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Search for Doubly-Charged Higgs Production at HERA

H1 Collaboration

Abstract

A search for the single production of doubly-charged Higgs bosons ($H^{\pm\pm}$) is performed in the framework of models where a Higgs triplet is coupled to leptons of the i^{th} generation via Yukawa couplings h_{ii}. The search is motivated by the observation of a few multi-electron events with a large di-electron mass, in a domain where the Standard Model expectation is small. The signal is searched for in decay modes of the $H^{\pm\pm}$ in either electrons or muons, using a sample of $e^{\pm}p$ events corresponding up to 115.2 pb^{-1} of data collected with the H1 detector at HERA. Only one of the multi-electron events is found to be compatible with the hypothesis of the decay of a heavy Higgs boson. Assuming that the doubly-charged Higgs only decays to electrons, we set a lower limit of about 131 GeV on the $H^{\pm\pm}$ mass for a value $h_{ee} = 0.3$ of the coupling, which corresponds to an interaction of the electromagnetic strength. This is the first search for doubly-charged Higgs production at HERA.

1 Introduction

The H1 collaboration recently reported [1] a preliminary measurement of multi-electron production at high transverse momentum at HERA. Six events were observed with a di-electron mass above 100 GeV, a domain where the Standard Model (SM) prediction is low. A preliminary measurement of multi-muon production in H1 [2] showed a good agreement between the data and the SM expectation over the whole mass range.

Based on these analyses, a search for the single production of doubly-charged Higgs bosons ($H^{\pm\pm}$), which may lead to high mass multi-lepton events, has been performed and is presented in this paper. In the mass range covered by this analysis, the decay mode of the doubly-charged Higgs boson into a pair of like-sign charged leptons is expected to be dominant. Other decay modes are considered to be either theoretically suppressed or kinematically forbidden. This signal is searched for in di- and tri-electron as well as di-muon final states. For the electron final states, the analysis makes use of all data collected from 1994 to 2000 corresponding to an integrated luminosity of 115.2 pb^{-1}. For the muon final state 70.9 pb^{-1} are used. This is the first search for doubly-charged Higgs production at HERA.

2 Phenomenology

Doubly-charged Higgs bosons appear in various extensions of the Standard Model, in which the usual Higgs sector is extended by one or more triplet(s) with non-zero hypercharge [3, 4, 5]. Examples are provided by some Left-Right Symmetric (LRS) models [6, 7], where the extended symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is spontaneously broken to the SM symmetry $SU(2)_L \times U(1)_Y$ by a $SU(2)_R$ triplet of scalar fields, whose neutral component acquires a non-vanishing vacuum expectation value (vev). The Higgs triplet(s) may be coupled to matter fields via Yukawa couplings. Whereas all charged fermions acquire their masses via their couplings with Higgs doublet(s), the vev of the neutral component of a Higgs triplet can give a Majorana mass to neutrinos, which is of particular interest since the existence of non-zero neutrino masses is suggested by recent experimental data.

At the tree level, doubly-charged Higgs bosons couple only to charged leptons and to other Higgs and gauge bosons. Couplings to quark pairs are not allowed by charge conservation. Although doubly-charged Higgs bosons may arise in various scenarios extending the SM, their couplings to charged leptons can be generically described by the Lagrangian :

$$\mathcal{L} = h_{ij}^{L,R} H^{--} \, \bar{l}_i^{\,c} P_{L,R} \, l_j \qquad + \text{ h.c.} \tag{1}$$

where $i, j = e, \mu, \tau$ denote generation indices, $P_{L,R} = (1 \mp \gamma^5)/2$, l are the charged lepton fields, and the superscript ^{c} denotes the charge conjugate spinors. The Yukawa couplings $h_{ij}^{L,R}$ are free parameters of the model. If the H^{--} field belongs to a $SU(2)_L$ triplet, H^{--} couples only to left-handed leptons; only the projector P_L and the couplings $h_{i,j}^L$ are then involved in equation (1). Models with an additional group $SU(2)_R$ and a $SU(2)_R$ Higgs triplet provide a H^{--} field coupling to right-handed leptons via $h_{i,j}^R$. In the particular case of LRS models two doubly-charged Higgs bosons H_L^{--} and H_R^{--} are present, which couple to left-handed and right-handed leptons respectively. Since the production processes at HERA are insensitive to the chirality of the lepton fields, we consider here the generic case of a doubly-charged Higgs boson, which couples to either left-handed or right-handed leptons, and denote its Yukawa couplings by h_{ij} in the following.

For a non-vanishing coupling h_{ee} the single production of a doubly-charged Higgs boson is possible via the diagrams shown in Fig. 1, where a photon is radiated by the proton or one of its constituent quarks[1]. The proton may be broken or remain intact during this interaction, leading to an inelastic or elastic reaction, respectively. The phenomenology of doubly-charged Higgs production at HERA was first discussed in Ref. [8], in which only the elastic channel was considered.

When only diagonal couplings h_{ii} are present in equation (1), the production process $e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X$ is followed by the decays $H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}(\mu^{\pm}\mu^{\pm}, \tau^{\pm}\tau^{\pm})$. Non-diagonal couplings (h_{ij} with $i \neq j$) would allow e.g. $e^{\pm}p \rightarrow \mu^{\mp}H^{\pm\pm}X$ followed by the decays $H^{\pm\pm} \rightarrow e^{\pm}\mu^{\pm}$ ($e^{\pm}\tau^{\pm}$, $\mu^{\pm}\tau^{\pm}$).

The indirect constraints [9, 10, 11, 12] on doubly-charged Higgs can be parameterized in terms of the Higgs mass M_H and the Higgs couplings to leptons. The off-diagonal products $h_{ij}h_{i'j'}$ with either $i \neq j$ or $i' \neq j'$ suffer from stringent constraints for the first and second generation charged leptons from bounds on $\mu \rightarrow e^+e^-e^-$ and $\mu \rightarrow e\gamma$ decays [12]. Constraints on purely diagonal couplings are less stringent. They come from the possible contribution of virtual $H^{\pm\pm}$ exchange to Bhabha scattering in e^+e^- collisions which yields [9] $h_{ee} \leq 3.1 \times 10^{-3}\mathrm{GeV}^{-1}M_H$, using e^+e^- data taken at center of mass energies of ~ 30 GeV, and from the search for muonium (μ^+e^-) to anti-muonium (μ^-e^+) conversion [9, 12] which yields $\sqrt{h_{ee}h_{\mu\mu}} \leq 7.6 \times 10^{-3}\mathrm{GeV}^{-1}M_H$. For the coupling $h_{\mu\mu}$ alone, avoiding possible extra contributions to $(g-2)_\mu$ yields $h_{\mu\mu} \leq 5 \times 10^{-3}\mathrm{GeV}^{-1}M_H$. No constraint involving the τ lepton has been established.

Previous direct searches for $H^{\pm\pm}$ pair production have been performed by the LEP experiments. For pair production in e^+e^- collisions, the kinematic reach is restricted to $M_H < \sqrt{s}/2$. Masses $M_H \leq 45.6$ GeV have been excluded by the OPAL experiment analyzing Z decays at LEP I [13]. This was extended by OPAL to $M_H \leq 98.5$ GeV in a search [14] for $H^{\pm\pm}$ pair production at center of mass energies between 189 and 209 GeV. Similar results are derived for any relative values of the h_{ee}, $h_{\mu\mu}$ and $h_{\tau\tau}$ couplings assuming a 100% decay branching fraction into charged leptons pairs. A similar lower limit on M_H was obtained recently by the DELPHI experiment at LEP II [15] assuming that the Higgs dominantly decays into a pair of τ leptons.

In this paper we only consider diagonal couplings for which the existing bounds are less stringent and the Higgs decays into electrons and muons. This leads to final states with three leptons, with two of them like-sign and expected at large invariant mass. It should be noted that the $e^{\pm}$ which does not come from the Higgs decay is often backscattered in the direction of the incident proton momentum and may be lost in the beam pipe.

[1]The contribution of Z exchange in the diagrams shown in Fig. 1 can be safely neglected.

3 Simulation of the Signal and Standard Model Backgrounds

The simulation of the doubly-charged Higgs signal, as well as the calculation of the signal cross-section, is performed using the CompHEP [16] package to evaluate the (lowest order) squared amplitudes corresponding to the elastic and inelastic processes[2]. The differential cross-sections are integrated with the VEGAS [19] package.

The parton densities in the proton used to estimate the inelastic contribution to the cross-section are taken from the CTEQ4L [20] parametrization. These are evaluated at the scale $\sqrt{Q^2}$, where Q^2 denotes the squared momentum transfer at the hadronic vertex. The inelastic cross-section is calculated in the range $Q^2 > 4$ GeV^2. The contribution to the inelastic cross-section of the exchange of lower Q^2 photons ("quasi-elastic" cross-section) has not been estimated yet and is conservatively neglected. At the generator level, the parton showers approach [21], relying on the DGLAP [22] evolution equations, is used to simulate QCD corrections in the initial and final states. The hadronization of colored particles is then performed via an interface to the PYTHIA [18] program.

For the elastic contribution, the $e^{\pm}p \to e^{\mp}H^{\pm\pm}p$ cross-section is calculated by adding explicitely the proton to the particle contents of CompHEP. The photon-proton-proton current is described by the electric and magnetic form factors G_E and G_M. The usual dipole fit

$$G_E(Q^2) \simeq G_M(Q^2)/\mu_p \simeq G_D(Q^2) \equiv (1 + Q^2/(0.71\ \mathrm{GeV}^2))^{-2}$$

is used, where $\mu_p = 2.973$ is the magnetic moment of the proton. Using a linear fit for G_E which takes into account the experimentally observed [23] decrease of $\mu_p G_E/G_M$ with increasing Q^2 changes the elastic cross-section by less than $\sim 2\%$.

For a Yukawa coupling $h_{ee} = 0.3$, the sum of the elastic and inelastic contributions leads to a cross-section of ~ 0.28 pb (~ 0.03 pb) for a Higgs mass of 100 GeV (150 GeV). The inelastic contribution is found to be $\sim 1/3$ of the elastic contribution in the mass range $80 - 150$ GeV. The theoretical uncertainty on the obtained cross-section is $\sim 4\%$ in this mass range. This is obtained by assessing an uncertainty of $\pm 2\%$ on the ratio $G_M(Q^2)/G_D(Q^2)$ [24], and by varying the scale at which the parton densities are evaluated to calculate the inelastic contribution between $\sqrt{Q^2}/2$ and $2\sqrt{Q^2}$.

The dominant SM contributions involved in multi-lepton production at HERA come from the interaction of two photons radiated from the incident electron and proton. Among these, the Bethe-Heitler process, where a lepton is exchanged in the t- or u-channel, is dominant. The Cabibbo-Parisi process, which involves an e^+e^- interaction where one of the electrons comes from a photon radiated from the proton, contributes at high transverse momentum only. The Drell-Yan process was calculated in [25] and was found to be negligible. All these processes are simulated with the GRAPE Monte Carlo generator [26], which also takes into account contributions from Bremsstrahlung with subsequent photon conversion into a lepton pair and electroweak contributions like real Z production with decay to l^+l^-. For multi-muon production additional contributions are considered, using DIFFVM [27] for the Υ resonance, LPAIR [28, 29]

[2]The CompHEP implementation of the doubly-charged Higgs Lagrangian was used in [17] to calculate $e^-\gamma \to e^+\mu^+\mu^-$ cross-sections. Note that the $e^-\gamma \to e^+H^{--}$ cross-sections obtained with CompHEP do not seem to agree with those obtained from PYTHIA 6.206 [18].

for muons arising from $\gamma\gamma \rightarrow \tau\tau$ and AROMA [30] for muons stemming from semi-leptonic decays in open heavy quark production ($c\bar{c}$ and $b\bar{b}$).

Experimental backgrounds are also present for multi-electron production, i.e. processes where, in addition to the scattered electron, one or more final state particles may be misidentified as electrons. They come dominantly from Neutral Current Deep Inelastic Scattering (NC-DIS) and from elastic Compton scattering, where a jet or a photon is misidentified as an electron. These processes are simulated with the DJANGO [31] and WABGEN [32] generators.

All Monte Carlo samples are subject to a full simulation of the H1 detector which takes into account the effects of energy loss, multiple scattering and showering in the detector.

4 Data Analysis

For the $e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X \rightarrow e^{\mp}e^{\pm}e^{\pm}X$ analysis we use the full $e^{\pm}p$ dataset recorded by the H1 experiment in the period 1994-2000. The total integrated luminosity of 115.2 pb^{-1} is shared between 36.5 pb^{-1} and 65.1 pb^{-1} of $e^{+}p$ collisions recorded at center of mass energies $\sqrt{s}$ of 300 GeV and 318 GeV respectively, and 13.6 pb^{-1} of $e^{-}p$ collisions recorded at $\sqrt{s} = 318$ GeV. For the $e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X \rightarrow e^{\mp}\mu^{\pm}\mu^{\pm}X$ analysis we use an $e^{\pm}p$ sample of 70.9 pb^{-1} at $\sqrt{s} = 318$ GeV.

This analysis is based on the H1 measurements of multi-electron production at high transverse momentum [1] and of multi-muon production [2]. The main selection criteria are summarized below and in Table 1. The selection of multi-electron events requires two central electron[3] candidates ($20^{\circ} < \theta^{e} < 150^{\circ}$, where θ^{e} is the electron polar angle measured with respect to the proton beam direction) one of which must have a transverse momentum $P_T^{e1} > 10$ GeV and the second $P_T^{e2} > 5$ GeV. Additional electron candidates are selected in the region ($5^{\circ} < \theta^{e} < 175^{\circ}$) when their energy is above 5 GeV (10 GeV if $5^{\circ} < \theta^{e} < 20^{\circ}$). The selected events are classified as di-electron (“2e”) in the case that only the two central electron candidates are visible, and tri-electron (“3e”) in the case in which exactly one additional electron candidate is identified. The muon-pair selection requires two central muon candidates ($20^{\circ} < \theta^{\mu} < 160^{\circ}$), with minimal transverse momentum requirements ($P_T^{\mu1} > 2$ GeV, $P_T^{\mu2} > 1.75$ GeV), and a muon pair invariant mass above 5 GeV. After this selection, we observe 105 (16) data events in the di-(tri-) electron final state, which is to be compared with 118.2 ± 12.8 (21.6 ± 3.0) from SM expectation, and 1243 data events in the di-muon final state which is to be compared with 1253 ± 125 from SM expectation. The distributions of the invariant mass M_{12} of the two highest P_T electrons and of the two muons $M_{\mu\mu}$ are shown in Fig. 2. Overall, a good agreement is observed between data and SM expectation. As can been seen in Fig. 2, the SM expectation is largely dominated by $\gamma\gamma$ contributions. In the multi-electron analysis and for masses $M_{12} > 100$ GeV, three “2e” events and three “3e” events are observed, compared to SM expectations of 0.25 ± 0.05 and 0.23 ± 0.04 respectively.

Further selection criteria are then applied, which are designed to maximize the sensitivity of the analysis to an eventual $H^{\pm\pm}$ signal.

[3] Unless otherwise stated, the term “electron” is used in this paper to describe generically electrons or positrons.

For a given $H^{\pm\pm}$ mass M_H, we define M_{ll} as the invariant mass of the two leptons (or, for "3e" events, the invariant dilepton mass which is closest to M_H). In the M_H range $80-150$ GeV, the resolution for M_{ee} varies from ~ 3 GeV to ~ 5 GeV, while the resolution $\sigma_{\mu\mu}$ for $M_{\mu\mu}$ varies from $\sim$ 4 GeV to $\sim$ 20 GeV. The selection of Higgs candidates of mass M_H further requires M_{ll} to be within a mass window designed to maximize the signal significance, which is found to be $M_H \pm 10$ GeV ($M_H \pm 2\sigma_{\mu\mu}$) for a Higgs decaying into electrons (muons).

For the electron channel, the precise measurement of the electron transverse momenta is further exploited by applying an additional M_H-dependent cut on the sum of the P_T of the two electrons assigned to the decay products of the Higgs candidate. The lower bound is chosen to keep 95% of the signal and is optimized separately for the di- and tri-electron final states. It varies between ~ 45 GeV and ~ 120 GeV in the considered M_H range.

Finally, the charge measurement of the two leptons assigned to the Higgs candidate is exploited. In e^+p (e^-p) collision mode, where H^{++} (H^{--}) bosons could be produced, events where at least one of the two leptons is reliably assigned a negative (positive) charge are rejected. The charge assignment requires that the curvature κ of the track associated to the lepton is measured with an error satisfying $\mid \kappa/\delta\kappa \mid > 2$.

<table>
<tr><th>multi-electron</th><th>di-muon</th></tr>
<tr><td colspan="2">Preselection criteria</td></tr>
<tr><td>$P_T^{e_1} > 10$ GeV
$P_T^{e_2} > 5$ GeV
$20^\circ < \theta^{e_1,e_2} < 150^\circ$</td><td>$P_T^{\mu_1} > 2$ GeV
$P_T^{\mu_2} > 1.75$ GeV
$20^\circ < \theta^{\mu_1,\mu_2} < 160^\circ$
$M_{\mu\mu} > 5$ GeV</td></tr>
<tr><td colspan="2">Final selection cuts</td></tr>
<tr><td>$\mid M_{ee} - M_H \mid < 10$ GeV
large $P_T^{e_1} + P_T^{e_2}$</td><td>$\mid M_{\mu\mu} - M_H \mid < 2\sigma_{\mu\mu}$</td></tr>
<tr><td colspan="2">no "wrong sign" lepton from $H^{\pm\pm}$ decay</td></tr>
</table>

Table 1: Selection criteria for the two Higgs decay channels analyzed.

Table 1 summarizes the selection criteria for both the multi-electron and the di-muon analyses. After these requirements, the efficiency for selecting signal events varies from ~ 50 (35)% for an $H^{\pm\pm}$ mass of 80 GeV to ~ 30 (20)% for an $H^{\pm\pm}$ mass of 150 GeV in the electron (muon) analysis. For the electron channel, about half of the selected signal events are classified as di-electron in the full mass range considered. The numbers of observed and expected events which satisfy all the above criteria are given in Table 2 for some typical M_H values, together with the final signal efficiencies. The three high mass events observed in the "3e" sample (see Fig. 2) do not fulfill the criteria on the sum of the P_T of the two leptons applied to select high mass Higgs candidates. Amongst the three high mass events observed in the "2e" sample, only one event (at $M_{ee} = 113$ GeV) satisfies the required condition on the lepton charges.

For the multi-electron analysis, the theoretical and experimental systematic uncertainties attributed to the Monte Carlo predictions are detailed in [1]. The main contribution to the experimental systematic error of the SM predictions is due to the tracker efficiency in the electron

M_H	electron analysis ("2e" + "3e")				muon analysis			
(GeV)	N_{obs}	N_{bckg}	ε	N_{signal}	N_{obs}	N_{bckg}	ε	N_{signal}
100	0	0.23	0.46	4.72	0	0.01	0.31	2.25
120	1	0.09	0.43	1.77	0	0.01	0.26	0.80
150	0	0.02	0.32	0.37	0	0.01	0.20	0.15

Table 2: Number of observed events (N_{obs}) and number of events expected from the Standard Model prediction (N_{bckg}) which satisfy all criteria designed to select Higgs candidates of mass M_H. The signal selection efficiencies ε are also shown, together with the number of signal events (N_{signal}) expected for a Yukawa coupling $h_{ee} = 0.3$.

identification procedure, which is 90% on average with an uncertainty increasing with decreasing polar angle from 3% to 15%. Systematic errors due to the uncertainty on the electromagnetic energy scale (known at the level of 0.7 to 3% in the central and forward regions of the detector, respectively), and to the trigger efficiency ($\sim 95\% \pm 3\%$) are also taken into account.

The total uncertainty of the SM expectation in the di-muon analysis is about 10%. The main contributions to this error are due to the trigger efficiency ($\sim 70\%$ and $\sim 60\%$ for inelastic and elastic events respectively, with an uncertainty of about 5.5%), and to the uncertainty of the muon identification which was found to be 5.8%.

In both analyses the statistical error of the Monte Carlo samples is taken into account as an additional systematic error. Finally, the luminosity measurement leads to a normalization uncertainty of 1.5%.

5 Interpretation

After the final Higgs selection criteria no significant excess over the SM expectation remains in the data. Upper limits on the signal cross-section and on the doubly-charged Higgs couplings to electrons h_{ee} are derived as a function of the $H^{\pm\pm}$ mass at 95% confidence level following a Bayesian approach [33] that takes statistical and systematic uncertainties into account. The limits at 95% confidence level on the product of the $H^{\pm\pm}$ production cross-section and the decay branching ratio, $\sigma(e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X) \times \mathrm{BR}(H^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$, for the leptonic decays $H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}$ and $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$ are shown in Fig. 3 as a function of the doubly-charged Higgs mass. The solid curves show the observed limits, while the dotted curves show the expected limits. The cross-section limits vary from 0.06 to 0.11 pb for the electron channel and from 0.12 to 0.23 pb for the muon channel.

The bound on $\sigma(e^{\pm}p \rightarrow e^{\mp}H^{\pm\pm}X) \times \mathrm{BR}(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm})$ is interpreted in terms of mass-dependent upper limits on the coupling h_{ee}. The resulting constraints are shown in Fig. 4 for two representative values of the branching ratio $\mathrm{BR}(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm})$. The results of this analysis are compared to indirect limits from Bhabha scattering [9] and limits from a direct search by OPAL [14]. Assuming that the doubly-charged Higgs bosons only decay to electrons, we set a lower limit of about 131 GeV for $h_{ee} = 0.3$, corresponding to an interaction of the electromagnetic strength ($h_{ee}^2/4\pi \simeq \alpha_{em}$). The sensitivity of this analysis is better than that derived from Bhabha scattering measurements for masses up to ~ 145 GeV. Assuming that $\mathrm{BR}(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}) = 1/3$ the lower limit is 102 GeV for $h_{ee} = 0.3$. The H1 limits extend the excluded region to masses that are beyond those reached in previous searches for pair production at LEP.

Assuming a democratic coupling of the doubly-charged Higgs to leptons, i.e. $\mathrm{BR}(H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}) = 1/3$, the multi-electron analysis, the di-muon analysis, and the combination of both channels allow to set the mass-dependent upper limits on $h_{ee} = h_{\mu\mu} = h_{\tau\tau}$ shown in Fig. 5. The results of this analysis are compared to indirect limits from Bhabha scattering and limits from a direct search at OPAL. The combination of the electron and muon channels enhances the limit set using the electron channel only from 102 GeV to 108 GeV.

6 Conclusion

We have presented a dedicated search for the single production of doubly-charged Higgs bosons, combining di- and tri-electron as well as di-muon final states. In a previous model independent analysis, H1 has observed six events with a di-electron mass above 100 GeV, i.e. a region where the Standard Model expectation is small. Out of the six events only one is compatible with the production of a doubly-charged Higgs boson, when kinematic cuts and lepton charges are taken into account. No di-muon event was found in the same mass domain.

This analysis places new limits on the $H^{\pm\pm}$ mass and its Yukawa coupling to electrons. Assuming that the doubly-charged Higgs only decays to electrons, we set a lower limit of about 131 GeV for a coupling value $h_{ee} = 0.3$, corresponding to an interaction of the electromagnetic strength.

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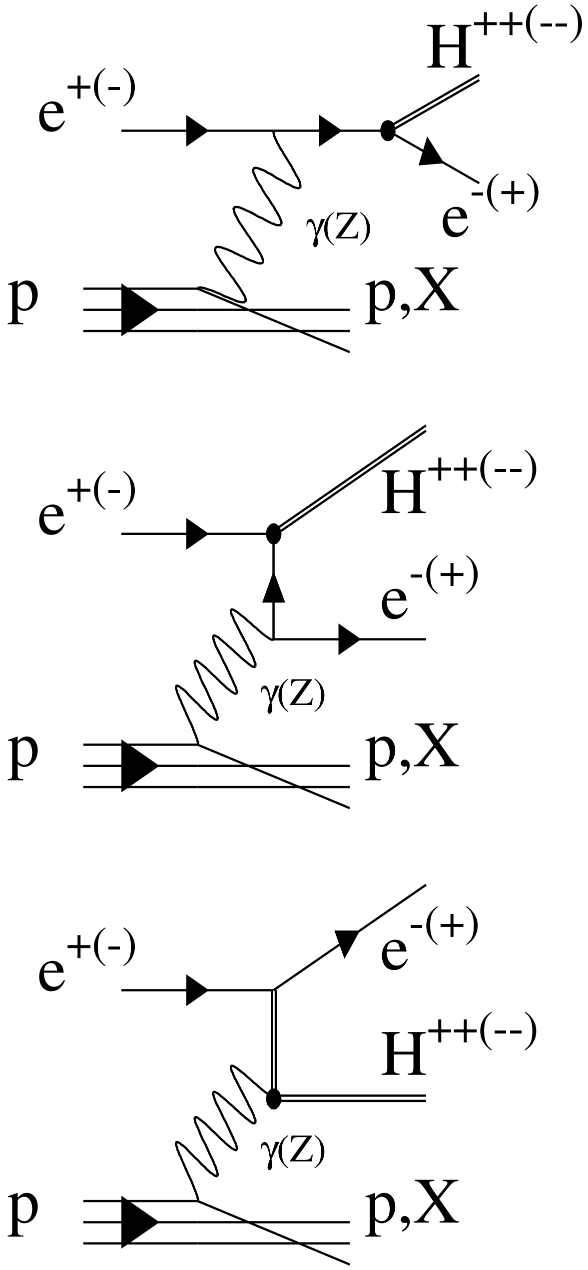

Figure 1: Feynman diagrams for the single production of doubly-charged Higgs bosons in $e^{\pm}p$ collisions at HERA. The hadronic final state is denoted by p (X) in the elastic (inelastic) case, where the initial proton remains intact (dissociates).

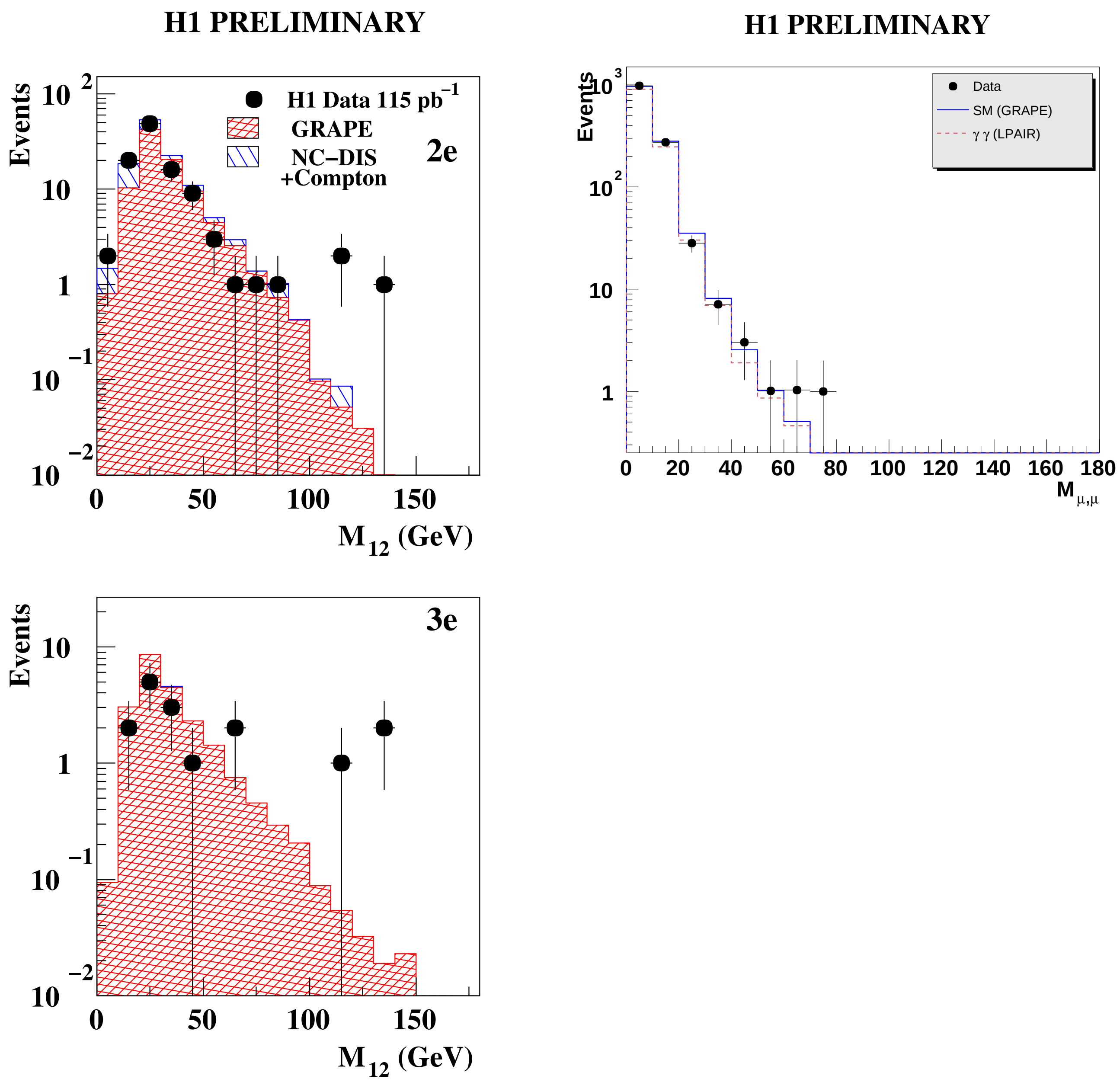

Figure 2: Invariant mass M_{12} of the two highest P_T electrons for events classified as di-electron (top left) and tri-electron (bottom left), and di-muon invariant mass $M_{\mu\mu}$ (right) in comparison with the Standard Model expectation.

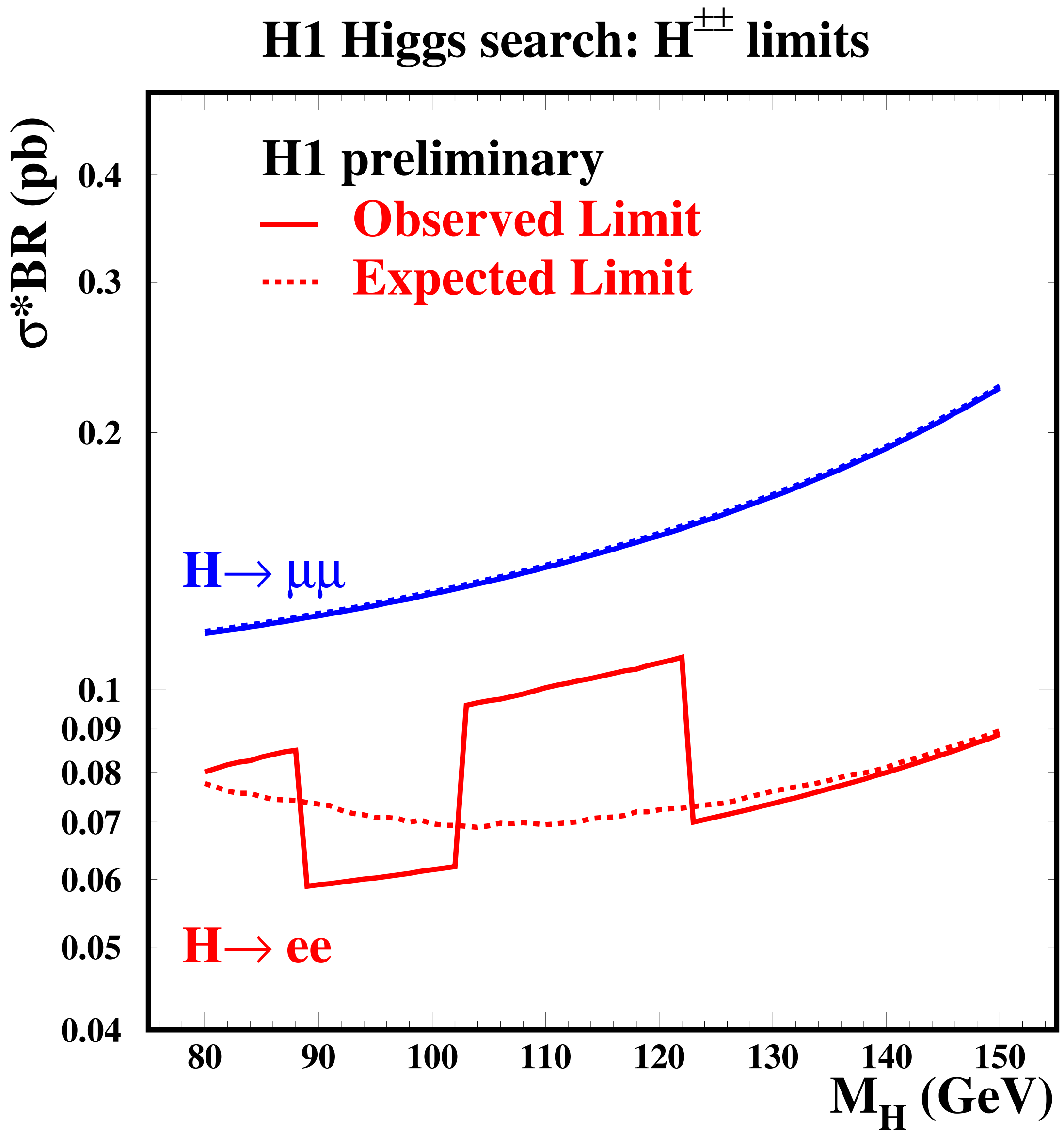

Figure 3: Upper limits at 95% confidence level on $\sigma(e^{\pm}p \to e^{\mp}H^{\pm\pm}X) \times \mathrm{BR}(H^{\pm\pm} \to l^{\pm}l^{\pm})$ for the leptonic decays $H^{\pm\pm} \to e^{\pm}e^{\pm}$ (lower set of curves) and $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ (upper set of curves), as a function of the doubly-charged Higgs mass. The solid (dashed) curves show the observed (expected) limits.

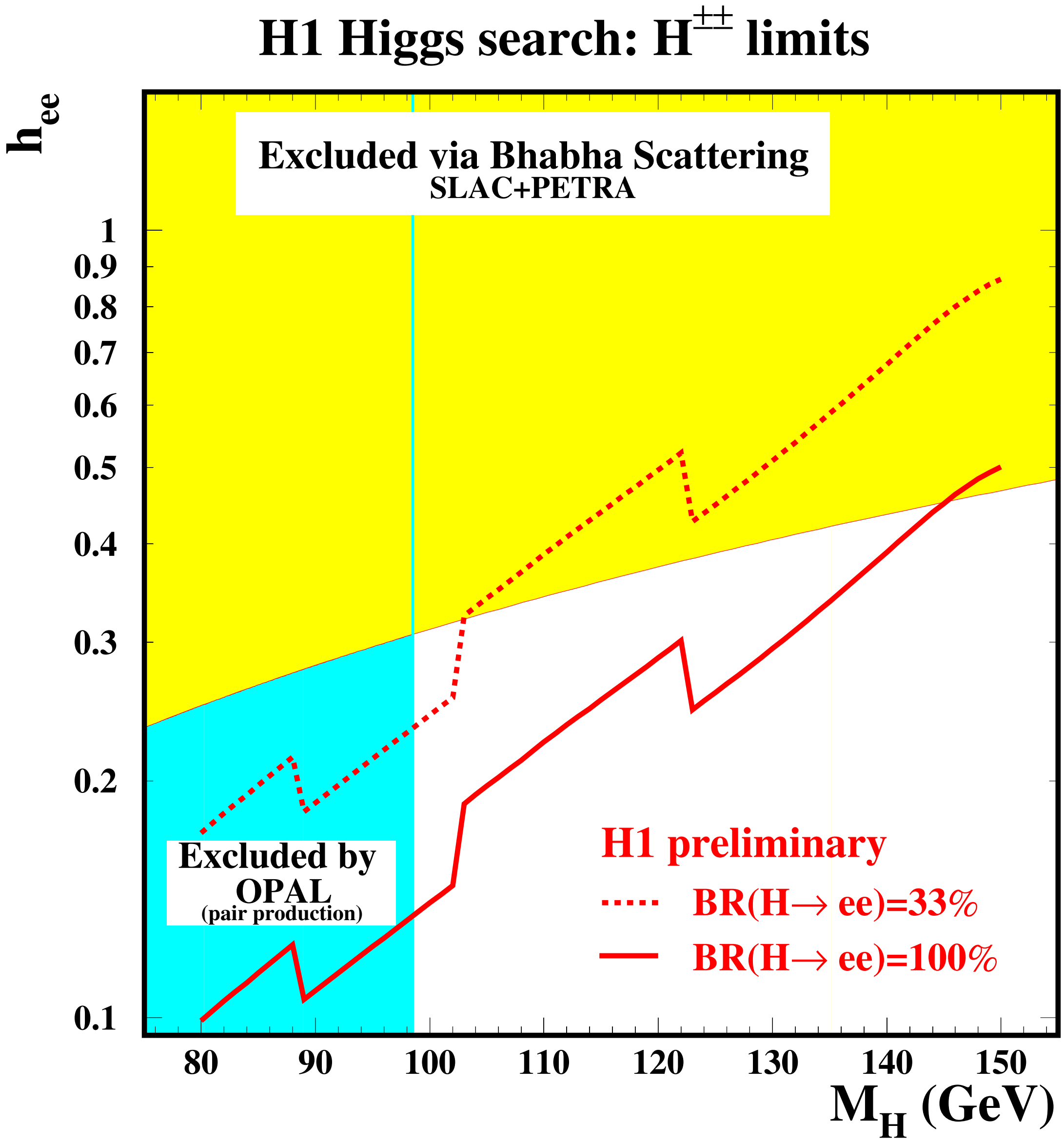

Figure 4: Exclusion limits on the coupling h_{ee} at 95% confidence level as a function of the doubly-charged Higgs mass from the multi-electron analysis assuming that (dashed curve) BR$(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}) = 1/3$ or (full curve) BR$(H^{\pm\pm} \rightarrow e^{\pm}e^{\pm}) = 1$. The results of this analysis are compared to indirect limits from Bhabha scattering and to limits from a direct search by OPAL.

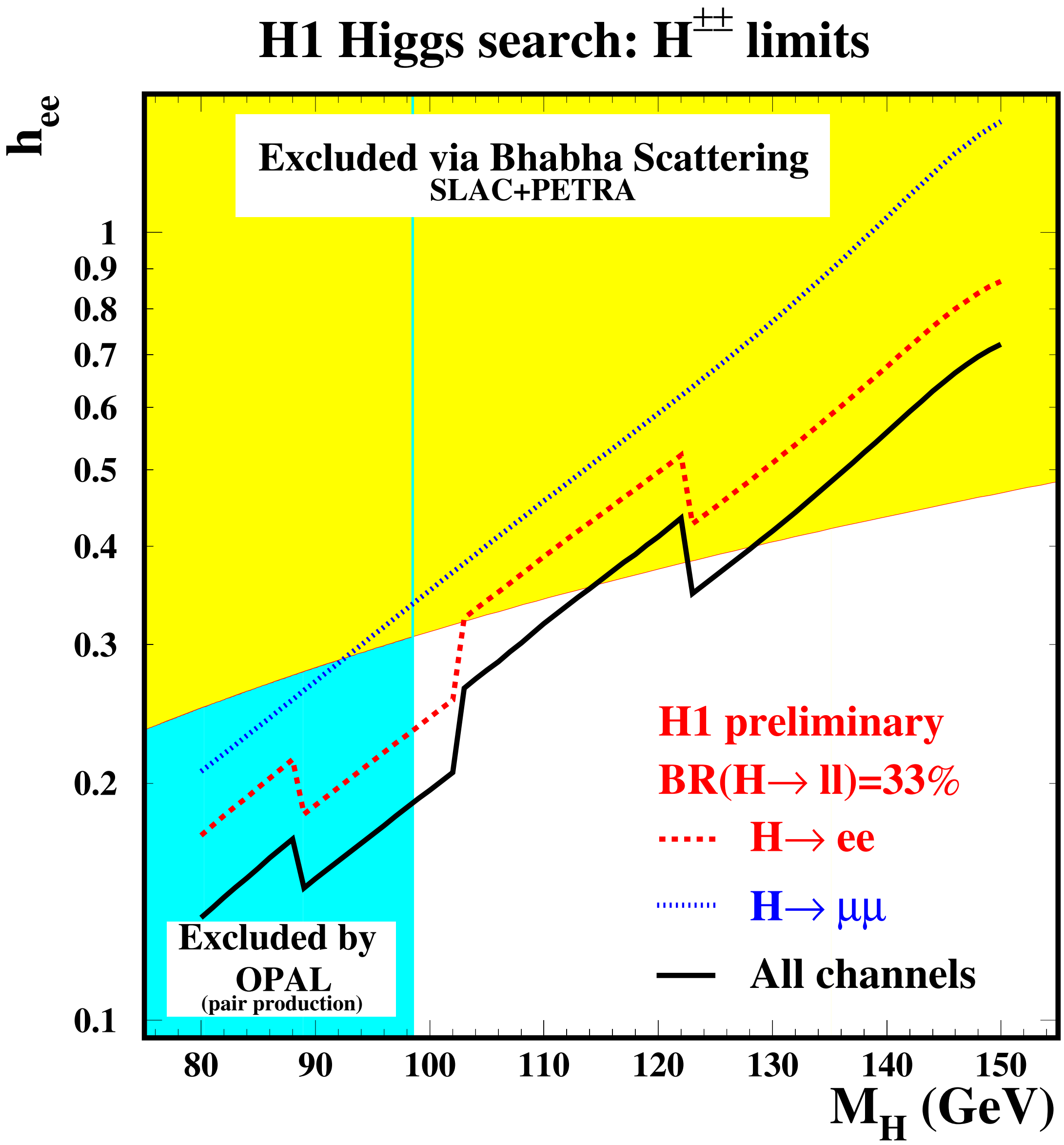

Figure 5: Exclusion limits on the coupling $h_{ee} = h_{\mu\mu} = h_{\tau\tau}$ at 95% confidence level as a function of the doubly-charged Higgs mass from the multi-electron analysis (dashed curve), the di-muon analysis (dotted curve), and from the combination of these channels (full curve), assuming a democratic coupling of the doubly-charged Higgs to leptons, i.e. $\mathrm{BR}(H^{\pm\pm} \to l^{\pm}l^{\pm}) = 1/3$. The results of this analysis are compared to indirect limits from Bhabha scattering and to limits from a direct search by OPAL.