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PRODUCTION OF THE HIGGS SCALARS IN ASSOCIATION WITH THE NEUTRAL GAUGE BOSONS AT MUON COLLIDER

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Abstract

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With the aim of muon collider physics potential researching, the cross sections for the production of Higgs Bosons in association with the neutral gauge bosons are studied. This new area of future research has raised a number of attractive both experimental and theoretical problems under consideration.

Аннотация

Тихонин Ф.Ф. Рождение скаляров Хиггса в совокупности с нейтральными калибровочными бозонами на мюонном коллайдере: Препринт ИФВЭ 98-18. – Протвино, 1998. – 5 с., 2 рис., библиогр.: 16.

С целью изучения физического потенциала мюонных коллайдеров изучаются процессы рождения бозонов Хиггса в совокупности с нейтральными калибровочными бозонами. Эта новая область будущих исследований поднимает ряд интересных как экспериментальных, так и теоретических вопросов, которые являются объектом данного доклада.

Introduction

The search for Higgs particles from various models and the study of the sundry scenarios for electroweak symmetry breaking mechanism is one of the most important goals of future high energy colliders [1]. Another important task is to make a detailed study of the basic properties of possible Higgs particles in all kinds of models. One of the most interesting and crucial parameters is the value of the couplings of Higgs bosons to other fundamental particles [2]. Measurements of those couplings would allow one to make choice between different Higgs schemes, but in this short paper we restrict our discussions to the Standard Model (SM) with a single neutral Higgs boson.

Presumably, the fundamental scalar will be revealed and investigated, to some extent, at the forthcoming LHC collider, but the precision will evidently be insufficient for the aims above. So, it is expedient to search for the other means to make precision measurements in a wide region of possible Higgs boson mass values. In this respect a crucial role will be played by colliding lepton beams. Among them, in turn, the future $\mu^+\mu^-$ colliders will be more preferable, in this respect, to electron-positron one, as it will be seen below. For the muon collider idea see the page "Muon Colliders: A Brief History" of the present workshop web announcements. The exact reference to the second paper of that list is [3]. Investigations of accelerator physicists of the past several years showed that technical difficulties expected were not insuperable [4]. At the same time the theoretical motivation for muon colliders has been growing with time [5]. The most elaborated idea is the possibility of constructing "Higgs boson factory". Here, we consider two related processes.

1. Associated HZ production in SM

Let's begin with the Bjorken process having muons as the initial state particles, $\mu^+\mu^- \to ZH^0$. The corresponding diagrams are depicted in Figure 1.

Usually, in the course of cross-section calculations, one uses the diagram of Fig.1-c alone. Let's do the same but take into account the masses of initial muons. Then, we obtain the following asymptotics of this process at $\sqrt{s} \to \infty$:

$$\sigma^{(c),as}_{\mu^+\mu^-\to ZH^0}\big|_{m_\mu\neq 0} = \frac{2\pi\ \alpha^2}{\sin^4(2\theta_W)}\cdot g_A^2\cdot\frac{m_\mu^2}{m_Z^4}. \tag{1}$$

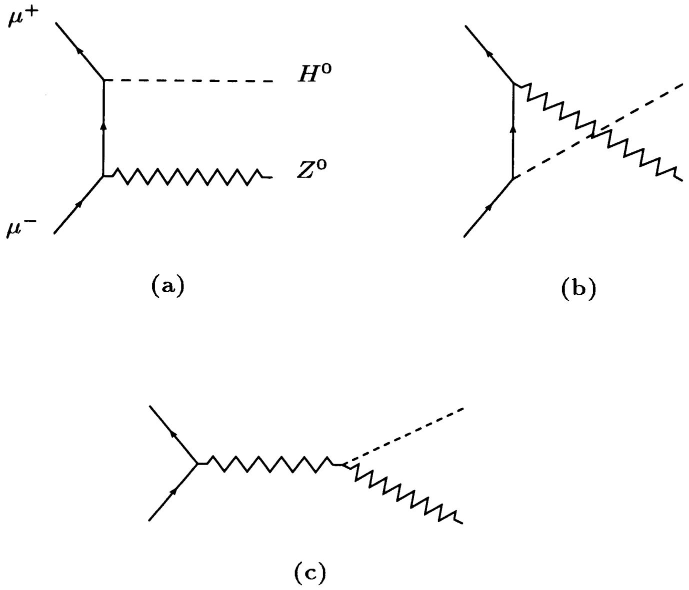

Fig. 1. Diagrams for the Bjorken process in the case of nonvanishing initial state masses.

It is seen, that despite the fact that this diagram is the pure s–channel one, the corresponding cross-section is not falling at high energy, but approaches a constant limit, whose value is equal to $\cong 1.2\cdot 10^{-2} fb$. Concerning the angular dependence of this cross-section, it could be seen, that this distribution is **flat**, and indicates that it comes entirely from the $J = 0$ partial wave. It is obvious, that this behaviour contradicts the unitarity condition, that requires $\sigma_{J=0}\leq s^{-1}$ at high energy.

Now we calculate the contribution into cross-section of the two remaining graphs of Fig.1-a and Fig.1-b. It turns out that the corresponding contribution is again equal exactly to the value of $\cong 1.2\cdot 10^{-2} fb$. The corresponding angular distribution is also flat. At last, let's take into account the interference term between the diagram of Fig.1-c, from the one hand side and those of joint contribution of Fig.1-a,b, from the other hand side. We have found that it is equal exactly to $\cong -2.4\cdot 10^{-2} fb$. Adding all the three contributions, we obtain the result, that removes a seeming contradiction. As it must be, the asymptotic form of cross section for the process under consideration at $\sqrt{s}\to\infty$ acquire "desired", i.e. falling with the energy, form

$$\sigma^{as}_{\mu^+\mu^-\to H^0Z} = \frac{1}{3}\cdot\frac{\pi\alpha^2}{sin^4(2\theta_W)}\cdot\left(g_V^2 + g_A^2\right)\cdot\frac{1}{s}. \tag{2}$$

Attention must be drawn to the difference between factors containing the coupling constants in (1) and (2). The cancellation obtained reflects the most fundamental property of electroweak theory. This is the consequence of tree-unitarity condition, which must be fulfilled in any nonabelian gauge theory with the symmetry broken in a manner like Higgs one [6,7].

Meaning to extract information about the Higgs-lepton sector interplay, let's look once more at the individual contributions to the cross section. In this respect it is worthwhile to note, that all the three contributions doesn't reach their constant asymptotic values simultaneously. Those, stemming from sum of Fig.1-a and Fig.1-b go to the plateau at the energy around 1 TeV. Negative contribution reaches its minimum value at $\sqrt{s}\cong 2.5$ TeV, while the cross-section, corresponding to Fig.1-c became constant (at finite muon mass) far away from 1–2 TeV region. However, in spite of different characters of contributions behaviour, it seems that there is little hope for success to distinguish t- and u-channels contribution experimentally owing to small value of μ-meson mass. Because of this, in the next paragraph we will consider the process in which the Higgs-Gauge-Boson vertex is not involved.

2. Associated $H^0\gamma$ production in SM

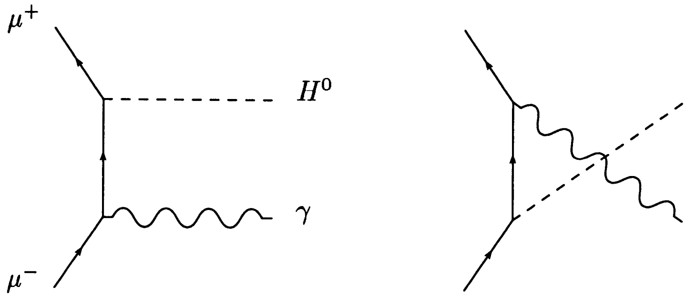

Fig. 2. Diagrams for $\mu^+\mu^- \to \gamma H^0$ are shown.

We now turn to the process anologues just considered, but free from the s-channel diagram complication, as is seen from Figure 2.

Differential cross section of the process $\mu^+\mu^- \to H\gamma$ corresponding to the graphs depicted in Fig.2 for the case when photon is hitting a non-forward detector and neglecting the muon mass except for the part of muon-higgs boson coupling constant, is as follows:

$$\frac{d\sigma^{\gamma H}}{d(\cos\theta)} = \frac{\pi\alpha^2}{2\sin^2\theta_W}\frac{m_\mu^2}{M_W^2}\frac{s^2+M_H^4}{s^2(s-M_H^2)}\frac{1}{(1-\cos^2\theta)}\,, \quad \cos\theta \le 1. \tag{3}$$

The corresponding expression without muon mass neglecting and for the 4π geometry detector see paper [8]. Integrated on the angle variable cross section has an extremely simple form even without muon mass neglecting, so it is expedient to write out a cross section for this case. Introducing in addition to the usual $\beta = \sqrt{1-4m_\mu^2/s}$ the notation $\beta_H = \sqrt{1-4m_\mu^2/m_H^2}$ and integrating the differential cross section, in which muon mass is retained, over $cos\theta$ in the $[-1,1]$ limits, we obtain the cross–section in the following final form:

$$\sigma^{\gamma H} = \frac{\pi\alpha^2}{2\sin^2\theta_W}\frac{m_\mu^2}{M_W^2}\frac{1}{s^2}\frac{1}{\beta}\frac{1}{s-m_H^2}\left[-2m_H^2 s\beta_H^2 + (s^2\beta^4 + m_H^4\beta_H^2)\frac{1}{\beta}\ln\frac{1+\beta}{1-\beta}\right]. \tag{4}$$

The cross section for the case $\sqrt{s} \gg m_\mu$ can be obtained from the expression above by letting $\beta, \beta_H \to 1$ and $\ln[(1+\beta)/(1-\beta)] \to \ln(s/m_\mu^2)$. Evidently, a resulting expression will be not much simpler than that of Eq.4.

With the yearly integrated luminosity of $\mathcal{L} \cong 10^3$ fb^{-1} expected at future $\mu^+\mu^-$ colliders, one could collect 20 to 30 $H^0\gamma$ events (detector efficiency is supposed equal to unity and acceptance – 4π). The signal, which mainly consists of a photon and $b\bar{b}$ pairs in the low Higgs mass range or WW/ZZ pairs for Higgs masses larger than $\cong$ 200 GeV, is extremely clean. The background should be very small since the photon must be very energetic and the $b\bar{b}$ or WW/ZZ pairs should peak at an invariant mass M_H. Therefore, despite the low rates, a clean signal gives a good possibility to detect these events.

3. Discussion and conclusion

Expressions (3) – (4) obtained for the cross-section of the process $\mu^+\mu^- \rightarrow H^0\gamma$ are applicable, on the equal foot, to the case of any other scalar particles production. Note, that at high energy, when the initial state masses can be safely neglected, formulae above can be used and for the case of the pseudoscalar production. However, when masses should be taken into account, there is sharp diffrence between two cases. This difference is another reflection of the fine tuning phenomenon, discussed above in the case of reaction $\mu^+\mu^- \rightarrow Z^0H^0$. First and foremost, a last remark pertains to the axion search problem. Fruitless efforts to find this particle undertaken up to now, produced a widely accepted opinion, that this pseudoscalar is extremely light and weakly interacting ("invisible axion"). However, in recent paper [9] the solution of strong CP – violation problem in QCD has been proposed, which may lead to a heavy axion, $M_a \leq 1$ TeV. Its interaction with usual matter is induced by mixing with axial Higgs boson. For example, in the case of fermions it has the form $\mathcal{L}_{\mathbf{int}} \sim \mathbf{const} \cdot \mathbf{m_f} \cdot (\mathbf{a\tilde{f}i\gamma_5 f})$. Mixing parameters are model dependent but might not be negligibly small, therefore, this interaction might lead to observable effects. Turning back to the Higgs boson, we note that apart from the tree-level amplitude for associated γH production considered here there exists one-loop amplitude with heavy particles in loops. This competitive mechanism, equally applicable both to the $\mu^+\mu^-$ and to the e^+e^- colliding beams, was considered in several papers [10],[11], [12], [13], [14] including recently published ones [15],[16]. Both mechanisms give the cross-sections which are of comparable size, but there's difference in the c.m. energy behaviours between tree level and one-loop amplitudes. As is seen from Eqs.3-4, above the tree-level the cross section grows when $\sqrt{s} \rightarrow m_H$ due to kinematical factor $1/(s - m_H^2)$ in front of it. Contrary to this case, the one-loop cross-section is negligible at the threshold and rises with the energy. Comparative pictures of the two types cross-section behaviours are depicted in Fig. 3 of papers [15] and [16] at some representative Higgs boson mass values. A remarkable feature of those figures is the equality of tree level and one loop cross-sections at the practically invariable point $m_H \cong \sqrt{s}/2$, after which the tree level cross section falls rapidly and the process is dominated by one-loop amplitudes, while up to this point the main contribution cross section receives from the tree level graphs of Fig.2. At first sight it seems that this difference provides a good opportunity for the study the Higgs and lepton sector interrelation. However, we must realize, that the tree level cross section have "bad behaviour" in the vicinity of point, where $\sqrt{s} \leq m_H$, so it is needed to take care of this region in order to smooth the front edge of cross section curve. Potential cure for this problem is the account for the radiative corrections to the process under consideration. It is hoped to turn to this problem in the near future.

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