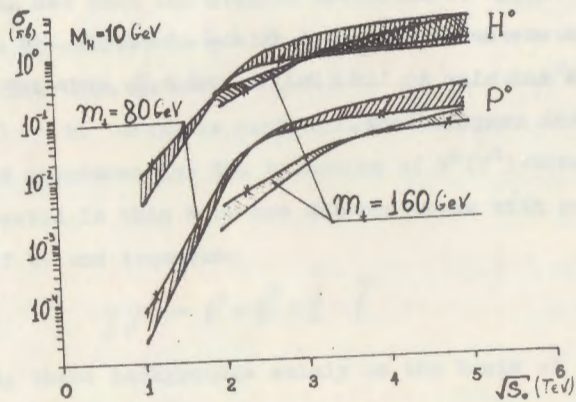


Fig.2

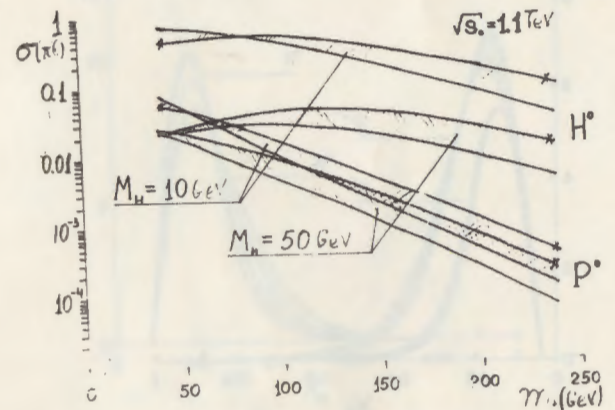


Fig.3a

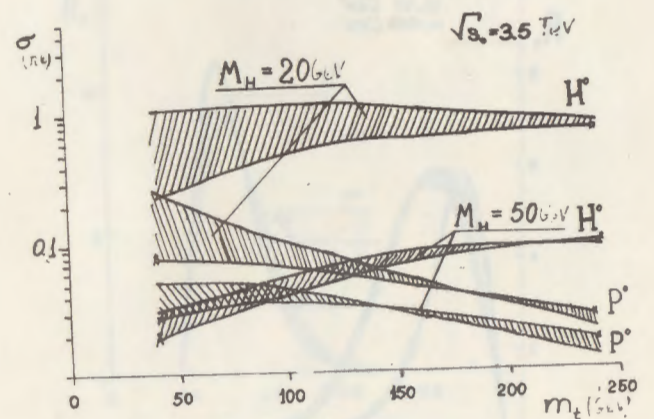


Fig.3b

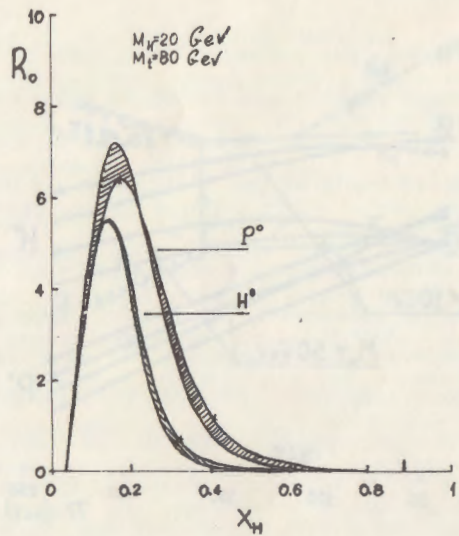


Fig. 4a

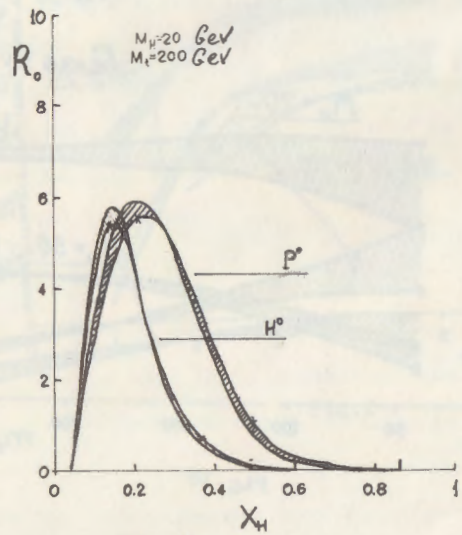


Fig. 4b

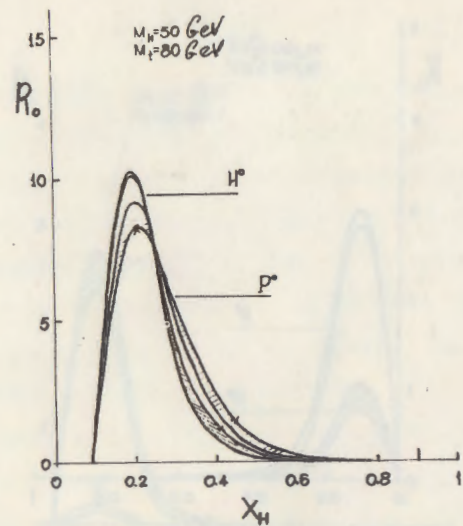


Fig. 5a

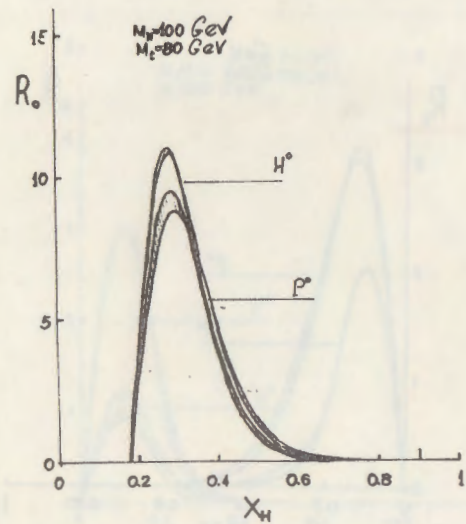


Fig. 5b

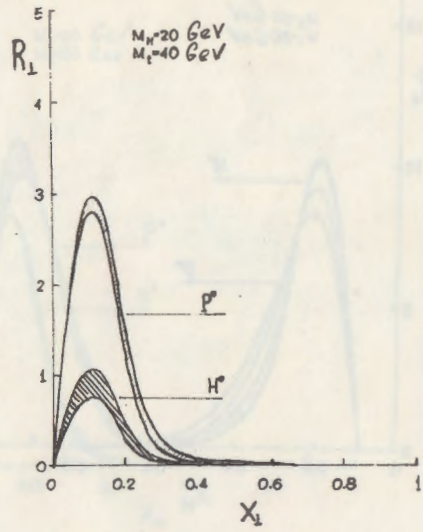


Fig. 6a

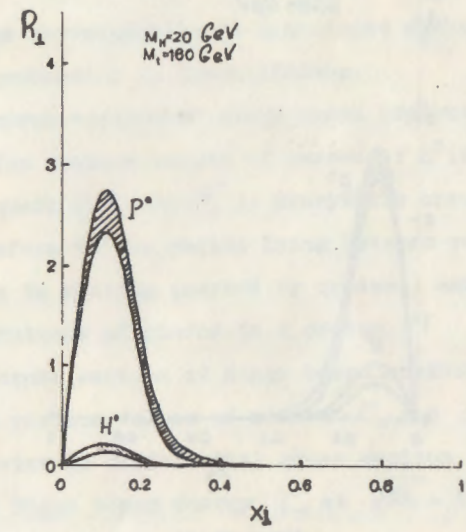


Fig. 7a

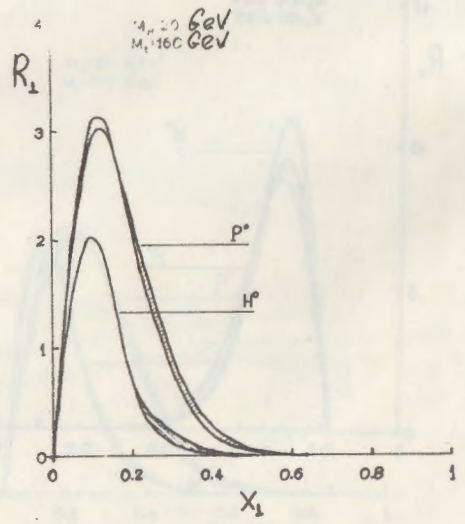


Fig. 6b

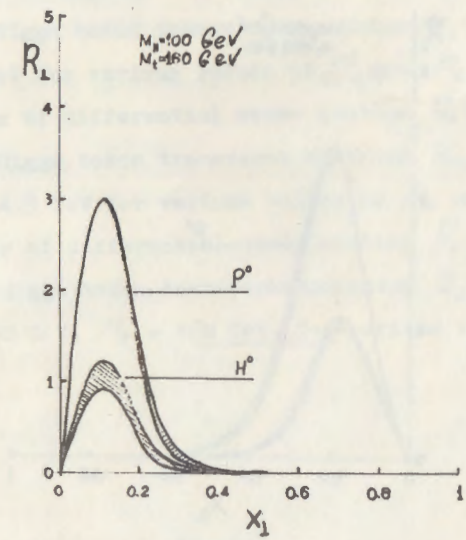


Fig. 7b

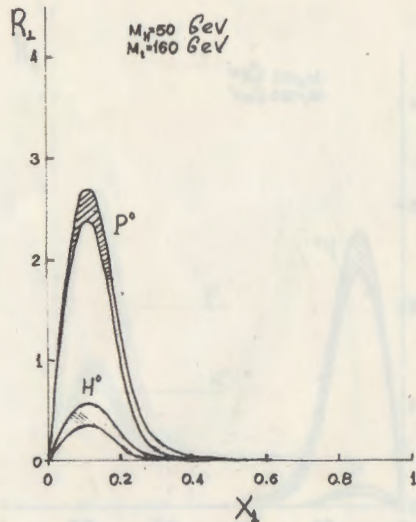


Fig.8a

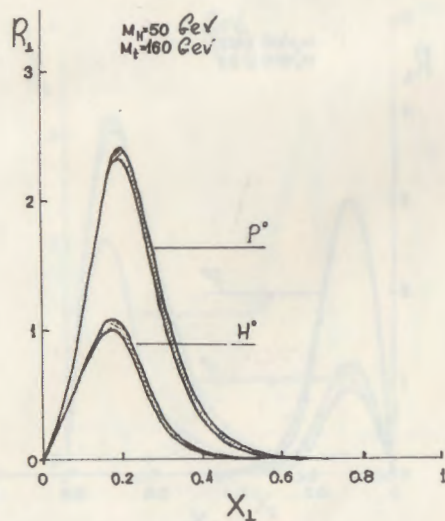


Fig.8b

Figure Captions

Fig.1. Diagrams corresponding to associated mechanism of Higgs boson production in  $\gamma p$ -collisions.

Fig.2. Total cross section of Higgs boson production versus  $\sqrt{s_0}$  for various values of masses of  $H^0(P^0)$ -bosons and t-quark ( $M_H$  and  $M_t$ ). Everywhere onward the dashed area refers to the region lying between curves corresponding to scaling (marked by crosses) and non-scaling distributions of gluons in a proton.

Fig.3. Total cross section of Higgs boson production versus  $M_t$  at various values of masses  $M_H$  and  $\sqrt{s_0}$ .

Fig.4,5. Behavior of differential cross section  $R_0 = 1/\epsilon d\sigma/dx_H$  versus Higgs boson energy  $x_H$  at  $\sqrt{s_0} = 1.1$  TeV for various values of  $M_H$  and  $M_t$ .

Fig.6. Behavior of differential cross section  $R_1 = 1/\sigma d\sigma/dx_1$  versus Higgs boson transverse momentum  $x_1$  at  $\sqrt{s_0} = 1.1$  TeV for various values of  $M_H$  and  $M_t$ .

Fig.7. Behavior of differential cross section  $R_1 = 1/\epsilon d\sigma/dx_1$  versus Higgs boson transverse momentum  $x_1$  at  $\sqrt{s_0} = 4.9$  TeV for various values of  $M_H$  and  $M_t$ .

Fig.8. Behavior of differential cross section  $R_1 = 1/\epsilon d\sigma/dx_1$  versus Higgs boson transverse momentum  $x_1$  at  $M_H = 50$  GeV,  $M_t = 160$  GeV, for various values of  $\sqrt{s_0}$ .

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АССОЦИАТИВНОЕ РОЖДЕНИЕ ХИГГСОВСКИХ БОЗОНОВ В  $УР$ -СТОЛКНОВЕНИЯХ

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