Exclusive doubly charged Higgs boson pair production in *pp* collisions at the LHC

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The type II seesaw model predicts the existence of a doubly charged Higgs boson ($H^{\pm\pm}$), which can be produced through the Drell-Yan process and photon-induced interactions at hadronic colliders. In recent years, such reactions have been largely investigated in inclusive processes, where both incident protons breakup and a large number of particles is produced in addition to the doubly charged Higgs pair. In this paper, we investigate, for the first time, the possibility of searching for $H^{\pm\pm}$ in exclusive processes, which are characterized by two rapidity gaps and two intact very forward protons in final state. We estimate the associated cross section making use of the exclusive nature of the final state, together with the use of timing information provided by forward proton detectors. Moreover, the background is estimated considering distinct amounts of pileup. Our results indicate that the exclusive doubly charged Higgs pair production is a promising way to search for signatures of the type II seesaw mechanism and to obtain lower mass bounds on $H^{\pm\pm}$.

I. INTRODUCTION

Many beyond Standard Model (SM) scenarios predict the existence of a scalar particle carrying two units of electric charge, especially those related to neutrino masses. One of the most popular scenarios featuring this kind of particle is the type II seesaw mechanism [1–4], in which a $SU(2)_L$ scalar triplet $\Delta = (H^{++}, H^+, H^0)$ accounts for the tiny neutrino masses after its neutral component develop a vacuum expectation value (VEV). Accompanying the

neutral scalar inside the triplet, there is the doubly charged scalar H^{++} (along with a singly charged scalar as well). Doubly charged scalars are also present in left-right symmetric models [5–7] (which were, in fact, the first models to propose the existence of these particles), coming from either a $SU(2)_L$ or a $SU(2)_R$ triplet. They can also arise from other scalar multiplet representations in models such as radiative seesaw models [8,9], 3-3-1 models [10–13], Georgi-Machacek models [14–16], and little Higgs models [17–19].

Several searches for doubly charged scalar particles have been performed recently, specially in high-energy colliders [20–27]. From the nonobservation of any excess compared to the SM background, limits on the production cross section of the H^{++} have been placed, which can be translated into bounds on the H^{++} mass, depending on the assumptions about its decays modes. Since in many scenarios neutrino masses are generated via the coupling between the SM lepton doublet and the scalar multiplet that hosts the H^{++}, a reasonable assumption is that H^{++} is able to decay into SM leptons. In particular, the decay into

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same-sign dileptons provides a smoking gun signature for a doubly charged particle and, for this reason, this signature has been used in most of the experimental analysis. The most stringent limits to date come from the searches by the ATLAS Collaboration obtained with 139 fb^{-1} data collected at 13 TeV [27]. Assuming that decays to each of the ee, $e\mu$, $\mu\mu$, $\mu\tau$, $e\tau$, $\tau\tau$ final states are equally probable, the lower limit on $H^{\pm\pm}$ mass is around 1080 GeV, at 95% C.L. within the type II seesaw model.

The current lower limit on the mass of the doubly charged Higgs in hadronic colliders have been mainly obtained by considering that the $H^{++}H^{--}$ pair can be produced via the Drell-Yan (DY) process as well as by photon-photon and gluon-gluon interactions. As demonstrated, e.g., in Ref. [28], photon-induced processes are suppressed by about an order of magnitude with respect to the DY production, and the gluon fusion is subdominant compared to the $\gamma\gamma$ fusion. The DY production is an inclusive process, characterized by the fragmentation of both incident protons and a large number of particles is produced in addition to the doubly charged Higgs pair. On the other hand, in $\gamma\gamma$ interactions, the processes can be classified as elastic, semielastic or inelastic, depending if both, only one or none of the incident protons remain intact (for previous studies see, e.g., Refs. [29,30]). As a consequence, the elastic events, represented in Fig. 1, although subdominant with respect to the other channels, has a final state characterized by the presence of two regions devoid of hadronic activity, called rapidity gaps, separating the intact very forward protons from the central massive object. Such a very clean final state is a characteristic of exclusive processes, which are generated by the exchange of color singlet objects (e.g., a photons or a Pomeron) [31]. Such distinct topology of exclusive processes was not explored in previous studies and will be considered, for the first time, in the present paper. In our

FIG. 1. Diagram for the exclusive doubly charged Higgs pair production in pp collisions at the LHC.

analysis we will consider that these events can be collected using the forward proton detectors (FPDs) such as the ATLAS forward proton detector (AFP) [32,33] and precision proton spectrometer (CT-PPS) [34] that are installed symmetrically around the interaction point at a distance of roughly 210 m from the interaction point. In particular, we will assume that $m(H^{\pm\pm}) \geq 350$ GeV and that the doubly charged Higgs decays into same-signal dileptons. The large invariant mass of the produced system implies that the intact protons in the final state can be tagged by FPDs. Consequently, such events can, in principle, be separated and be used to searching for the doubly charged Higgs and/ or impose limits on its mass. In our analysis we will also consider the presence of pileup events, which is a reality in current and future LHC runs, and arise due to the presence of extra pp interactions per bunch crossing in high luminosity pp collisions at the LHC. These extra interactions generate additional tracks, which increase the background stemming from the inelastic doubly charged Higgs pair produced in a different primary vertex and, in general, destroy the signature associated to two rapidity gaps. Following Refs. [35,36], such background will be suppressed by considering the time-of-flight (TOF) detectors [37–40]. As we will demonstrate below, the exclusive $H^{++}H^{--}$ production is a promising alternative to searching for signals of the type II seesaw mechanism. It is important to emphasize that over the last years the searching of beyond the standard model physics in exclusive processes has been proposed by several groups (see, e.g., Refs. [37,41–52]) and that the experimental analysis performed by the ATLAS and CMS collaborations of events with proton tagging already have imposed important constraints on several scenarios for new physics [53–57]. Our results indicate that an experimental analysis is feasible and that the associated data will be very useful to improve our understanding of the type II seesaw mechanism.

This paper is organized as follows. In the next section we present a brief review of the formalism for the doubly charged Higgs interactions and for the treatment of the $H^{\pm\pm}$ pair production in photon-induced interactions in pp collisions. In Sec. III we discuss the backgrounds considered in our analysis as well as the exclusivity cuts. In addition, we present our predictions for the invariant mass, transverse momentum, and rapidity distributions as well as for the total cross sections for the $H^{\pm\pm}$ pair production in $\gamma\gamma$ interactions. Finally, in Sec. IV we summarize our main conclusions.

II. FORMALISM

In this section we describe the H^{++} basic features and the relevant interactions for its production and decay at the LHC. Since doubly charged scalar bosons appear in several extensions of the SM [8,14,58,59], here we will first focus on the case of the Higgs triplet model, which is a minimal realization of the type II seesaw mechanism, and later
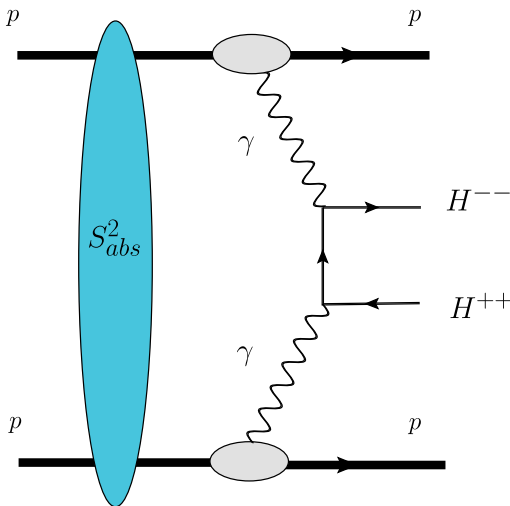
extend to more general H^{++} particles, keeping some of the key features from this prototypical case.

In the Higgs triplet model, the SM scalar sector is extended by adding a weak scalar triplet Δ,

$$\Delta(1,2,1) = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}, \qquad (1)$$

where the numbers in parentheses denote the representation under the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group of the SM.[1] The most general renormalizable scalar potential is given by

$$
\begin{aligned}
V = &-m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{4}(\Phi^\dagger \Phi)^2 + m_\Delta^2 \mathrm{Tr}\Delta^\dagger \Delta \\
&+ (\mu \Phi^T i\sigma^2 \Delta^\dagger \Phi + \mathrm{H.c.}) \\
&+ \lambda_1 \Phi^\dagger \Phi \mathrm{Tr}\Delta^\dagger \Delta + \lambda_2 (\mathrm{Tr}\Delta^\dagger \Delta)^2 \\
&+ \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi, \qquad (2)
\end{aligned}
$$

where Φ is the SM-like scalar doublet, m_Φ^2, m_Δ^2, and μ are mass parameters, and λ and λ_i ($i = 1, ..., 4$) are independent dimensionless couplings. After spontaneous symmetry breaking, both scalars Φ^0 and Δ^0 acquire VEVs, denoted by $\langle\Phi^0\rangle = v/\sqrt{2}$ and $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$. From the two minimization conditions of the scalar potential, we can express m_Φ^2 and m_Δ^2 in terms of other parameters as

$$
\begin{aligned}
m_\Phi^2 &= \frac{\lambda}{4}v^2 + \frac{\lambda_1 + \lambda_4}{2}v_\Delta^2 - \sqrt{2}\mu v_\Delta, \\
m_\Delta^2 &= -\frac{(\lambda_1 + \lambda_2)}{2}v^2 - (\lambda_2 + \lambda_3)v_\Delta^2 + \frac{\mu v^2}{\sqrt{2}v_\Delta}. \qquad (3)
\end{aligned}
$$

The neutral components of Φ and Δ can be parametrized as

$$
\begin{aligned}
\Phi^0 &= (\rho_1 + v + i\eta_1)/\sqrt{2}, \\
\Delta^0 &= (\rho_2 + v_\Delta + i\eta_2)/\sqrt{2}, \qquad (4)
\end{aligned}
$$

and after the electroweak symmetry breaking, the mixing among the scalar fields lead to several Higgs bosons. The gauge eigenstates can be rotated to obtain the mass eigenstates as in the following:

$$
\begin{pmatrix} h \\ H \end{pmatrix} = R(\alpha)\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}, \qquad \begin{pmatrix} G \\ A \end{pmatrix} = R(\beta)\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix},
$$

$$
\begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = R(\beta')\begin{pmatrix} \phi_1^+ \\ \Delta^+ \end{pmatrix},
$$

where $R(\theta)$ is the usual rotation matrix,

---

[1]We are using the convention $Q = T_3 + Y$ for the electric charge and hypercharge.

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix},$$

and α, β and β' are the rotation angles in the CP-even, CP-odd, and singly charged Higgs sectors. h and H are the CP-even neutral Higgs with masses m_h and m_H given by

$$
\begin{aligned}
m_h &= \frac{1}{2}\left(a + c - \sqrt{(a-c)^2 + 4b^2}\right), \\
m_H &= \frac{1}{2}\left(a + c + \sqrt{(a-c)^2 + 4b^2}\right), \qquad (5)
\end{aligned}
$$

where $a = \frac{\lambda}{2}v^2$, $b = -\sqrt{2}\mu v + (\lambda_1 + \lambda_4)vv_\Delta$, and $c = \frac{\mu v^2}{\sqrt{2}v_\Delta} + 2(\lambda_2 + \lambda_3)v_\Delta^2$. The lightest of the neutral scalar mass eigenstates, h, is identified with the 125 GeV SM-like Higgs boson. The field A is the CP-odd neutral scalar with mass m_A,

$$m_A^2 = \frac{\mu(v^2 + 4v_\Delta^2)}{\sqrt{2}v_\Delta}, \qquad (6)$$

while G^+ and G^0 are the Nambu-Goldstone bosons that become the longitudinal modes of Z and W^+, respectively. H^+ is the singly charged Higgs boson, whose mass m_{H^+} is given by

$$m_{H^+} = \frac{(v^2 + v_\Delta^2)(2\sqrt{2}\mu - \lambda_4 v_\Delta)}{4v_\Delta}. \qquad (7)$$

Finally, the doubly charged Higgs $H^{++}(\equiv \Delta^{\pm\pm})$ comes solely from the triplet and has a mass

$$m_{H^{++}}^2 = \frac{\mu v^2}{\sqrt{2}v_\Delta} - \frac{1}{2}(\lambda_4 v^2 + 2\lambda_3 v_\Delta^2). \qquad (8)$$

The triplet Δ interacts with the SM leptons via the coupling,

$$\mathcal{L}_Y \supset -y\overline{L^c}i\sigma^2\Delta L + \mathrm{H.c.}, \qquad (9)$$

where y is the matrix of Yukawa coupling constants, $L = (\nu_L \quad e_L)^T$ is the SM lepton doublet, σ^2 is the second Pauli matrix and the superscript c denotes charge conjugation. By means of this interaction, neutrino masses are generated after Δ^0 develops its VEV, v_Δ. As the masses will be proportional to v_Δ, it is clear that this VEV is required to be small in order to account for the tiny neutrino masses. On the other hand, a small v_Δ value lead to high triplet scalar masses. For values of the μ parameter around the electroweak scale, scalars with masses of hundreds of GeV to TeV are easily attainable. Although these extra scalars are very important if one wants to verify the Higgs triplet model, for the searches of the H^{++} that we will focus on

this paper, they will play no role. Therefore, in what follows we will no longer discuss about them.

The H^{++} in the Higgs triplet model further couples to gauge bosons and other scalars at tree level. The coupling to quarks, however, is forbidden (note that the $Y = 1$ hypercharge that allows the coupling of Δ with the leptons in Eq. (9), automatically forbids a coupling to the quark doublets). Thus, the H^{++} has basically two decays modes: $H^{\pm\pm} \to \ell_i^\pm \ell_j^\pm$ and $H^{\pm\pm} \to W^\pm W^\pm$. The widths for these two body decays are given by [60]

$$\Gamma(H^{\pm\pm} \to \ell_i^\pm \ell_j^\pm) = \frac{m_{H^{\pm\pm}}}{8\pi(1 + \delta_{ij})} \frac{|\mathcal{M}_\nu^{ij}|^2}{v_\Delta^2}, \qquad (10)$$

$$\Gamma(H^{\pm\pm} \to W^\pm W^\pm)$$
$$= \frac{g^4 v_\Delta^2}{8\pi m_{H^{\pm\pm}}} \sqrt{1 - \frac{4m_W^2}{m_{H^{\pm\pm}}^2}} \left[2 + \left(\frac{m_{H^{\pm\pm}}^2}{2m_W^2} - 1 \right)^2 \right], \qquad (11)$$

where δ_{ij} is the Kronecker delta, $\mathcal{M}_\nu^{ij}$ are the elements of the neutrino mass matrix and $\ell_i^\pm = e^\pm, \mu^\pm, \tau^\pm$. From these expressions, it is clear that the branching ratios for H^{++} decays are very sensitive to v_Δ. Most of the searches so far have been focused in the same sign dilepton decays $H^{\pm\pm} \to \ell_i^\pm \ell_j^\pm$, which provides a clean distinctive signature. This amounts to assume that $v_\Delta \leq 10^{-4}$ GeV, so that this decay is dominant over the $H^{\pm\pm} \to W^\pm W^\pm$ channel. Although this channel is more difficult to analyze due to the presence of neutrinos in the final state, and the consequent larger SM backgrounds, searches in this channel have been done [26,27]. It should be mentioned that, if kinematically allowed, H^{++} can also have cascade decays to scalar and vector bosons, such as $H^{\pm\pm} \to H^\pm W^\pm \to H^0 W^\pm W^\pm$. However, these decays are much more challenging to probe experimentally.

Doubly charged Higgs bosons can be pair produced at the LHC via the DY process $q\bar{q} \to \gamma^*/Z^* \to H^{\pm\pm} H^{\mp\mp}$. The trilinear and quartic gauge interactions relevant for the calculation of the pair production come from the kinetic Lagrangian for H^{++}, and can be written as

$$\mathcal{L}_{\text{kin}} = i \left[2eA_\mu + \frac{g}{c_W}(2 - Y - 2s_W^2)Z_\mu \right] H^{++} \partial^\mu H^{--}$$
$$+ \left[2eA_\mu + \frac{g}{c_W}(2 - Y - 2s_W^2)Z_\mu \right]$$
$$\times \left[2eA^\mu + \frac{g}{c_W}(2 - Y - 2s_W^2)Z^\mu \right] H^{++} H^{--}, \qquad (12)$$

where $c_W = \cos\theta_W$, $s_W = \sin\theta_W$, with θ_W being the weak mixing angle. The H^{++} can also be produced in association with a W boson. However, in the Higgs triplet model this production rate is highly suppressed, since it is proportional to the factor (v_Δ^2/m_W^2). Production of H^{++} in association

with H^- can occur at significant rates via the process $u\bar{d} \to W^{+*} \to H^{++} H^-$ (see e.g. Ref. [61]). However, the pair production of a doubly charged scalar points more precisely to the doubly charged scalar mass, which is a common particle in several model building endeavors [21,62]. For these reasons, in their searches for doubly charged Higgs bosons, the ATLAS and CMS collaborations have focused on the pair production via DY process. In the next section we shall discuss a new way to search for the H^{++}, employing elastic photon fusion production, combined with the tagging of the intact protons after the collision, which is complementary to the ATLAS and CMS searches and leads to excellent detection prospects.

In our analysis, we also consider doubly charged scalars arising from more general $SU(2)_L$ representations. We assume that most of the features of the H^{++} from the Higgs triplet model remain valid for these other cases, in particular concerning its production and decay modes. More specifically, our analysis includes the following:

(i) H^{++} from a $SU(2)_L$ singlet: $\phi = H^{++}$; ($T_3 = 0$, $Y = 2$).
(ii) H^{++} from a $SU(2)_L$ doublet: $\phi = (H^{++} H^+)$; ($T_3 = 1/2, Y = 3/2$).
(iii) H^{++} from a $SU(2)_L$ triplet: $\phi = (H^{++} H^+ H^0)$; ($T_3 = 1, Y = 1$).

These representations arise quite commonly in a variety of models. For instance, in some versions of the 3-3-1 model [12,13], an scalar triplet emerges from an original $SU(3)_L$ scalar sextet, after this symmetry is spontaneously broken down to the SM gauge group. In the left-right symmetric model [63,64], besides the H_L^{++} from the $SU(2)_L$ triplet Δ_L, there is also a companion H_R^{++} from the $SU(2)_R$ triplet Δ_R [which is however singlet under $SU(2)_L$]. In radiative neutrino mass models [8,9], the doubly charged Higgs boson is analogous to the singlet H_R^{++} of the left-right model. As the presence of singlets, doublets, or triplets containing a doubly charged boson is very common in several neutrino mass studies [65–70], we will stick to these representations. It should be noted that other scalar multiplets, such as $SU(2)_L$ quadruplets or quintuplets, can also host a H^{++}. In these cases, however, the coupling of H^{++} to the leptons would require the presence of extra vectorlike fermions that mix with the SM leptons. For this reason, we will not consider these higher isospin representations here. It is important to emphasize that the gauge interactions for the DY pair production given in Eq. (12) remain valid for all the aforementioned representations (provided the appropriate hypercharge value is used), while the production via photon-photon fusion, discussed below, is insensitive to the multiplet representation the H^{++} originates from. In addition, we will assume that, similarly to the case of the Higgs triplet model in the regime of small v_Δ, the H^{++} decays dominantly into same-sign dileptons, also for the singlet and doublet cases.

A. Production via photon-photon fusion

As discussed in the Introduction, our focus in this paper is on the analysis of the doubly charged Higgs production by elastic $\gamma\gamma$ interactions, as represented in Fig. 1. The total cross section for these interactions can be factorized in terms of the equivalent flux of photons into the hadron projectiles and the photon-photon cross section. In particular, the $H^{++}H^{--}$ production in photon-photon interactions is described by

$$\sigma(h_1 h_2 \to h_1 \otimes H^{++}H^{--} \otimes h_2)$$
$$= S_{abs}^2 \int dx_1 \int dx_2 \gamma_1^{el}(x_1) \cdot \gamma_2^{el}(x_2) \cdot \hat{\sigma}(\gamma\gamma \to H^{++}H^{--}), \quad (13)$$

where $\otimes$ represents the presence of a rapidity gap in the final state, S_{abs}^2 is the absorptive factor (see below), x is the fraction of the hadron energy carried by the photon and $\gamma^{el}(x)$ is the elastic equivalent photon distribution of the hadron. The general expression for the elastic photon flux of the proton is given by [71]

$$\gamma^{el}(x) = -\frac{\alpha}{2\pi} \int_{-\infty}^{-\frac{m^2 x^2}{1-x}} \frac{dt}{t}$$
$$\times \left\{ \left[2\left(\frac{1}{x} - 1\right) + \frac{2m^2 x}{t} \right] H_1(t) + x G_M^2(t) \right\}, \quad (14)$$

where $t = q^2$ is the momentum transfer squared of the photon,

$$H_1(t) \equiv \frac{G_E^2(t) + \tau G_M^2(t)}{1 + \tau} \quad (15)$$

with $\tau \equiv -t/m^2$, m being the nucleon mass, and where G_E and G_M are the Sachs elastic form factors. In our analysis, we will use the photon flux derived in Ref. [72], where an analytical expression is presented. Moreover, we will also assume that the absorptive factor S_{abs}^2, which takes into account of additional soft interactions between incident protons and which leads to an extra production of particles that destroy the rapidity gaps in the final state [73], is equal to the unity. Such assumption is a reasonable approximation since the contribution of the soft interactions is expected to be small in $\gamma\gamma$ interactions due to the long range of the electromagnetic interaction. However, it is important to emphasize that the theoretical treatment of S_{abs}^2 for $\gamma\gamma$ interactions is still a theme of intense debate in the literature (see, e.g., Refs. [74–78]). In particular, its dependence on the center-of-mass energy, invariant mass and rapidity of the final state are not well established, with the predictions for the LHC energy, large invariant masses and central rapidities being largely distinct, varying between 0.6 and ≈ 1. Therefore, our predictions for the

production of doubly charged Higgs in $\gamma\gamma$ interactions should be considered an upper bound. Another important aspect is that for exclusive processes mediated by a Pomeron, such a factor can be $\mathcal{O}(10^{-2})$ and its precise value is also a theme of intense debate (for reviews see Refs. [79–81]).

Some comments are in order. First, a detailed study of the production of the single charged Higgs $H^{\pm}$ in pp collisions via $\gamma\gamma$ interactions was performed in Ref. [46], which has demonstrated that the experimental analysis of this process can be useful to probe the existence and properties of $H^{\pm}$. Such study can be considered as complementary to that performed here. In a forthcoming analysis, we intend to improve Ref. [46] by including the possible $H^{\pm}$ decays and the full simulation of backgrounds and pileup, as considered in this paper, which will allow us to derive lower mass bounds on $H^{\pm}$. Second, in recent years, the determination of photon parton distribution function (PDF) in a global analysis was performed by different groups assuming distinct assumptions for, e.g., the initial conditions and the treatment of the higher order corrections [82–84]. In general, in these analyses the authors have considered that the photon PDF is given by the elastic γ^{el} and the inelastic γ^{inel} contributions (for a more detailed discussion see, e.g., Refs. [85,86]). The elastic photon distribution is associated to the probability that a proton emits a photon and remains intact and can be expressed in terms of the electric and magnetic form factors using the equivalent photon approximation method [71,72], as in Eq. (14) above. On the other hand, the inelastic photon distribution γ^{inel} provides the probability for a photon emission from a proton in an inelastic interaction and can be estimated assuming that the photon is a constituent of the proton, along with quarks and gluons, with its contribution being derived by solving the Dokshitzer, Gribov, Lipatov, Altarelli, Parisi evolution equations modified by the inclusion of the QED parton splittings. The resulting predictions for γ^{inel}, and consequently for the photon PDF, are dependent on the assumptions assumed in the global analysis, implying a larger uncertainty on the predictions for the inclusive processes. In contrast, for exclusive (elastic) processes, the uncertainty on the predictions is strongly reduced since it depends only on γ^{el}, which is well known.

III. RESULTS

In what follows we will present our results for the doubly charged Higgs production in exclusive processes considering pp collisions at $\sqrt{s} = 13$ TeV. In our analysis, we will take into account of the current detector acceptances and resolutions as well as the pile–up effects. We will assume that the $H^{++}H^{--}$ system decays leptonically, $H^{++}H^{--} \to e^+ e^+ e^- e^-$, both forward protons are tagged and pileup is present. In particular, we will consider two

different amounts for the pileup, $\langle \mu \rangle = 5$ and 50. Moreover, our results will derived by considering additional exclusivity cuts and utilizing the TOF detectors for suppressing the combinatorial background coming from pileup. The signal is assumed to be the $pp \to p \otimes H^{++}H^{--} \otimes p \to p \otimes (e^+e^+)(e^-e^-) \otimes p$ process, which will be generated using MadGraph 5 [87,88]. For the background we will consider the photon-induced processes $pp \to p \otimes e^+e^-e^+e^- \otimes p$ and $pp \to p \otimes ZZ \otimes p \to p \otimes e^+e^-e^+e^- \otimes p$, where the last process occurs via the box diagram. In addition, the inclusive $H^{++}H^{--}$ production via the DY production is also estimated, considering the probably of fake double tagging. All these backgrounds are also generated by MadGraph 5 [87]. As in Refs. [35,36], each event is then properly mixed with such a number of pileup interactions that corresponds to the studied luminosity scenario. Detector effects are incorporated and the pileup mixing is done using DELPHES 3.5 [89] with input cards with CMS detector specifications. In order to perform the separation of the signal from backgrounds, we first select the central system as in the inclusive processes and

then we apply exclusivity criteria. We require both forward protons to be detected by FPDs and processed by TOF detectors, such as the AFP [90] and CT-PPS [34] that are installed symmetrically around the interaction point at a distance of roughly 210 m from the interaction point. The TOF suppression factors are 17.65 and 9.45 for $\langle \mu \rangle = 5$ and 50, respectively, considering that the time resolution of TOF is $\sigma_t = 10$ ps and the signal is collected in a $2 - \sigma_t$ window. The background with pileup is evaluated as a combinatorial background coming from the rate of fake DT events [39]. The final suppression factors representing the rates of fake double-tagged events for $\langle \mu \rangle = 5$ and 50 are 0.005 and 0.338, respectively.

Initially, we will focus on the $H^{\pm\pm}$ from the Higgs triplet model, in which $Y = 1$, and let us estimate the differential distributions at the generation level. In Fig. 2 (upper left panel) we present the associated predictions for the invariant mass distribution of the $e^+e^+e^-e^-$ system, denoted $m(4lep)$, considering $m(H^{\pm\pm}) = 350$ GeV. The signal and the main background contributions are shown. The results for the $pp \to p \otimes ZZ \otimes p \to p \otimes e^+e^-e^+e^- \otimes p$
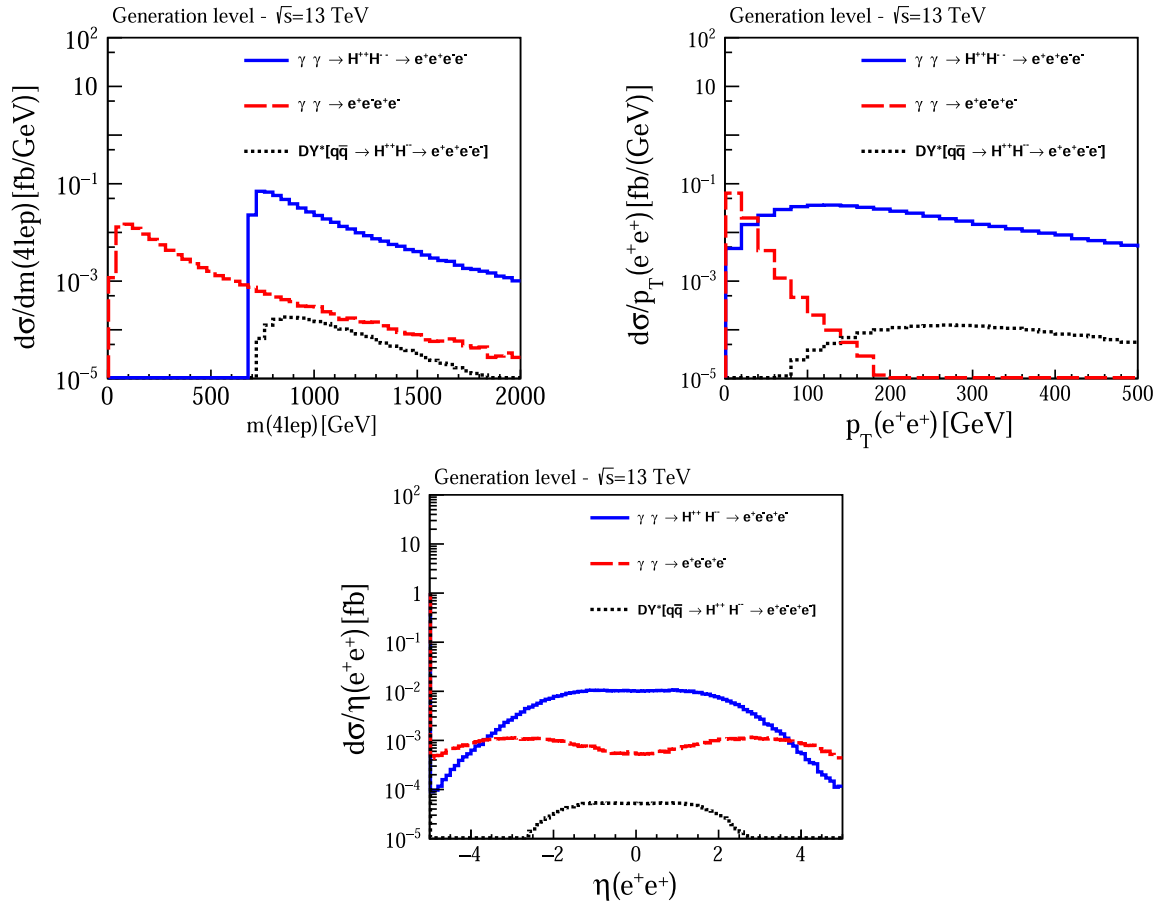

FIG. 2. Predictions for the invariant mass distribution of the four lepton system (upper left panel), transverse momentum (upper right panel) and rapidity (lower panel) distributions of the e^+e^+ pair at the generation level considering $m(H^{\pm\pm}) = 350$ GeV and pp collisions at $\sqrt{s} = 13$ TeV. DY* indicates that the double tagging (DT) and TOF suppression factors have been applied to the inclusive DY predictions.

TABLE I. Predictions for the total cross sections of the signal and background at the detector level considering two different values of the doubly charged Higgs mass and two scenarios for the pileup. The model considered here is the Higgs triplet model ($Y = 1$).

p-p @ $\sqrt{s} = 13$ TeV	$\gamma\gamma \to H^{++}H^{--}$ $\to (e^+e^+)(e^-e^-)$	DY[After DT and TOF]: $q\bar{q} \to H^{++}H^{--} \to (e^+e^+)(e^-e^-)$	$\gamma\gamma \to e^+e^-e^+e^-$	$\gamma\gamma \to ZZ$ $\to (e^+e^-)(e^+e^-)$ [box]
	$m(H^{\pm\pm}) = 350.0$ GeV, $\langle\mu\rangle = 5$			
Total Cross section (fb)	0.53	0.0023	0.09	$\lesssim 10^{-7}$
$p_T(e^+e^+, e^-e^-) > 50.0$ GeV	0.44	0.0023	$\lesssim 10^{-5}$	0.0
$|\eta| < 2.5$	0.44	0.0023	$\lesssim 10^{-5}$	0.0
$m(H^{\pm\pm}) \pm 10$ GeV	0.34	0.0016	0.0	0.0
	$m(H^{\pm\pm}) = 350.0$ GeV, $\langle\mu\rangle = 50$			
Total Cross section (fb)	0.53	0.29	0.09	$\lesssim 10^{-7}$
$p_T(e^+e^+, e^-e^-) > 50.0$ GeV	0.44	0.29	$\lesssim 10^{-5}$	0.0
$|\eta| < 2.5$	0.43	0.29	$\lesssim 10^{-5}$	0.0
$m(H^{\pm\pm}) \pm 10$ GeV	0.32	0.20	0.0	0.0
	$m(H^{\pm\pm}) = 850.0$ GeV, $\langle\mu\rangle = 5$			
Total Cross section (fb)	0.061	0.00013	0.09	$\lesssim 10^{-7}$
$p_T(e^+e^+, e^-e^-) > 50.0$ GeV	0.060	0.00013	$\lesssim 10^{-5}$	0.0
$|\eta| < 2.5$	0.060	0.00012	$\lesssim 10^{-5}$	0.0
$m(H^{\pm\pm}) \pm 10$ GeV	0.046	0.00008	0.0	0.0
	$m(H^{\pm\pm}) = 850.0$ GeV, $\langle\mu\rangle = 50$			
Total Cross section (fb)	0.061	0.016	0.09	$\lesssim 10^{-7}$
$p_T(e^+e^+, e^-e^-) > 50.0$ GeV	0.060	0.016	$\lesssim 10^{-5}$	0.0
$|\eta| < 2.5$	0.060	0.016	$\lesssim 10^{-5}$	0.0
$m(H^{\pm\pm}) \pm 10$ GeV	0.046	0.010	0.0	0.0

process are not presented since they are six orders of magnitude smaller than the signal. The background associated to the inclusive DY contribution is evaluated by applying the suppression factors related to the probability of fake double tagging and TOF in the forward detector. As expected, the four lepton production by the QED process $\gamma\gamma \to e^+e^-e^+e^-$ dominates at small invariant mass, below the production threshold of the doubly charged Higgs pair. On the other hand, for $m(4lep) > 2m(H^{\pm\pm})$, one has that this contribution is suppressed by two orders of magnitude in comparison to the signal but is still larger than the corrected DY background.

In Fig. 2 (upper right panel) we present our predictions for the transverse momentum distribution of the e^+e^+ system, denoted by $p_T(e^+e^+)$. One has that the four lepton production by the QED process $\gamma\gamma \to e^+e^-e^+e^-$ dominates at small $p_T(e^+e^+)$, but is strongly suppressed with the increasing of the transverse momentum. In particular, our results indicate that the signal dominates for $p_T(e^+e^+) > 50$ GeV. Moreover, one has that in this kinematical range the signal is larger than the DY contribution by ≈ 2 orders of magnitude. Finally, in Fig. 2 (lower panel) we present our predictions for the rapidity distribution of the e^+e^+ system, denoted by $\eta(e^+e^+)$. One has that for central rapidities $|\eta(e^+e^+)| \leq 2.5$ the signal dominates, with the

QED process becoming competitive only for large values of $|\eta(e^+e^+)|$.

In Table I we present our predictions at the detector level, which have been derived assuming the following cuts: (i) $p_T(e^\pm e^\pm) > 50$ GeV; (ii) that the leptons are in the rapidity range $|\eta| \leq 2.5$, and (iii) that the invariant mass of the dilepton system $m(e^\pm e^\pm)$ is in the range $m(H^{\pm\pm}) \pm 10$ GeV. The results are presented for two values of the doubly charged Higgs and two scenarios for the pileup. One has that the signal and corrected DY cross sections, denoted DY (after DT and TOF) in the Table, decrease for larger values of $m(H^{\pm\pm})$, with the inclusive DY production being the main background. For a small amount of the pileup and $m(H^{\pm\pm}) = 350$ GeV, one has that signal is two orders of magnitude larger than the background, as expected from Fig. 2. Such a conclusion is also valid for $m(H^{\pm\pm}) = 850$ GeV and $\langle\mu\rangle = 5$. In contrast, for a larger amount of pileup, $\langle\mu\rangle = 50$, the difference between signal and background decreases and both cross sections become of the same order of magnitude, with the signal being still larger than the corrected DY prediction.

The previous results allows to estimate the statistical significance and the signal to background ratio, S/B. In order to estimate these quantities, we consider two luminosity scenarios in terms of $\langle\mu\rangle$ and $\mathcal{L}$, where $\langle\mu\rangle$ represents
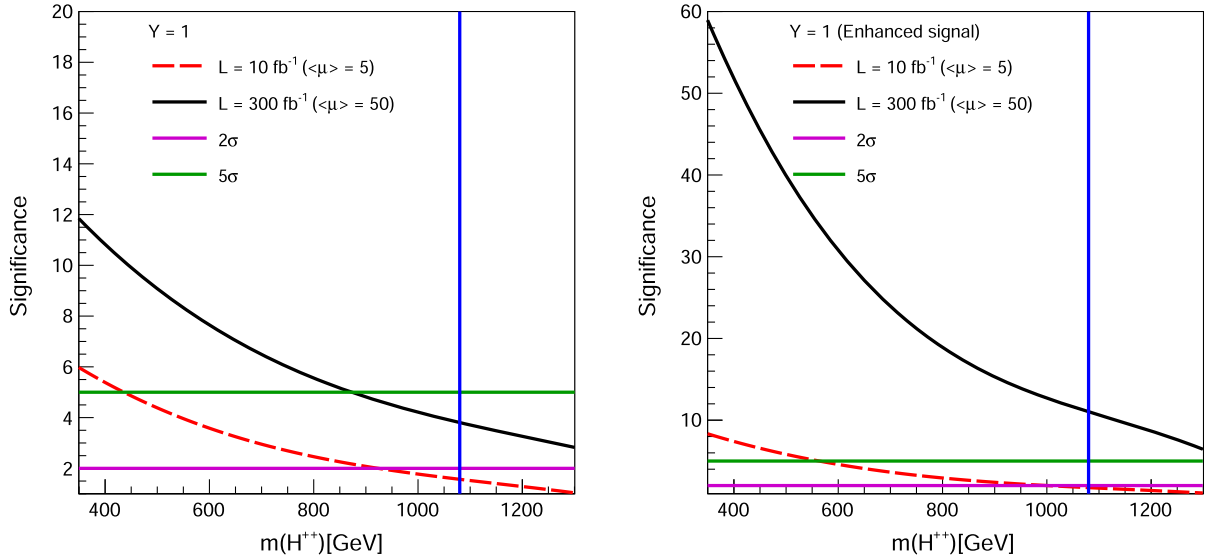
FIG. 3. Mass dependence of the statistical significance for the exclusive doubly charge Higgs production in pp collisions at $\sqrt{s} = 13$ TeV considering two scenarios for the pileup configuration and integrated luminosity ($\langle \mu \rangle, L$) and to distinct scenarios for the background: (a) the standard approach considering the inclusive DY production as a background (left panel), and (b) that the remaining contribution of the inclusive process enhance the number of doubly charged Higgs events (right panel). Results for the Higgs triplet model ($Y = 1$). The vertical black line indicates the current upper value for $m(H^{\pm\pm}) = 1080$ GeV obtained in Ref. [27].

the average number of pileup interactions per event and $\mathcal{L}$ is the integrated luminosity. Moreover, we assume $\mathcal{L}$ to be 10 and 300 fb^{-1} for $\langle \mu \rangle = 5$ and 50, respectively. In addition, the significance will be estimated using the formula based on Asimov data set [91], which is more reliable for $S \approx B$ and reduces to the $S/\sqrt{B}$ ratio if $S \ll B$. The results are presented in Fig. 3 (left panel) as a function of doubly charged Higgs mass. We restrict our study for the mass range $m_{H^{\pm\pm}} \lesssim 1300$ GeV due to the current limitations of the forward detectors, which are not able to measure final states with an invariant mass larger than ≈ 2600 GeV, due to the limited detector angular acceptance for the outgoing protons. Our results indicate that the ATLAS and CMS forward detectors have the potential to detect a $H^{\pm\pm}$ particle with a significance higher than 5σ, if it has a mass up to ~ 870 GeV, and hint at the existence of such a particle, with a significance of at least 3σ, throughout the entire mass range from very small masses up to the limit of $m_{H^{++}} \sim 1300$ GeV, set by the detector acceptance. In the mass window between 870 and 1300 GeV, however, the H^{++} detection would require an independent confirmation from other experiments, possibly from inclusive searches, to cross the 5σ threshold and claim a discovery. In any event, it is clear that a future experimental analysis of the exclusive production at the HL-LHC will be able to improve the current limits on $m_{H^{\pm\pm}}$, obtained by the analysis of inclusive processes that, for an H^{++} belonging to a scalar triplet, are around 1080 GeV [27].

In the previous analysis we have considered the standard approach that the contribution of inclusive processes is a background for the exclusive production. However, as our

goal is to probe the existence of the doubly charged Higgs and determine its mass, the remaining inclusive DY events after the implementation of the exclusive cuts can also be considered as signals of the type II seesaw mechanism. As a consequence, the signal becomes the sum of the exclusive and DY (after DT and TOF) contributions and the statistical significance is enhanced. The associated predictions for this scenario are presented in Fig. 3 (right panel). Our results indicate that, in this scenario, the significance is larger than 5σ for $\langle \mu \rangle = 50$ in the range not yet covered by the inclusive measurements. In what follows, we will restrict our analysis to the standard procedure, but the reader should keep in mind that the predictions for the significance must be considered a pessimistic estimate and represent a lower bound for the number of events that are predicted for the future runs of LHC.

In Fig. 4 we present the results of the standard analysis applied to the cases where the $H^{\pm\pm}$ particle arises from more general $SU(2)_L$ representations, as discussed in the Sec. II. Besides the triplet representation ($Y = 1$) we also analyzed the singlet ($Y = 2$) and doublet ($Y = 3/2$) cases. It is apparent from the plots that the discovery potential for the singlet scenario is very similar to that of the triplet case, discussed above. On the other hand, one can notice a substantial enhancement on the sensitivity for the case of the doublet representation, which enjoys a detection prospect above 5σ in the entire mass range up to 1300 GeV. This result can be understood by looking at the behavior of the H^{++} production cross section via DY and $\gamma\gamma$ fusion processes. Notice that while the $\gamma\gamma$ fusion is indifferent to the multiplet the H^{++} originates from, the DY process
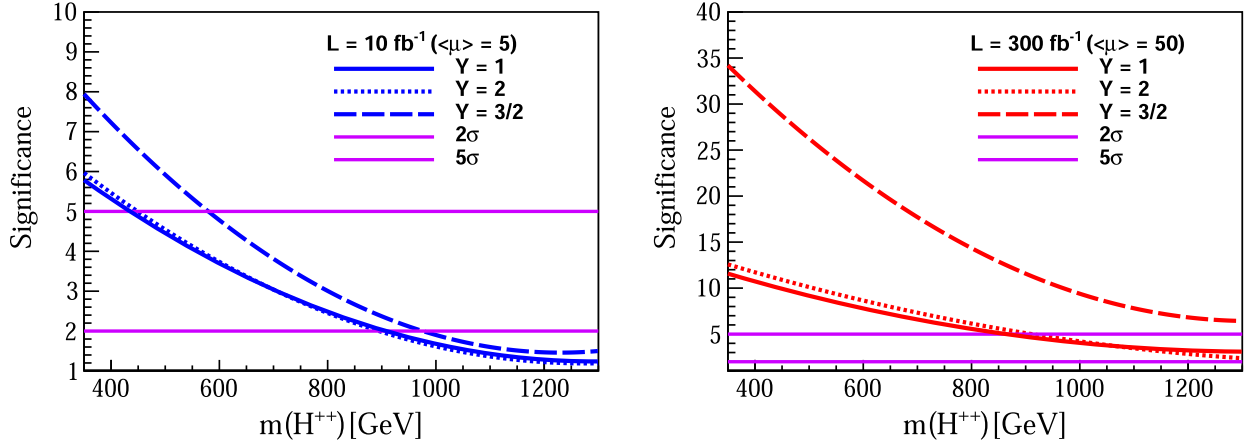
FIG. 4. Mass dependence of the statistical significance for the exclusive doubly charge Higgs production in pp collisions at $\sqrt{s} = 13$ TeV considering distinct $SU(2)_L$ representations and different scenarios for the pileup configuration and integrated luminosity $(\langle\mu\rangle, L)$.

depends on the strength of the $Z_\mu H^{++}\partial^\mu H^{--}$ coupling, which varies for the different multiplets. According to the Eq. (12), we have $\mathcal{C}_{ZH^{++}H^{--}} = \frac{g}{c_W}(2 - Y - 2s_W^2)$, such that $\mathcal{C}_{ZH^{++}H^{--}} = -0.388$ for the singlet, $\mathcal{C}_{ZH^{++}H^{--}} = 0.034$ for the doublet, and $\mathcal{C}_{ZH^{++}H^{--}} = 0.455$ for the triplet. Notice that while the singlet and triplet couplings have similar magnitudes (with opposite signs that, nevertheless, do not affect the final cross section), the coupling in the doublet case is one order of magnitude smaller, leading to a smaller DY production cross section of the H^{++}. Therefore, an even larger suppression of the DY background takes place in the doublet case, as compared to the singlet and triplet cases, thus enhancing the sensitivity. Notice further that, while this small coupling increases the sensitivity of the exclusive search, it operates in the opposite direction for the traditional inclusive searches, insofar as it reduces the number of H^{++} signal events. Therefore, in this particular case of the H^{++} from a scalar doublet, the exclusive search using the forward LHC detectors features a clear advantage compared to the inclusive searches focusing on the central detectors only. As for the other cases, in which the exclusive analysis has a comparable sensitivity compared to the inclusive searches, it is important to emphasize the complementary aspect of this kind of analysis, which has the potential to strengthen the results obtained with the usual inclusive processes, be it a constraint or a discovery.

IV. SUMMARY

One of the challenge problems in particle physics today is the description of the neutrino masses and all neutrino oscillation data. One of the simplest ways to describe these data is provided by the type II seesaw model, which predicts the existence of seven physical Higgs bosons, two of them being doubly charged. Another feature of the type II seesaw model is that the Higgs triplet can be produced directly through gauge interactions with electroweak bosons. Such aspect has motivated the study of the doubly charged Higgs pair production through the Drell-Yan process, where the pair is produced via s-channel γ^*/Z exchange, or via the vector boson fusion processes $\gamma\gamma \to H^{++}H^{--}$ and $ZZ \to H^{++}H^{--}$. In recent years, several experimental studies in high-energy colliders have searched for doubly charged scalar particles and derived bounds on the $H^{\pm\pm}$ mass. Distinctly from previous studies, which focused on inclusive reactions, in this paper we have proposed the study of exclusive processes as an alternative to searching for the doubly charged Higgs. As demonstrated in our analysis, although the associated cross sections are smaller than those predicted for the inclusive reactions, the very clean final state and possibility of tagging of the intact protons in the final states and the reduction of the impact of the pileup using the time-of-flight detectors, makes feasible the study of the exclusive $H^{++}H^{--}$ production in pp collisions at the LHC. In particular, we have shown that the ATLAS and CMS forward detectors can extend the H^{++} searches towards higher masses, complementing and improving the current limits obtained by the inclusive processes.

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