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Production of Isolated Higgs Particle at the Large Hadron Collider

R. Gastmans\(^{\ast}\), Sau Lan Wu\(^{1,2}\) and Tai Tsun Wu\(^{3,4}\)

\(^1\)Instituut voor Theoretische Fysica, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
\(^2\)Department of Physics, University of Wisconsin, Madison WI 53706, USA
\(^3\)Gordon McKay Laboratory, Harvard University, Cambridge MA 02138, USA
\(^4\)Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Theoretical predictions are presented for the process \(p + p \rightarrow A + H + B\), where \(H\) is the Higgs particle and \(A (B)\) is a group of particles that mostly goes down one (the other) beam pipe. These predictions are obtained using results from relativistic quantum gauge field theory and the fact that, for the Large Hadron Collider (LHC), the center-of-mass energy \(\sqrt{s}\) Higgs mass \(\gg\) proton mass. The average transverse momentum of the produced Higgs Particle is of the order of 1 GeV/c. This process leads naturally to the concept of considering the LHC as a Pomeron Collider.

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1. The Large Hadron Collider (LHC) at CERN is expected to become operational in the very near future. It is the purpose of this Letter to describe a class of events for Higgs [1] production at the LHC and to predict its differential cross section.

This class of events may be described as

\[
p + p \rightarrow A + H + B ,
\]

where \(A\) represents a group of particles that mostly go down one beam pipe, \(B\) a similar one going down the other beam pipe, and \(H\) the produced Higgs particle whose velocity is moderate in the center-of-mass system. This process (1) shall be referred to as semi-exclusive as distinct from the exclusive one

\[
p + p \rightarrow p + H + p .
\]

2. There are several physics motivations for this investigation. Forty years ago, it was predicted theoretically that all hadron-hadron total cross sections must rise with increasing high energies [2], contrary to the belief at that time. This prediction, which was verified experimentally three years later, has remained mostly as an isolated fact. Thus, a first motivation is to look for other effects that are related to the rising cross section; because of the imminent operation of LHC, the production process (1) is a good candidate.

A second motivation comes from the present situation in particle physics that no electron-positron collider in the energy range of about \(\frac{1}{2}\) TeV is likely to be operational in the next decade. Under this circumstance, it may be asked whether some of the physics information from such an electron-positron may be obtained by studying a suitably chosen class of events at LHC. Once again, the production process (1) is a good candidate.

For both these motivations, the Higgs particle \(H\) in the process (1) may be replaced by any particle \(X\) that has not been observed experimentally, including the possibility of additional Higgs particles:

\[
p + p \rightarrow A + X + B .
\]

3. The Higgs production processes (1) and (2) are characterized by two large parameters, namely,

\[
\frac{\sqrt{s}}{M} \quad \text{and} \quad \frac{M}{m} ,
\]

where \(\sqrt{s}\) is the center-of-mass energy of the two incoming protons, \(M\) is the Higgs mass, and \(m\) is the proton mass. With the center-of-mass design energy at LHC of 14 TeV, both of the large parameters (4) are about 122, if \(M\) is taken to be 115 GeV/c\(^2\), the value of the preliminary experimental evidence from LEP [3, 4]. That there are two large parameters is a distinctive feature here, to be contrasted with just one large parameter \(\sqrt{s}/m\) for the elastic scattering \(p + p \rightarrow p + p\).

4. A theoretical consequence of having these two large parameters (4) is that the ratio of cross sections

\[
R_H = \frac{\text{cross section for the process (1)}}{\text{cross section for the process (2)}}
\]

is large at the LHC energy of 14 TeV. This is to be compared with the similar ratio

\[
R_{el} = \frac{\text{total cross section } p + p \rightarrow \text{anything}}{\text{integrated elastic cross section } p + p \rightarrow p + p} .
\]

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FIG. 1: Schematic representation for (a) pp elastic scattering and (b) the exclusive process $p + p \rightarrow p + H + p$. The semi-exclusive process (1) $p + p \rightarrow A + H + B$ is obtained from Fig. 1(b) by replacing the outgoing protons by $A$ and $B$ respectively.

which is expected to be about 3.5 at the same energy of 14 TeV [5].

The large value of this $R_H$ of (5) has the immediate experimental consequence that the process (1) provides a much better way to study the Higgs particle than (2). The signature for such an event is, aside from possible particles that escape out of the beam pipes, the Higgs particle with a small transverse momentum of the order of 1 GeV/c, or rather its decay products. Thus, these semi-exclusive events have the following two important characteristics:

(a) The number of particles observed in the detector is relatively small; and

(b) The sum of the transverse momenta of the Higgs decay products is of the order of 1 GeV/c. Since this transverse momentum is often negligible, there are two additional constraints.

Because of these properties, the Higgs data analysis for these semi-exclusive events is necessarily different. The five decay modes $H \rightarrow \gamma\gamma$, $\tau^+\tau^-$, $b\bar{b}$, $W^+W^-$ and $ZZ$ have been studied in some detail [6]. Some interesting feature of the $\gamma\gamma$ mode has been noted before [7].

5. Similar to the previous prediction of the rising total cross sections, the present study of the Higgs production processes (1) and (2) is based on relativistic quantum field theory with a gauge invariance of the second kind [8]. Schematically, the diagrams under consideration are those of Fig. 1. The rising total cross section [2] is obtained from that of Fig. 1(a) through unitarity and pionization [9].

Fig 1(b) represents the Higgs production process (2), where two $Q$’s are exchanged. This $Q$ is not the same as the Pomeron $P$ exchanged in Fig. 1(a); this important point is to be discussed in some detail in Sec. 6 below.

The seminal paper on such ‘two-Pomeron processes’ was by Schäfer, Nachtmann, and Schöpf [10] nearly twenty years ago. A second paper by Müller and Schramm [11], also on Higgs production, followed two months later. A sample of the large number of later papers is given in Ref. [12].

The present work differs from these papers [10–12] in the realization that there are two independent large parameters as given by (4), not just one large parameter. One consequence of these two independent large parameters has already been given in Sec. 4, namely, $R_H \gg R_{Q1} \sim 3.5$. There are many other consequences, one important example being that the $Q$ of Fig. 1(b) is not the same as the $P$ of Fig. 1(a).

6. That the $Q$ and $P$ are not the same can be easily seen: aside from their dependence on energy, $P$ is a function of $m$ while $Q$ is a function of both $m$ and $M$. In order to be able to obtain any theoretical predictions for the production processes (1) and (2), it is essential to relate the $Q$ of Fig. 1(b) to the Pomeron $P$ of Fig. 1(a) for elastic scattering.

Let the momenta of the incoming protons be along the $+$z and the $-$z directions respectively. It turns out that the dependence of $Q$ on $M$ can be removed by applying a Lorentz transformation along the $z$-direction, the magnitude of this Lorentz transformation being specified by $M/m$. In this way, the $Q$ is related to $P$ at a different energy.

Note that this use of the Lorentz transformation is somewhat unusual: it is applied to a part of a diagram, not the entire diagram. The two Lorentz transforms, for the upper part and the lower part of the diagram of Fig. 1(b), are both specified by $M/m$, but they are in the opposite directions.

7. The results from relativistic quantum gauge field theory cannot be applied directly to the production processes (1) and (2), mainly because the quark and the gluon structures of the proton are not properly taken into account in such field theory. Instead, such field-theoretic results are used to formulate a phenomenological model, and then the results of the phenomenological model are used to make predictions for the future data from the Large Hadron Collider. In this procedure, the structure of the proton is incorporated through the parameters used in the phenomenology of proton-proton elastic scattering [13]. The values of the five phenomenological parameters are

$$c = 0.167, \quad c' = 0.748,$$

$$m_1 = 0.586 \text{ GeV}, \quad m_2 = 1.704 \text{ GeV},$$

and

$$f = 7.115 \text{ GeV}^{-2}.$$  (7)
In terms of these parameters, the following functions have been introduced in Ref. [13]:

\[
S(y) = \frac{y_f e^{-y_c}}{(\ln y)^c} + \frac{y_f e^{-i\pi c}}{(\ln y - i\pi)^c},
\]

\[
F(t) = f \frac{1}{[G(t)]^2},
\]

\[
G(t) = \frac{1}{\left(1 - \frac{t}{m_{H_1}^2}\right) \left(1 - \frac{t}{m_{H_2}^2}\right)},
\]

(8)

and \( F(x^2) \) is the two-dimensional Fourier transform of \( F(t) \). Actually, there is in Ref. [13] a sixth parameter \( a \), which has been replaced by infinity for the present purpose.

8. In terms of (7) and (8) from proton-proton elastic scattering, the matrix element of the semi-exclusive Higgs production process (1) in the phenomenological model is given by, with \( p_{H_2} \) the \( z \)-component of the momentum of the produced Higgs,

\[
ME(p_{H_2}, \Delta_{1\perp}, \Delta_{2\perp}) = C_0 S \left(\frac{8}{M^2}\right) f \times \left\{ \int_0^\infty d_x J_0(x_1 \Delta_{1\perp}) e^{-S(y_1)} F(x_1^2) \right\} \left\{ \int_0^\infty d_1 \xi_1 J_0(x_1 \xi_1) \left[ G(-\xi_1^2) \right]^{\alpha_1} \right\}
\]

\[
\times \left\{ \int_0^\infty d_2 x_2 J_0(x_2 \Delta_{2\perp}) e^{-S(y_2)} F(x_2^2) \right\} \left\{ \int_0^\infty d_2 \xi_2 J_0(x_2 \xi_2) \left[ G(-\xi_2^2) \right]^{\alpha_2} \right\},
\]

(9)

where

\[
C_0 = \frac{g_s^2 g_{ew}}{(2\pi)^2} \frac{m_t^2}{m_W}
\]

\[
\times \int_0^1 d\gamma_1 \int_{0}^{1-\gamma_1} d\gamma_2 \frac{1 - A\gamma_1 \gamma_2}{m_t^2 - \gamma_1 \gamma_2 M^2 - i\epsilon},
\]

(10)

comes from the top triangle in gluon fusion [14] \( g_s \) and \( g_{ew} \) are the usual strong and electroweak coupling constants; \( m_t \) and \( m_W \) are the masses of the top quark and the \( W \) boson, \( J_0 \) is the Bessel function of order 0,

\[
y_1 = \frac{\sqrt{8}}{M^2} \left( \sqrt{M^2 + p_{H_2}^2} - p_{H_2} \right),
\]

\[
y_2 = \frac{\sqrt{8}}{M^2} \left( \sqrt{M^2 + p_{H_2}^2} + p_{H_2} \right),
\]

(11)

\[
\alpha_1 = 2 \frac{\ln y_1}{\ln y_1 + \ln y_2},
\]

\[
\alpha_2 = 2 \frac{\ln y_2}{\ln y_1 + \ln y_2},
\]

and

In terms of the notation of Fig. 1(b), the two momentum transfers are

\[
\Delta_{1\perp} = ||p_{1\perp} - p_{1\perp}'|| \quad \text{and} \quad \Delta_{2\perp} = ||p_{2\perp} - p_{2\perp}'||.
\]

(13)

9. The derivation of the phenomenological model as given by eq. (9) is fairly complicated, and is given in Ref. [6]. Here, we limit ourselves to the following comments.

a) In this entire approach, parton distribution functions are nowhere used.

b) As shown in Fig. 1, the exchange of the Pomeron \( P \) controls elastic scattering, while the exchange of the two objects called \( Q \)’s determines the production processes (1) and (2). That the \( P \) and \( Q \) are related to each other is what makes it possible to study these processes theoretically — see Sec. 6.

c) This relation between \( P \) and \( Q \) is far from being sufficient for our purposes. The basic reason is that the elastic scattering of Fig. 1(a) gives only information about the diagonal element of \( P \) taken between two proton states, while the production process of Fig. 1(b) requires knowledge about off-diagonal elements of \( Q \).

d) Fortunately, there is a special case where \( \Delta_{1\perp} = \Delta_{2\perp} \) when this dependence on the off-diagonal elements of \( Q \) is unimportant, and the above phenomenological model can be developed in a relatively straightforward manner. Furthermore, the Higgs production cross section is largest in this special case.

e) The extension of this phenomenological model to the general case where \( \Delta_{1\perp} \neq \Delta_{2\perp} \) requires the introduction of less accurate approximations. This leads to the model as given by eq. (9). Because of these less accurate approximations, the validity of this model is limited by \( \alpha_1 \) and \( \alpha_2 \) both being larger than \( 1/2 \). Physically, this means that the \( p_{H_2} \) cannot be too large:

\[
p_{H_2}^2 < \frac{1}{2} \sqrt{s} M.
\]

10. Some numerical results from this phenomenological model of Sec. 9 for the Higgs production cross section of the semi-exclusive process (1) are shown in Fig. 2, for various Higgs masses. The rapidity \( \eta \) in this figure is simply \( \eta = \frac{1}{2} \ln(y_2/y_1) \).

A rough estimate of the semi-exclusive total cross section then yields \( \sigma \sim 150 \text{ fb} \), not very dependent on the Higgs mass. This is to be compared to the inclusive cross section that varies from 40 pb for \( M = 115 \text{ GeV}/c^2 \) to 0.2 pb for \( M = 1000 \text{ GeV}/c^2 \) [15]. In this analysis, however, use is made of parton densities.
The transverse momentum distribution $d^2\sigma/dp_T^2 d\eta$ of the produced Higgs has also been calculated in the special case $p_{H_z} = 0$. This distribution has its peak at $p_{H_z} = 0$ with a very narrow width of less than 1 GeV/c. While the narrowness of this width can be easily understood, it is nevertheless pertinent to raise the following question: Does this Higgs transverse distribution become significantly broadened by the emission of one or more jets? Such broadening is expected to be unimportant because of the suppression of the emission of one jet. This suppression is a consequence of color conservation, i.e., the Pomeron-Pomeron-jet coupling is zero.

11. With reference to Fig. 1(b), the semi-exclusive process (1) can be viewed as each of the incident protons emitting a $Q$ and the two $Q$'s annihilating each other to produce the Higgs particle. If the difference between this $Q$ and the Pomeron $P$ is ignored, then this process (1) can be represented by

$$\text{Pomeron} + \text{Pomeron} \rightarrow H.$$  \hspace{1cm} (14)

Similarly, the semi-exclusive process (3) can be written as

$$\text{Pomeron} + \text{Pomeron} \rightarrow X.$$  \hspace{1cm} (15)

Of course, it should be remembered that the Pomerons in (14) and (15) are not exactly Pomerons; in particular, their properties depend on the mass of the produced $H$ or $X$.

Because of (15), the Large Hadron Collider may be considered to be a Pomeron collider. The systematic study of the large number of such processes (15), and to relate them to those from an electron-positron collider, is a very major job. An initial step in this direction has been taken in Ref. [6].

Since the design luminosity, $10^{34}$ cm$^{-2}$s$^{-1}$, of the Large Hadron Collider is exceptionally high for a proton-proton collider, and since the cross section for Pomeron-Pomeron annihilation is fairly constant over a large energy range, the Large Hadron Collider is an excellent accelerator as a Pomeron Collider.

(1964).


