PROCEEDINGS OF SCIENCE

Production of charged Higgs boson pairs in the $pp \to ppH^+H^-$ reaction at the LHC and FCC

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We present differential cross sections for the $pp \to ppH^+H^-$ reaction via photon-photon fusion with exact kinematics. We show predictions for $\sqrt{s}$ = 14 TeV (LHC) and at the Future Circular Collider (FCC) for $\sqrt{s}$ = 100 TeV. The integrated cross section for $\sqrt{s}$ = 14 TeV (LHC) is about 0.1 fb and about 0.9 fb at the FCC for $\sqrt{s}$ = 100 TeV when assuming $m_{H^\pm} = 150$ GeV. We present distributions in diHiggs boson invariant mass. The results are compared with those obtained within equivalent-photon approximation. We discuss also first calculations of cross section for exclusive diffractive pQCD mechanism with estimated limits on the $g_{hH^+H^-}$ coupling constant within 2HDM based on the LHC experimental data. The diffractive contribution is much smaller than the $\gamma\gamma$ one. Absorption corrections are calculated differentially for various distributions. In general, they lead to a damping of the cross section. The damping depends on $M_{H^+H^-}$ invariant mass and on four-momentum transfers squared in the proton line. We discuss a possibility to measure the exclusive production of $H^\pm$ bosons.

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1. Introduction

There are extensive phenomenological studies of exclusive processes in search for effects beyond the Standard Model. The Higgs sector in both the MSSM and 2HDM contains five states: three neutral [two CP-even (h, H) and one CP-odd (A)] and two charged (H^+, H^-) Higgs bosons. In general, either h or H could correspond to the SM Higgs. Discovery of the heavy Higgs bosons of the Minimal Supersymmetric Standard Model (MSSM) or more generic Two-Higgs Doublet Models (2HDMs) poses a special challenge for future colliders. One of the international projects currently under consideration is the Future Circular Collider (FCC) [1].

The main advantage of exclusive processes is that background contributions are strongly reduced compared to inclusive processes. A good example are searches for exclusive production of supersymmetric Higgs boson [2], anomalous boson couplings for $\gamma\gamma \to W^+W^-$ [3] or for $\gamma\gamma \to \gamma\gamma$ [4]. So far these processes are usually studied in the so-called equivalent-photon approximation (EPA), see e.g. [5]. Within the Standard Model the cross section for the $pp \to ppW^+W^-$ reaction is about 100 fb at $\sqrt{s} = 14$ TeV [6]. The exclusive two-photon induced reactions could be also used in searches for neutral technipion in the diphoton final state [7]. Gluon-induced processes could also contribute to the exclusive production of W^+W^- [6], $W^\pm H^\mp$ [8], H^+H^- [9] via quark loops. However, the corresponding cross sections are rather small mainly due to suppression by Sudakov form factors and the gap survival factor.

2. Formalism

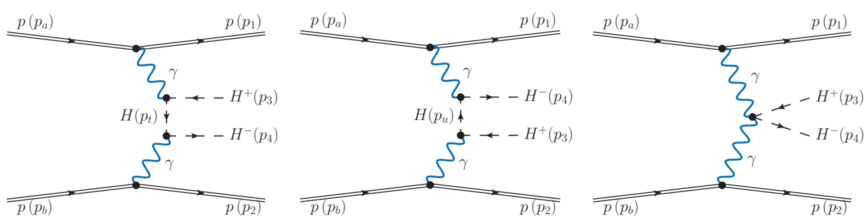

Figure 1: Born diagrams for exclusive production of H^+H^- pairs in pp-collisions via $\gamma\gamma$ exchanges.

We consider the exclusive production of charged Higgs bosons discussed recently in [9]

$$p(p_a,\lambda_a) + p(p_b,\lambda_b) \to p(p_1,\lambda_1) + H^+(p_3) + H^-(p_4) + p(p_2,\lambda_2)\,, \qquad (2.1)$$

where $p_{a,b}$, $p_{1,2}$ and $\lambda_{a,b}$, $\lambda_{1,2} = \pm\frac{1}{2}$ denote the four-momenta and helicities of the protons, and $p_{3,4}$ denote the four-momenta of the charged Higgs bosons, respectively. In general, the cross section for the considered exclusive $2 \to 4$ process (2.1) can be written as

$$d\sigma = \frac{(2\pi)^4}{2s}\overline{|\mathscr{M}_{pp\to ppH^+H^-}|^2}\frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\delta^4\left(E_a+E_b-p_1-p_2-p_3-p_4\right)\,, \qquad (2.2)$$

where energy and momentum conservations have been made explicit [1].

The full amplitude for the $pp \to ppH^+H^-$ reaction is

$$\mathscr{M}_{pp\to ppH^+H^-} = \mathscr{M}^{\rm Born}_{pp\to ppH^+H^-} + \mathscr{M}^{\rm absorption}_{pp\to ppH^+H^-}\,, \tag{2.3}$$

where the Born amplitudes via $\gamma\gamma$ exchanges (see diagrams of Fig. 1) are calculated as

$$\mathscr{M}^{Born}_{\lambda_a\lambda_b\to\lambda_1\lambda_2H^+H^-}(t_1,t_2) = V^{\mu_1}_{\lambda_a\to\lambda_1}(t_1)D_{\mu_1\nu_1}(t_1)V^{\nu_1\nu_2}_{\gamma\gamma\to H^+H^-}D_{\nu_2\mu_2}(t_2)V^{\mu_2}_{\lambda_b\to\lambda_2}(t_2)\,, \tag{2.4}$$

where $D_{\mu\nu}(t) = -ig_{\mu\nu}/t$ is the photon propagator. The γpp vertex takes the form

$$V^{(\gamma pp)\mu}_{\lambda\to\lambda'}(t) = e\,\bar{u}(p',\lambda')\left(\gamma^\mu F_1(t) + \frac{i}{2m_p}\sigma^{\mu\nu}(p'-p)_\nu F_2(t)\right)u(p,\lambda)\,, \tag{2.5}$$

where $u(p,\lambda)$ is a Dirac spinor and p,λ and p',λ' are initial and final four-momenta and helicities of the protons, respectively. In the high-energy approximation one gets the simple formula

$$V^{(\gamma pp)\mu}_{\lambda\to\lambda'}(t) \simeq e\left(\frac{\sqrt{-t}}{2m_p}\right)^{|\lambda'-\lambda|} F_i(t)(p'+p)^\mu\,. \tag{2.6}$$

The tensorial vertex in Eq. (2.4) for the $\gamma\gamma\to H^+H^-$ subprocess is a sum of three-level amplitudes corresponding to t, u and contact diagrams of Fig. 1,

$$V^{\nu_1\nu_2}_{\gamma\gamma\to H^+H^-} = ie^2\frac{(q_2-p_4+p_3)^{\nu_1}(q_2-2p_4)^{\nu_2}}{p_t^2-m_H^2} + ie^2\frac{(q_1-2p_4)^{\nu_1}(q_1-p_4+p_3)^{\nu_2}}{p_u^2-m_H^2} - 2ie^2g^{\nu_1\nu_2}\,, \tag{2.7}$$

where $p_t^2 = (q_2-p_4)^2 = (q_1-p_3)^2$ and $p_u^2 = (q_1-p_4)^2 = (q_2-p_3)^2$.

The amplitude including pp-rescattering corrections between the initial- and final-state protons in the four-body reaction discussed here can be written as

$$\mathscr{M}^{\rm absorption}_{\lambda_a\lambda_b\to\lambda_1\lambda_2H^+H^-}(s,\mathbf{p}_{1t},\mathbf{p}_{2t}) = \frac{i}{8\pi^2 s}\int d^2\mathbf{k}_t\;\mathscr{M}_{\lambda_a\lambda_b\to\lambda'_a\lambda'_b}(s,-\mathbf{k}_t^2)\;\mathscr{M}^{\rm Born}_{\lambda'_a\lambda'_b\to\lambda_1\lambda_2H^+H^-}(s,\tilde{\mathbf{p}}_{1t},\tilde{\mathbf{p}}_{2t})\,, \tag{2.8}$$

where $\tilde{\mathbf{p}}_{1t} = \mathbf{p}_{1t} - \mathbf{k}_t$ and $\tilde{\mathbf{p}}_{2t} = \mathbf{p}_{2t} + \mathbf{k}_t$. Here $\mathbf{p}_{1t}$ and $\mathbf{p}_{2t}$ are the transverse components of the momenta of the final-state protons and $\mathbf{k}_t$ is the transverse momentum carried by additional pomeron exchange. $\mathscr{M}_{pp\to pp}(s,-\mathbf{k}_t^2)$ is the elastic pp-scattering amplitude for large s and with the momentum transfer $t = -\mathbf{k}_t^2$.

The photon induced processes are treated usually in the equivalent-photon approximation (EPA) in the momentum space, see e.g. [6, 7, 9]. [2] In this approximation, when neglecting photon transverse momenta, one can write the differential cross section as [3]

$$\frac{d\sigma}{dy_3dy_4d^2p_{tH}} = \frac{1}{16\pi^2\hat{s}^2}x_1f(x_1)x_2f(x_2)\overline{|\mathscr{M}_{\gamma\gamma\to H^+H^-}|^2}\,, \tag{2.9}$$

[1] The details on how to conveniently reduce the number of kinematic integration variables are discussed in [10]. Above $\overline{|\mathscr{M}|^2}$ is the $2\to4$ amplitude squared averaged over initial and summed over final proton polarization states. The phase space integration variables are taken the same as in [10], except that proton transverse momenta p_{1t} and p_{2t} are replaced by $\xi_1 = \log_{10}(p_{1t}/p_{0t})$ and $\xi_2 = \log_{10}(p_{2t}/p_{0t})$, respectively, where p_{0t} = 1 GeV.

[2] An impact parameter EPA was considered recently in [11]. Only very few differential distributions can be obtained in the EPA approach.

[3] An approach including transverse momenta of photons was discussed recently in [12].

where $\hat{s} = sx_1x_2$ and $f(x)$'s are elastic fluxes of the equivalent photons (see e.g.[5]) as a function of longitudinal momentum fraction with respect to the parent proton defined by the kinematical variables of the charged Higgs bosons: $x_1 = \frac{m_{tH}}{\sqrt{s}}(e^{y_3}+e^{y_4})$, $x_2 = \frac{m_{tH}}{\sqrt{s}}(e^{-y_3}+e^{-y_4})$, $m_{tH} = \sqrt{|\vec{p}_{tH}|^2 + m_H^2}$. $\overline{|\mathscr{M}|^2}$ is the $\gamma\gamma \to H^+H^-$ amplitude squared averaged over the γ polarization states.

3. Results

In Fig. 2 we show invariant mass distribution of the H^+H^- system in a broad range of the invariant masses. In the left panel we compare results for the exact kinematics and for the EPA calculations. In contrast to inclusive processes, the exclusive reaction (2.1) is free of the model parameter uncertainties, at least in the leading order, except of the mass of the Higgs bosons. In the right panel we show the dependence of absorption on $M_{H^+H^-}$. This is quantified by the ratio of full (with the absorption corrections) and Born differential cross sections $\langle S^2(M_{H^+H^-})\rangle$. The values of the gap survival factor $\langle S^2\rangle$ for different masses of $H^\pm$ bosons $m_{H^\pm} = 150, 300, 500$ GeV are, respectively, $0.77, 0.67, 0.57$ for $\sqrt{s} = 14$ TeV (LHC) and $0.89, 0.86, 0.82$ for $\sqrt{s} = 100$ TeV (FCC). In contrast to diffractive processes, the larger the collision energy, the smaller the effect of absorption.

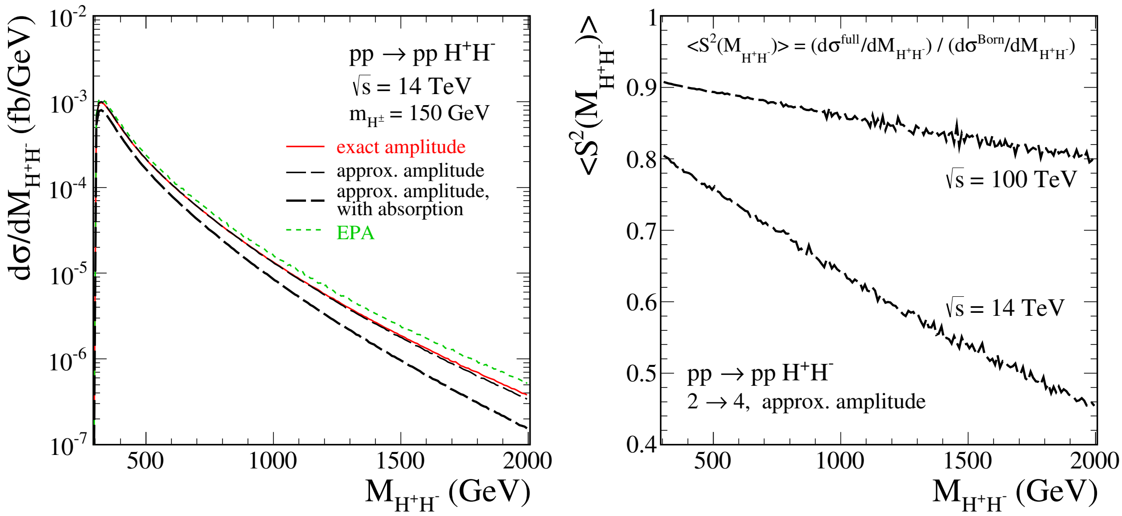

Figure 2: In the left panel we show diHiggs boson invariant mass distribution at $\sqrt{s} = 14$ TeV. The red solid line represents the calculation for exact $2 \to 4$ kinematics and amplitude (including spinors of protons, see Eq. (2.5)). The black upper and lower long-dashed lines correspond to calculations in the high-energy approximation Eq. (2.6) without and with the absorption corrections, respectively. The green short-dashed line represents results of EPA, see Eq. (2.9). In the right panel we show the dependence of the gap survival factor due to pp interactions on $M_{H^+H^-}$ for exact $2 \to 4$ kinematics for the LHC and FCC energies.

So far we have considered a purely electromagnetic process, the contribution of which is model independent. In Fig. 3 we show also corresponding results for the diffractive contribution for $m_{H^\pm} = 150$ GeV including the "effective" gap survival factor $\langle S^2\rangle = 0.03$ for $\sqrt{s} = 14$ TeV (left panel) and $\sqrt{s} = 100$ TeV (right panel). The $g^*g^* \to H^+H^-$ hard subprocess amplitude for the diffractive KMR mechanism through the t-loop and s-channel SM Higgs boson (h^0) is given by

$$V_{g^*g^* \to H^+H^-} = V_{gg \to h} \frac{i}{s_{34} - m_h^2 + i m_h \Gamma_h} g_{hH^+H^-} \tag{3.1}$$

and enters into $\mathscr{M}_{pp \to ppH^+H^-}$ invariant $2 \to 4$ amplitude for the diffractive process as in [13, 6]. The triple-Higgs coupling constant $g_{hH^+H^-}$ is model dependent. In the MSSM model it depends only on the parameters α and β. In the general 2HDM it depends also on other parameters such as the Higgs potential λ-parameters or masses of Higgs bosons. In addition to the result for the 2HDM set of parameters (alignment limit, $\beta - \alpha \approx \pi/2$), we also show result with the upper limit $g_{hH^+H^-} = 1000$ GeV. The corresponding couplings in the MSSM are smaller than 50 GeV. One can observe from Fig. 3 that the cross section for the exclusive diffractive process is much smaller than that for $\gamma\gamma$ mechanism both for LHC and FCC.

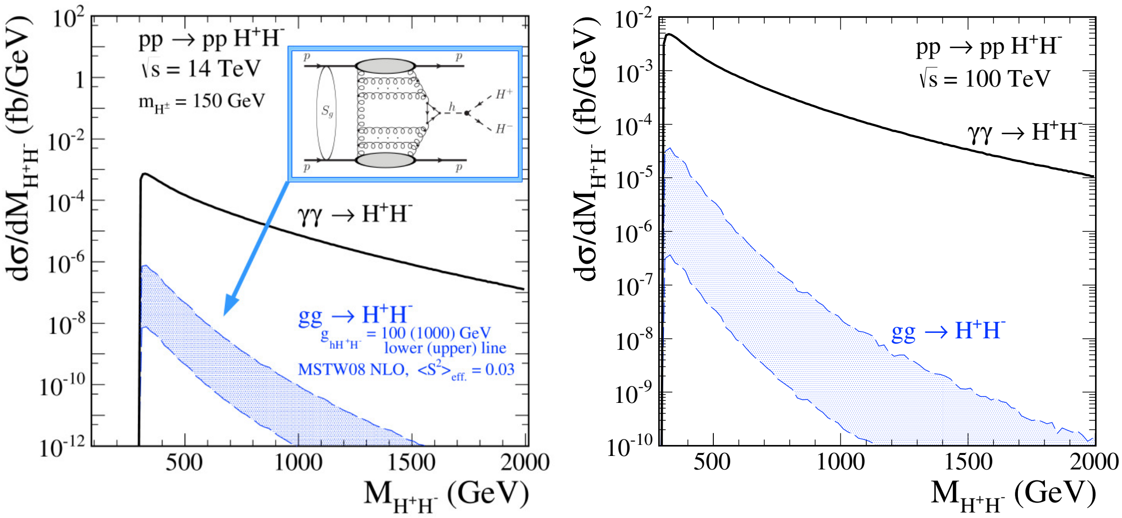

Figure 3: DiHiggs boson invariant mass distributions at $\sqrt{s} = 14$ TeV (left panel) and 100 TeV (right panel). The short-dashed (online green) lines represent results of EPA. The upper lines represent the $\gamma\gamma$ contribution. We also show contribution of the diffractive mechanism (the shaded area) for the MSTW08 NLO collinear gluon distribution [14] and $g_{hH^+H^-} = 100$ (1000) GeV for the lower (upper) limit.

4. Conclusions

We have discussed the exclusive $pp \to ppH^+H^-$ process at the LHC and FCC. Results of our exact ($2 \to 4$ kinematics) calculations have been compared with those for the equivalent-photon approximation for observables accessible in EPA. We wish to emphasize that some correlation observables in EPA are not realistic, or even not accessible, to mention here only correlations in azimuthal angle between the outgoing protons or the charged Higgs bosons. We have studied the absorption effects due to proton-proton nonperturbative interactions. The absorptive effects lead to a reduction of the cross section. We have found interesting dependence of the absorption on $M_{H^+H^-}$. The relative effect of absorption is growing with growing $M_{H^+H^-}$. We have predicted that the absorption effects for our two-photon-induced process become weaker at larger collision energy which is in contrast to the typical situation for diffractive exclusive processes. Our study shows that an assumption of no absorption or constant (independent of phase space) absorption, often assumed in the literature for photon-photon-induced processes, is rather incorrect.

In addition to calculating differential distributions corresponding to the $\gamma\gamma$ mechanism we have performed first calculations of the H^+H^- invariant mass for the diffractive KMR mechanism. We have tried to estimate limits on the $g_{hH^+H^-}$ coupling constant within 2HDM based on recent analyses related to the Higgs boson discovery. The diffractive contribution, even with the overestimated $|g_{hH^+H^-}|$ coupling constant, gives a much smaller cross section than the $\gamma\gamma$ mechanism.

Whether the $pp \to ppH^+H^-$ reaction can be identified at the LHC (run 2) or FCC requires further studies including simulations of the $H^\pm$ decays. Two $H^\pm$ decay channels seem to be worth studying in the case of light $H^\pm$: $H^\pm \to \tau^+\nu_\tau(\tau^-\bar{\nu}_\tau)$ or $H^\pm \to c\bar{s}(\bar{c}s)$. The first decay channel may be difficult due to a competition of the $pp \to ppW^+W^-$ reaction which can also contribute to the $\tau^+\tau^-$ channels. Although the branching fraction $W^+ \to \tau^+\nu_\tau$ or $W^- \to \tau^-\bar{\nu}_\tau$ is only about $\frac{1}{9}$, it is expected to be a difficult irreducible background because of the relatively large cross section for the $pp \to ppW^+W^-$. In the second case (four quark jets), one could measure invariant masses of all dijet systems to reduce the W^+W^- background. In the case of the heavy $H^\pm$ Higgs boson, the $H^\pm \to t\bar{b}(\bar{t}b)$ decay can be considered. In principle, both the t quark and b jet can be measured. In contrast to the previous case we do not know about any sizeable irreducible background.

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