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Can a Higgs boson be produced at the LHC?*

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Abstract: A simple model is designed to simulate, by using the mean free path method, the probability of Higgs boson production at the Large Hadron Collider (LHC). The probability that the colliding particles could get close to a given distance with different colliding energies is discussed in this model. Calculated results imply that the probability of producing a Higgs boson is near zero according to the existing theoretical mechanism for Higgs boson production.

Key words: Higgs, probability, collision, LHC, model

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1 Introduction

The Higgs boson is one of the most important ingredients of the standard model (SM). It is responsible for the breaking of electroweak symmetry and the origin of the mass for fundamental particles [1]. Unfortunately, the Higgs boson has not yet been directly observed in experiments. The search for the Higgs boson is one of the most important tasks for high energy collisions.

Since the mass of a Higgs boson is the only unknown in the SM, many experimental collaborations and theoretical groups have studied the Higgs boson and tried to determine its mass. The four LEP experiments set a lower limit on the SM Higgs boson mass as 114.4 GeV at 95% confidence level [2]. The D0 Collaboration presented a search for the SM Higgs boson in 1 fb^{-1} of data collected at Fermilab by using hadronically decaying τ leptons [3]. Recently, the CDF and D0 Collaborations showed that there is a small ($\simeq 1\sigma$) excess of data events with respect to the background estimation in search for the SM Higgs boson in the mass range $125 < m_{\mathrm{H}} < 155$ GeV and they excluded a region at high mass between $156 < m_{\mathrm{H}} < 170$ GeV at 95% confidence level by combining the results from CDF and D0 [4]. Fedor L. Bezrukov et al. found that inflation is possible provided that the Higgs boson mass lies in the interval 136.7 GeV $< m_{\mathrm{H}} <$ 184.5 GeV for a top quark mass $m_{\mathrm{t}} = 171.2$ GeV [5]. There are many other works about the search for the SM Higgs boson in the framework of different models or from experimental data, and we will not list all of them here. The LHC has collected data for almost two years and there is a high expectation that they will catch this 'God particle' at the LHC, where the colliding center-of-mass energy can reach 14 TeV for nucleon-nucleon collisions. Recently, P. Cea and L. Cosmai claimed that they have found the first evidence for an SM Higgs boson with mass around 754 GeV from the LHC [6], but their Higgs mass is much larger than the one found before. It seems that the mass of the SM Higgs boson is still a mystery.

In this paper, we build a simple model according to the conventional Higgs production mechanism and use it to investigate the probability of finding a Higgs boson at the LHC energy.

This paper is organized as follows. In the next section, we will address the physical theory of the Higgs boson and the conditions for production of the Higgs boson in our model. In Sec. 3, we introduce the details of our model. We show our results in Sec. 4. The last section will be a brief conclusion.

2 Basic theory

In the work [7], it was suggested that the Higgs boson can be produced through vacuum excitations. Let

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us consider the conventional spontaneous symmetry breaking (SSB) for $U(1)$ symmetry: the Lagrangian is

$$\mathcal{L}=(D_\mu\varphi)^*(D^\mu\varphi)-V(\varphi)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{1}$$

with

$$V(\varphi)=-\mu^2\varphi^*\varphi+\lambda(\varphi^*\varphi)^2, \tag{2}$$

where $D_\mu=\partial_\mu-\mathrm{i}gA_\mu$ is the covariant derivative and $F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu$ is the electromagnetic tensor. In Ref. [7], a coherent state

$$|vac'\rangle=\exp\left[\nu\int\left(\frac{\lambda z}{2}\right)^{1/2}[a(\boldsymbol{z})^\dagger-a(\boldsymbol{z})]\mathrm{d}\boldsymbol{z}\right]|vac\rangle, \tag{3}$$

is defined, where λ is the same constant as in Eq. (2), $|vac\rangle$ is the vacuum defined by $a(\boldsymbol{z})|vac\rangle=0$ and $a(\boldsymbol{z})$ is the annihilation operator which satisfies the commutation relation

$$[a(\boldsymbol{x}),a(\boldsymbol{y})^\dagger]=\delta(\boldsymbol{x}-\boldsymbol{y}). \tag{4}$$

With the help of Eqs. (1, 2, 3), the expectation value of the Hamiltonian density is

$$\varepsilon_0=\langle vac'|\mathcal{T}^{00}|vac'\rangle=-\frac{1}{2}\mu^2\nu^2+\frac{\lambda}{4}\nu^4. \tag{5}$$

The minimum of energy density ϵ_0 is

$$\epsilon_0=-\frac{1}{4}\frac{\mu^4}{\lambda}, \tag{6}$$

which corresponds to $\nu\equiv\nu_0=\left(\frac{\mu^2}{\lambda}\right)^{1/2}$. It is obvious to see that the minimum of energy density is negative when $\mu^2>0$ from Eq. (6) which demonstrates that $|vac'\rangle$ is the ground state.

In Ref. [7], the authors had proved that one can get the usual masses of gauge bosons and Higgs bosons in the same way as from the Salam-Weinberg theory from SSB with new quantum state $|vac'\rangle$. The mass of the Higgs boson is

$$m_{\mathrm{H}}=\sqrt{2\lambda}\nu_0\,, \tag{7}$$

where

$$\nu_0=(\mu^2/\lambda)^{1/2}=\sqrt{\frac{1}{2G_{\mathrm{F}}}}\approx 246\ \mathrm{GeV},$$

fixed by the Fermi coupling G_{F} which is determined from muon decay measurements [8]. Therefore, the minimum energy density for producing a Higgs boson is

$$\varepsilon_{\mathrm{H}}=\frac{m_{\mathrm{H}}^2\nu_0^2}{8}. \tag{8}$$

Now it is very straightforward to calculate the probability for producing Higgs bosons in pp collisions by comparing the local energy density in a collision with the minimum energy density ε_{H} for Higgs production. Let $\varepsilon(r)$ be the local energy density at the position where the relative distance between the colliding pair is r, the same definition as in the previous work [9–11]

$$\varepsilon(r)=\frac{\sqrt{s}}{4/3\pi r^3}, \tag{9}$$

where $\sqrt{s}$ is the center-of-mass energy. For each colliding event, if the following conditions

$$\varepsilon(r)\geqslant\varepsilon_{\mathrm{H}}, \tag{10}$$

$$\sqrt{s}\geqslant m_{\mathrm{H}}, \tag{11}$$

can be fulfilled at some moment, we will count it as an event where the Higgs boson is produced.

Since Eq. (9), and Eqs. (10, 11) imply that the colliding particles should be close enough to make sufficient high energy density and center-of-mass energy to produce a Higgs boson. For the probable mass of the Higgs boson, we take $m_{\mathrm{H}}=140$ GeV as a test, which is in the mass range of the CDF and D0 Collaborations [4]. In this case, the minimum energy density for Higgs production is

$$\varepsilon_{\mathrm{H}}=1.93\times10^{10}\ \mathrm{GeV/fm^3}. \tag{12}$$

At the LHC, Eq. (11) can be fulfilled easily, but such a high energy density in Eq. (10) can not be reached for sure, even for the maximum energy 14 TeV. From Eqs. (9, 10) one can see that the colliding protons must reach a distance of $r<5.6\times10^{-3}$ fm to have a local energy density higher than ε_{H} in Eq. (12). So for Higgs production, one can ask: what is the probability of the colliding protons reaching such a tiny distance? We will use a simple model to estimate it.

3 Our model consideration

Denote $P(r)$ as the probability of the collising protons to reach the distance r without a collision. Inspired by the works [9–11], we build a simple model to simulate $P(r)$ for proton-proton collision at the LHC. Normally the protons can participate in some interactions and generate new particles. One of the consequences of the interactions will be the decrease of the energy of the initial protons. Therefore, we think that Higgs bosons can be produced only in an initial pp interaction.

We let the projectile and target proton locate at a given distance $r=\infty$ with an initial momentum directed along the z axis. During the evolution process, we follow the mean free path method and define a collision probability in each time step

$$\Pi = 1 - \mathrm{e}^{-v\mathrm{d}t/f} = 1 - \mathrm{e}^{-\sigma\rho v\mathrm{d}t}, \tag{13}$$

where $f = \dfrac{1}{\sigma\rho}$ is the mean free path and σ is the total cross-section which depends on the colliding energy of protons in the center of mass. The total cross-section of nucleon-nucleon collision in terms of the center-of-mass energy has been given in [12]

$$\sigma = 52.9 + 2.27 \times (\ln\sqrt{s})^2 - 11.5 \times (\ln\sqrt{s})\,(\mathrm{mb}). \tag{14}$$

In Eq. (13), $\rho = 2/(4/3\pi r^3)$ is the local particle number density defined the same way as in [9–11], and v is the relative velocity between the colliding protons.

For a given proton-proton colliding energy, we can calculate the collision probability at each evolution time step, then compare it with a random number to decide whether the collision will happen or not. When the colliding protons reach the distance r and a collision happens, but they do not satisfy Eqs. (10, 11), the evolution will be terminated and we count one event for colliding protons reaching the distance r. If Eqs. (10, 11) are fulfilled we count one event for producing one Higgs boson.

In addition, we can analytically calculate the probability $P(r)$ for the two protons to reach the distance r from infinitely far away without any interactions. After one time step $\mathrm{d}t$, the distance between them becomes $r - \mathrm{d}r$ and the corresponding probability is then

$$P(r - \mathrm{d}r) = P(r) \times (1 - \Pi). \tag{15}$$

Substituting Eq. (13) into Eq. (15), one can get the analytical expression for $P(r)$

$$P(r) = \exp\left(-\frac{3\sigma}{4\pi}\frac{1}{r^2}\right), \tag{16}$$

where the initial condition for survival probability is set as $P(\infty) = 1$.

4 Simulation and analytical calculation results

We simulate the approaching process for proton-proton collision under $\sqrt{s} = 14$ TeV. An event is defined as a process before an interaction takes place between the two protons with the probability given by Eq. (13). After running a billion events, we did not get any Higgs event with the local energy density higher than ε_{H} in Eq. (12) . Now we look at the probability density for our simulated process to terminate at a distance r, which will be denoted as $p(r)$. In the simulation, the probability density $p(r)$ can be defined as

$$p = \frac{N_i/\Delta r}{\sum_i N_i} = \frac{N_i/\Delta r}{N_{\mathrm{event}}}, \tag{17}$$

where N_i is the event number for the approaching process to terminate with the bin Δr at r_i. One can show that $p(r)$ can be related to $P(r)$ as

$$p(r) = \frac{\mathrm{d}P(r)}{\mathrm{d}r} = \frac{3\sigma}{2\pi r^3}\exp\left(-\frac{3\sigma}{4\pi r^2}\right). \tag{18}$$

The results for $p(r)$ from our simulation and analytical calculation are shown in Fig. 1. Obviously, the analytical results agree with the simulation very well, as expected for self-consistency.

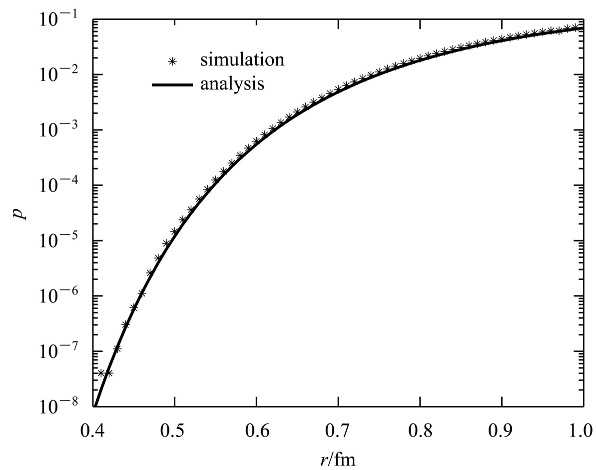

Fig. 1. Probabilities for the colliding nucleons to reach a distance r without any interaction at the center-of-mass energy 14 TeV. The symbols in the star are from our simulation of the collisions while the curve is from the analytical formula Eq. (18).

From Fig. 1 we note the probability that the colliding pairs could reach a distance about 0.4 fm is still less than 10^{-8} even for the maximum energy at the LHC.

One should notice that the cross-section σ in Eq. (18) is energy- dependent. This dependence means that the probabilities for the two protons to reach the distance r are different at different center-of-mass energies. Since the energy dependence of the cross-section is known, one can plot $p(r)$ for different energies. Of course, one can show the energy dependence in another way. One can look at the distance r_m between the two nucleons for different colliding energies when the probability is fixed. Before any calculation, one can guess the behavior of such a relation. With the increase of the center-of-mass energy, the cross-section increases quite quickly. This increase will make the probability $p(r)$ decrease for a given r. In another way, when the probability p is

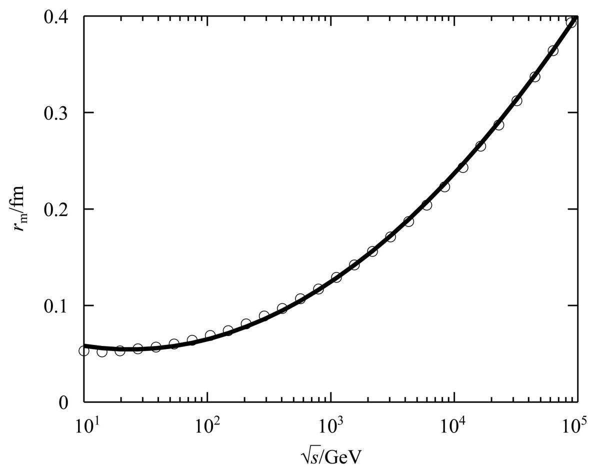

Fig. 2. The distances r_m between the colliding nucleons just before the first interaction as a function of colliding energy for a given probability 10^{-8}. The curve is the fitted result as in Eq. (19).

fixed, the corresponding r_m will be larger for a higher center of mass energy $\sqrt{s}$. For a given probability, say 10^{-8}, the relation is shown in Fig. 2 and can be fitted by a formula

$$r_m = 0.104 + 0.005 \times (\ln\sqrt{s})^2 - 0.0314 \times (\ln\sqrt{s})(\text{fm}). \tag{19}$$

Obviously, even at $\sqrt{s} = 10^5$ GeV, with the probability 10^{-8} the colliding particles can reach a distance of about 0.40 fm, and the corresponding energy density is only 3.73×10^5 GeV/fm^3, which is still much smaller than the one for producing a Higgs boson, as shown in Eq. (12). Of course, our consideration is basically classical, since only "the static" energy density is included in the model. Further studies, with quantum effects considered, would shed some light on Higgs production.

5 Conclusion

In this work we proposed a simple model to simulate the approaching process of two nucleons in order to discuss Higgs production. It seems impossible to produce a Higgs boson by nucleon-nucleon collisions when quantum fluctuations are not considered. We hope that these results may shed light on the future search for the Higgs boson.

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