Searching a doubly charged Higgs boson at Hera

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ABSTRACT

The production of a single exotic Higgs particle is studied at Hera. Within the present limits on the Yukawa couplings this doubly charged particle, suggested by the left-right symmetric models, can be observed at Hera up to values of its mass of about 150 GeV.

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The doubly charged Higgs bosons are the basic particles of a class of models of electroweak interactions, beyond the Standard Model, with spontaneous parity violation \[1\],\[2\]. In the left-right symmetric model of Senjanovic and Mohapatra \[1\], based on the gauge group \(G = SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}\) \[1\], the scalar sector contains two triplets of Higgs fields \(H_L\) and \(H_R\) which transform as \((3,1,2)\) and \((1,3,2)\) under \(G\).

The phenomenology of the Higgs particle is uniquely determined once its mass \(M_H\) and its Yukawa couplings to the leptons \(g_{ll'}\) are given. Therefore, we briefly summarize the present experimental limits on the above two parameters. In the framework of the left-right symmetric model, by taking into account the experimental limits on the neutrinoless double-\(\beta\) decay of Ge\(^{76}\), Mohapatra found that \(g_{ee}^2 \leq 0.1\) \[3\]. This bound is in agreement with the allowed values of \(g_{ee}\) given in ref.\[4\], where the limits on the \((\beta\beta)_{0\nu}\) decay of the Te\(^{130}\) are also considered.

The case of a nondiagonal coupling (in the lepton flavour) of the \(H^{-+}\) to the charged leptons has been considered by Swartz \[5\]. In his analysis, taking into account the spontaneous conversion of muonium into antimuonium, the high-energy Bhabha scattering and the flavour changing \(\mu \rightarrow ee\bar{e}\) decay, the following limits are established:

\[
g_{ee}g_{ee} < 5.8 \times 10^{-5}(M_H/1\text{ GeV})^2, \quad g_{ee}^2 < 9.7 \times 10^{-6}(M_H/1\text{ GeV})^2
\]

as well as the most stringent one

\[
\frac{g_{ee}g_{e\mu}}{M_H^2} < 4.8 \times 10^{-11}\text{ GeV}^{-2}
\]

Concerning the values of the doubly charged Higgs masses, the range \(6.5\text{ GeV} \leq M_H \leq 36.5\text{ GeV}\) has been excluded by a recent experimental search of Higgs triplets at the SLAC collider \[6\]. These bounds are obtained assuming \(g_{ll'} \geq 3 \cdot 10^{-7}\) and examining the decay of the \(Z\) boson into a \((H^{++}, H^{--})\) pair.

In ref.\[9\] it has been pointed out that at LEP1 these masses can be probed up to \(M_H \sim 100\text{ GeV}\) through the single \(H^{--}\) production, when two alternative scenarios are assumed for the Yukawa couplings: \(g_{ee} \gg g_{e\mu}\) or \(g_{e\mu} \gg g_{ee}\).
In this letter we adopt a point of view analogous to that of ref. [9] to the aim of discussing the possible production of a single doubly charged Higgs boson at HERA, the new ep collider in Hamburg, where an electron beam with $E_e = 30 \text{ GeV}$ and a proton beam with $E_p = 820 \text{ GeV}$ collide head-on ($\sqrt{s} \simeq 313 \text{ GeV}$), with a luminosity up to $1.5 \cdot 10^{31} \text{ cm}^{-2} \text{s}^{-1}$, according to the project.

We calculated the following processes:

$$e^-p \rightarrow e^+pH^{--} \quad H^{--} \rightarrow e^-e^-(\mu^-\mu^-,\tau^-\tau^-) \quad (2)$$
$$e^-p \rightarrow \mu^+pH^{--} \quad H^{--} \rightarrow e^-\mu^-(e^-\tau^-,\mu^-\tau^-) \quad (3)$$

whose diagrams are drawn in Fig.[1].

Joining together the results obtained by Mohapatra and Swartz, we assume for $g_{ee}$ in reaction (2) the value corresponding to the upper limit $g_{ee}^2 = 9.7 \times 10^{-6}(M_H/1 \text{ GeV})^2$ for $50 < M_H < 100 \text{ GeV}$ and the value $g_{ee}^2 = 0.1$ for $M_H \geq 100 \text{ GeV}$. Moreover, in reaction (3) we assume Mohapatra’s limit $g_{e\mu}^2 = 0.1$ that is the only bound for $g_{e\mu}$. With these reasonable values of the parameters, we find that it is possible to probe at HERA doubly charged Higgs particles with masses up to 150 GeV.

We computed the cross sections for the processes (2) and (3) using the Weizsacker-Williams method of the Equivalent Photons Approximation (EPA) applied to the vertex $p \rightarrow p'\gamma^*$ (for a review of EPA see [12]). In this approximation, the single $H^{--}$ production cross section is given by

$$\sigma_{ep} = \int N(\omega)\sigma_{e\gamma}(\omega)\frac{d\omega}{\omega} \quad (4)$$

where the quantity

$$N(\omega)/\omega = \int dn(\omega,q^2)dq^2 \quad (5)$$

is the photon spectrum (see ref. [12]) and $\sigma_{e\gamma}(\omega)$ is the cross section of the sub-process induced by the photon generated by the proton current. The dependence of $N(\omega)$ on the photon frequency $\omega$ is obtained by integrating the
photon distribution $dn(\omega, q^2)$ over the squared momentum of the space-like photon, $q^2$. In the EPA, the $q^2$-dependence appears only in $dn(\omega, q^2)$ whose expression is determined by the structure of the $p \rightarrow p' \gamma^*$ hadronic vertex. Moreover, $\sigma_{\gamma\gamma}$ is the cross section for the absorption of a real unpolarized photon of frequency $\omega$.

The electric and magnetic Sachs form factors of the proton $G_E(q^2)$ and $G_M(q^2)$, have been included in the proton current to evaluate $dn(\omega, q^2)$. We adopted the usual dipole expression for the Sachs form factor $s$:

$$G_E(q^2) = \frac{q^4_0}{(q^2_0 - q^2)^2} \quad G_M(q^2) = \mu_p G_E(q^2) \quad (6)$$

where $\mu_p$ is the proton magnetic moment and with $q^2_0 = 0.71$ GeV$^2$.

We checked numerically that the necessary condition for the validity of EPA (the scalar and longitudinal photons contribution is much less than the transverse one) is verified in the kinematic domain of our process. More sophisticated checks that confirm the applicability of EPA in our case are discussed in ref.[14].

The amplitudes contributing to the $e^-\gamma \rightarrow e^+ H^{--}$ interaction can be written as

$$\mathcal{M}_a = \frac{ge}{2\sqrt{2}} i\bar{u}(k'')(1 + a\gamma_5)(\hat{k} + \hat{q} + m_e)\frac{\epsilon_\alpha(q)\gamma_\alpha u(k)}{(|k + q|^2 - m_e^2)} \quad (7)$$

$$\mathcal{M}_b = \frac{ge}{2\sqrt{2}} i\bar{u}(k')\epsilon_\alpha(q)\gamma_\alpha \frac{(\hat{p}_H - \hat{k} + m_l)}{(|p_H - k|^2 - m_l^2)}(1 + a\gamma_5)u(k) \quad (8)$$

$$\mathcal{M}_c = 2\frac{ge}{2\sqrt{2}} i\bar{u}(k'')(1 + a\gamma_5)u(k')\frac{(p_H + k - k')_\alpha\epsilon_\alpha(q)}{(|p_H - q|^2 - M_H^2)} \quad (9)$$

where $l$ is $e$ or $\mu$ and $a = +1(-1)$ for $H_R$ ($H_L$) production.

The analytical part of the calculation has been done by REDUCE and the results for the total cross sections versus the $H$ boson’s mass are plotted in Fig.[2]. The resulting cross-sections are independent of the sign of $a$ and the same is true for the decay’s rate: $\Gamma(H_L \rightarrow ll') = \Gamma(H_R \rightarrow ll')$. The differences
between the two curves for $M_H < 100 \text{ GeV}$ are uniquely due to the smaller values taken by the coupling constant $g_{ee}$ of the process (2), compared to $g_{e\mu}$. Both the cross sections, $\sigma_{e\mu}$ and $\sigma_{ee}$, decrease rapidly when the value of $M_H$ increases (for $M_H = 150 \text{ GeV}$ $\sigma = 2.7 \times 10^{-2} \text{ pb}$ ). We stress that the numerical integration is not completely straightforward. In fact, since the energies involved in the process are much larger than the leptonic masses, the electron (muon) propagator in $M_b$ is very close to a pole. We have accurately checked the numerical convergence of the integration and we estimate that our results are affected by a numerical error of about 10%.

In the final state, the $H^{--}$ longitudinal momentum has the same sign of the incoming proton’s momentum, since the relative velocity between the centre of mass and HERA frames is always greater than the $H^{--}$ velocity in the CMS. The angular distributions of the positron and scattered proton are peaked along the initial proton direction. So, with high probability, the process is projected forward on account of the particular kinematics of HERA.

In order to evaluate the final decay’s leptons distribution at HERA, we performed a Monte Carlo simulation of the $H^{--}$ decay. We adopted the value $1/3$ for the branching ratio of both processes (2) and (3), having assumed the $g_{ll'}$ values to be generation independent, i.e. $g_{ee} \approx g_{\mu\mu} \approx g_{\tau\tau}$ and $g_{e\mu} \approx g_{e\tau} \approx g_{\mu\tau}$ [9]. The results are drawn in Fig.[3]. The distribution of one of the negative leptons in the final state with respect to the angle $\theta$, that is the angle between the direction of the incoming proton and the outgoing decay’s lepton, shifts at smaller values of $\theta$, as $M_H$ increases. Nevertheless this distribution is still peaked at large angles up to $M_H = 150 \text{ GeV}$. It is worth noting that the lepton pairs are produced with a large opening angle, never lower than $15^o$ for $M_H \leq 150 \text{ GeV}$.

In order to estimate the number of observable events at HERA, we assume [10] the range: $4^o \leq \theta \leq 176^o$ as the angular acceptance of the HERA detectors and a luminosity $L = 1.5 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$.

In Tab.[1], the number of events/year as a function of $M_H$ are shown; we find that more than 92% of the lepton pairs overcome the angular cuts for
$M_H > 50$ GeV. Increasing the value of $M_H$, the number of events rapidly decreases. Although the events are few for $M_H \geq 120$ GeV, the detection of the $H^{-+}$ may still be possible even at large mass values. In fact the signature of the event is very particular because the proton goes into the pion and therefore the final state consists of three leptons, two of them (those coming from the $H^{-+}$ decay) with the same sign and with large value of the invariant mass.

In conclusion, under reasonable assumption on the coupling constant values, a single $H^{-+}$ production may be observed at HERA through the $H$ decay in a same-sign lepton pair up to $M_H \approx 150$ GeV.

We strongly encourage an experimental investigation of the $H^{-+}$ production at HERA.

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TABLE and FIGURE CAPTIONS

**TAB.1**: Number of events/year versus $M_H$ at HERA for the two reactions: $e^-p \rightarrow e^+pH^{--}$ and $e^-p \rightarrow \mu^+pH^{--}$. The accuracy of the numerical calculation is of the order 10%.

**FIG.1**: Feynman graphs for single $H^{--}$ production at HERA.

**FIG.2**: Plot of the total cross sections at $\sqrt{s} = 313$ GeV versus $M_H$: the dashed line refers to the process $e^-p \rightarrow e^+pH^{--}$, the full line to the reaction $e^-p \rightarrow \mu^+pH^{--}$.

**FIG.3**: The full, dashed and dot-dashed lines are the normalized angular distribution of the decay’s lepton at HERA for $M_H=70,100,150$ GeV respectively.
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