New Method for Detecting Charged Scalars at Colliders

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We propose a new method for detecting a charged (pseudo)scalar at colliders, based upon the observation that its Yukawa coupling to charm and bottom quarks can be large due to a significant mixing of the top and charm quarks. After analyzing the typical flavor mixing allowed by low energy data in the topcolor and the generic two-Higgs doublet models, we study the physics potential of the Tevatron, LHC, and linear colliders for probing such an s-channel charged resonance via the single-top (as well as $W^{\pm}h^0$) production. We show that studying its detection at colliders can also provide information on the dynamics of flavor-changing neutral current phenomena.

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The large mass of the top quark (t) suggests that it may play a special role in the dynamics of the electroweak symmetry breaking (EWSB) and/or the flavor symmetry breaking. The topcolor models [1,2] and the supersymmetric theories with radiative breaking [3] are two such examples, in which the Higgs sector generically contains at least two (composite or fundamental) scalar doublets and hence predicts the existence of physical charged (pseudo)scalars as an unambiguous signal beyond the standard model (SM). We point out that a large flavor mixing (FM) between the right-handed top and charm quarks can induce a large FM Yukawa coupling of a charged (pseudo)scalar with charm (c) and bottom (b) quarks. This is different from the usual Cabibbo-Kobayashi-Maskawa (CKM) mixing which involves only left-handed fermions in the charged weak current. Furthermore, when the neutral scalar (ϕ^0) and the charged scalar ($\phi^{\pm}$) form an SU(2) doublet, the weak isospin symmetry connects the flavor-changing neutral coupling (FCNC) ϕ^0-t-c to the flavor-mixing charged coupling (FMCC) $\phi^{\pm}$-c-b through the CKM matrix. Hence, a direct measurement of the FMCC at high energy colliders can also provide information on the FCNC, which may give better constraint than that inferred from the low energy kaon and bottom physics.

In this Letter, we show that with a large FMCC $\phi^{\pm}$-c-b, $\phi^{\pm}$ can be copiously produced via the s-channel partonic process $c\bar{b}, \bar{c}b \rightarrow \phi^{\pm}$ at colliders, such as the Fermilab Tevatron, CERN Large Hadron Collider (LHC), and electron/photon linear colliders (LCs). After analyzing the production rates of $\phi^{\pm}$ as a function of its mass m_{ϕ} and its coupling strength to the c and b quarks, we discuss the typical range of these parameters (allowed by the low energy data) in the topcolor model (TopC) [1] and the generic two-Higgs doublet model (2HDM) [4,5]. We show that with a significant mixing between the right-handed top and charm quarks, a sizable coupling of $\phi^{\pm}$-c-b can be induced from a top-mass-enhanced $\phi^{\pm}$-t-b Yukawa coupling, so that Tevatron can probe the charged top-pion mass up to $\sim$300–350 GeV in the TopC model, LHC can probe the mass range of charged Higgs bosons up to $\sim O(1)$ TeV, and the high energy $\gamma\gamma$ LCs can also be sensitive to such a production mechanism.

s-channel production of charged (pseudo)scalars.—With a large FM coupling of $\phi^{\pm}$-t-b, it is possible to study the charged scalar or pseudoscalar $\phi^{\pm}$ via the partonic s-channel production mechanism, $c\bar{b}, \bar{c}b \rightarrow \phi^{\pm}$. Defining the $\bar{q}$-q'-$\phi^{\pm}$ coupling as $C_L\hat{L} + C_R\hat{R}$ in which $\hat{L}(\hat{R}) = (1 \mp \gamma_5)/2$, we derive the total cross section for ϕ^+ production at hadron colliders as

$$\sigma[h_1h_2(c\bar{b}) \rightarrow \phi^+X] = \frac{\pi}{12S}(|C_L|^2 + |C_R|^2)\int_{\ln\sqrt{\tau_0}}^{-\ln\sqrt{\tau_0}} dy[f_{c/h_1}(x_1, Q^2)f_{\bar{b}/h_2}(x_2, Q^2) + (c \leftrightarrow \bar{b})], \quad (1)$$

where $\sqrt{S}$ is the collider energy, $\tau_0 = m_{\phi}^2/s$, $x_{1,2} = \sqrt{\tau_0}\,e^{\pm y}$, and $f_{q/h}(x, Q^2)$ is the parton distribution function (PDF) with Q the factorization scale (chosen as m_{ϕ}). Similarly, we can derive the cross section formula for $e^-e^+(\gamma\gamma) \rightarrow \phi^+\bar{c}b$ and $\gamma\gamma \rightarrow \phi^+\bar{c}b$ at electron and photon linear colliders. For the e^-e^+ process we have used the Williams-Weizsacker equivalent photon approximation. The present analysis for the signal event is confined to the tree level, and the CTEQ4L PDFs are used for hadron collisions. The complete next-to-leading order (NLO) QCD correction [including the $b(c)$-gluon fusions] will improve the numerical results but will not change our main conclusion [6].

To illustrate the $\phi^{\pm}$ production rates at various colliders, we consider its Yukawa couplings to be the typical values of TopC models [cf. Eqs. (6) and (7) below]: $C_L^{tb} = C_L^{cb} = 0$ and $C_R^{tb} = y_{t0}\tan\beta$, $C_R^{cb} \simeq C_R^{tb} \times 0.2$, with $y_{t0} = \sqrt{2}m_t/v$, $\tan\beta \simeq 3$, and $v \simeq 246$ GeV, which serves as a benchmark of our general analysis. In Fig. 1 we plot the s-channel resonance cross section versus the mass of $\phi^{\pm}$ at hadron and electron/photon colliders. For $m_{\phi} = 200$ (1000) GeV at the 1.8 and

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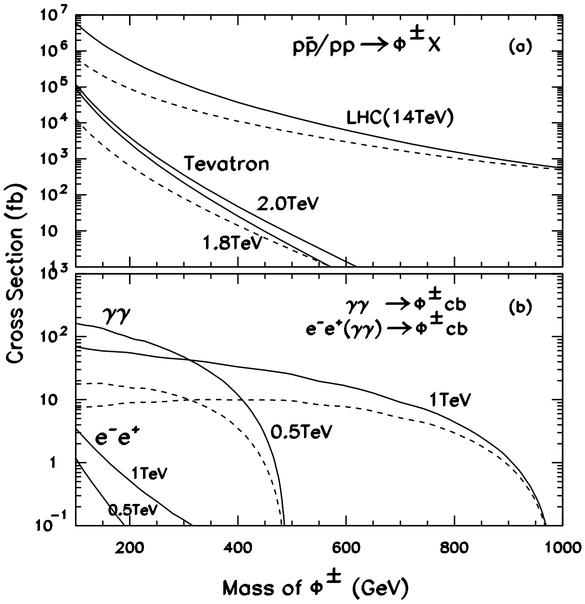

FIG. 1. The s-channel $\phi^{\pm}$ production with the benchmark parameter choice of TopC models. As a reference, dashed curves show the results at Tevatron (2 TeV), LHC, and $\gamma\gamma$ LCs, with top-pion Yukawa couplings satisfying the roughly estimated 3σ R_b bound [7] (reanalyzed with new $R_b^{\rm exp}$ data).

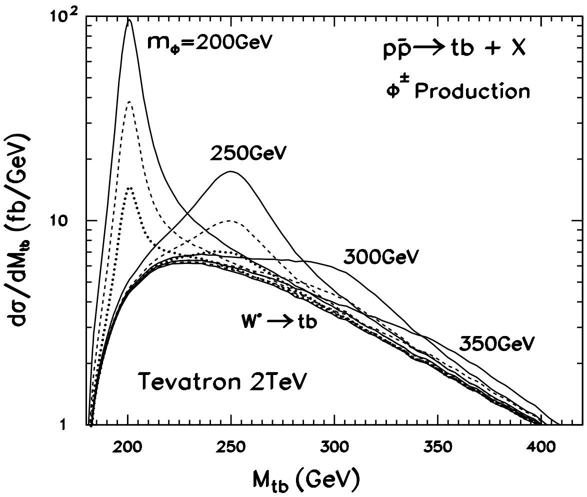

FIG. 2. tb invariant-mass distribution of charged top-pion production, with its Yukawa coupling constrained by the estimated 3σ R_b bound. The (solid, dashed, dotted) curves are plotted for $C_R^{cb} = C_R^{tb} \times (0.33, 0.2, 0.11)$, corresponding to three typical values of t_R-c_R mixing parameter K_{UR}^{tc} in Eq. (6).

2 TeV Tevatron (14 TeV LHC), the total cross sections are 2.7 and 4.0 (0.55) pb, respectively. The production rates, calculated from a complete gauge invariant set of c-b fusion diagrams, are also large at the γ-γ LCs. (Here, we do not include the production of the $\phi^{\pm}$ pair with one scalar decaying into bc, whose cross section is large for $m_\phi \ll \sqrt{S}/2$.) It is trivial to rescale our results to other values of $C_{L,R}$. For instance, the typical couplings of the generic 2HDM [cf. Eqs. (9) and (10)] are $C_L^{tb} = C_L^{cb} \simeq 0$ and $C_R^{tb} = \xi_{tt}^U$, $C_R^{cb} \simeq \xi_{tc}^U \times 9\%$. Taking the sample value $\xi_{tc}^U \sim 1.5$, we find that a typical prediction of this 2HDM can be obtained from rescaling the solid curves in Fig. 1 by a factor of $1/19$.

For $m_\phi > 190$ GeV, the dominant decay mode of $\phi^{\pm}$ can be the $t\bar{b}$ pair, which is the case for TopC-type models (cf. Fig. 3). Therefore, $\phi^{\pm}$ may be detected via single-top production. The $\phi^{\pm}$ production rate at the Tevatron drops very fast for $m_\phi \geq 300$ GeV and becomes comparable with the SM s-channel single-top rate, via $q\bar{q}' \to W^* \to t\bar{b}, \bar{t}b$. [The NLO W^* rate is about 0.70, 0.86, and 11.0 pb at the 1.8, 2 TeV Tevatron and the 14 TeV LHC, respectively. Although the t-channel single-top rate (via Wg fusion) is larger [8], its event topology is different from the s-channel single-top event. Therefore, we compare only the $\phi^{\pm}$ signal rate with the W^* rate.] Thus, an analysis on the distribution of the t-b (or W-b-$\bar{b}$) invariant mass will ensure the identification of $\phi^{\pm}$ due to its resonance peak (cf. Fig. 2). The Tevatron Run I data (at 1.8 TeV) may already put important bounds on some parameter space of m_ϕ and $C_{L,R}$.

Flavor-mixing and top-pion $\pi_t^{\pm}$ production in TopC.— The topcolor scenario [1,9] is attractive because it explains the large top quark mass and provides possible dynamics of the EWSB. Such type of models generally predict light composite (pseudo)scalars with large Yukawa coupling to the third family. This induces distinct new FM phenomena which can be tested at both low and high energies. In the typical topcolor-I class of models [10], three light pseudoscalars, called top pions, are predicted with masses around of $O(150-300)$ GeV. The up(down)-type quark mass matrices $M_U(M_D)$ exhibit an approximate triangular texture due to the generic top-color breaking pattern [10]. For generality, we can write

$$M_U = \begin{pmatrix} m_{11} & m_{12} & \delta_1 \\ m_{21} & m_{22} & \delta_2 \\ \delta_3 & \delta_4 & m_t' \end{pmatrix}, \quad (2)$$

where the small nondiagonal pieces $\delta_{1,2} = O(\epsilon^4)v$, $\delta_{3,4} = O(\epsilon)v$ and thus the 33 element m_t' is very close to the physical top mass m_t. Here, $\epsilon = O(\langle\Phi\rangle/\Lambda_0)$, with Λ_0 being the breaking scale of a larger group down to the topcolor group, and the vacuum expectation value $\langle\Phi\rangle$ being the topcolor breaking scale. So, we expect $\epsilon < 1$. A proper rotation of the quarks from weak eigenstates into mass eigenstates will diagonalize M_U and M_D, so that $K_{UL}^{\dagger} M_U K_{UR} = M_U^{\rm dia}$ and $K_{DL}^{\dagger} M_D K_{DR} = M_D^{\rm dia}$, from which the CKM matrix can be derived as $V = K_{UL}^{\dagger} K_{DL}$. We show that it is possible to construct a realistic but simple pattern of the left-handed rotation matrices K_{UL} and K_{DL} such that (i) the Wolfenstein parametrization [11] of CKM is reproduced, (ii) Cabibbio mixing is mainly generated from K_{DL} while the mixings between the 3rd and 2nd families are mainly from K_{UL}, (iii) all dangerous contributions to low energy data (such as the K-$\overline{K}$, D-$\overline{D}$, and B-$\overline{B}$ mixings and the $b \to s\gamma$ rate) can be evaded. In fact, point (ii) may help to explain the successful empirical relations $\lambda \approx \sqrt{m_d/m_s}$ and $V_{cb} \approx \sqrt{m_c/m_t}$, where λ is the Wolfenstein parameter. By introducing the unitary matrices K_{UL} and K_{DL},

$$K_{UL} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c & -sx \\ 0 & sx^* & c \end{pmatrix}, \quad K_{DL} = \begin{pmatrix} c_\phi & s_\phi c_\theta & s_\phi s_\theta y \\ -s_\phi & c_\phi c_\theta & c_\phi s_\theta y \\ 0 & -y^* s_\theta & c_\theta \end{pmatrix}, \tag{3}$$

with $|x| = |y| = 1$ and $s_j^2 + c_j^2 = 1$, we find the solution to reproduce Wolfenstein parametrization:

$$\begin{aligned} & c, c_\theta = 1 + O(\lambda^4), \quad c_\phi = 1 - \tfrac{\lambda^2}{2}, \quad s_\phi = \lambda + O(\lambda^3), \\ & s = \lambda^2 A[(1-\rho)^2 + \eta^2]^{1/2}, \quad s_\theta = \lambda^2 A[\rho^2 + \eta^2]^{1/2}, \\ & x = (1 - \rho + i\eta)/[(1-\rho)^2 + \eta^2]^{1/2}, \\ & y = (\rho - i\eta)/[\rho^2 + \eta^2]^{1/2}, \end{aligned} \tag{4}$$

where $\lambda \simeq 0.22$, $A \simeq 0.82$, and $\sqrt{\rho^2 + \eta^2} \simeq 0.43$. Given the matrices M_U, K_{UL} and the known $M_U^{\rm dia} = {\rm diag}(m_u, m_c, m_t)$, the right-handed rotation matrix K_{UR} is constrained, and the matrix elements

$$K_{UR}^{tt} \simeq \frac{m_t'}{m_t}, \qquad K_{UR}^{tc} \le \sqrt{1 - K_{UR}^{tt\,2}}. \tag{5}$$

For the reasonable values of $\delta m_t = m_t - m_t' = O(1\text{–}10\ \text{GeV})$, (5) gives

$$K_{UR}^{tt} = 0.99\text{–}0.94, \qquad K_{UR}^{tc} \le 0.11\text{–}0.33, \tag{6}$$

which shows that the t_R-c_R transition can be naturally around 10%–30%. [It also requires $\delta_{1,2}(= O(\epsilon^4)v) = O(\text{GeV})$, which suggests $\epsilon = O(0.2\text{–}0.4)$.] Since the mass hierarchy in the down-quark sector is much smaller than that in M_U, the mass pattern of M_D is taken to be less restrictive. It is easy to check that the above $K_{UL,DL}$ and K_{UR} satisfy the requirement of point (iii), in contrast to the naive $\sqrt{\text{CKM}}$ ansatz [10]. [The $b \to s\gamma$ rate also has a contribution $C_7'(M_W)$ depending on K_{DR}^{bs} [10]. Since the pattern of M_D is less certain in this model, we take K_{DR}^{bs} more or less free, e.g., a simple $\sqrt{\text{CKM}}$ ansatz for K_{DR} can already accommodate $B(b \to s\gamma)_{\rm exp}$ data [10].]

The relevant FM vertices including the large t_R-c_R transition for the top pions can be written as

$$\begin{aligned} \frac{m_t \tan\beta}{v} \Big[& iK_{UR}^{tt}K_{UL}^{tt*}\overline{t_L}t_R\pi_t^0 + \sqrt{2}\,K_{UR}^{tt*}K_{DL}^{bb}\overline{t_R}b_L\pi_t^+ \\ & + iK_{UR}^{tc}K_{UL}^{tt*}\overline{t_L}c_R\pi_t^0 + \sqrt{2}\,K_{UR}^{tc*}K_{DL}^{bb}\overline{c_R}b_L\pi_t^+ \\ & + \text{h.c.}\Big], \end{aligned} \tag{7}$$

where $\tan\beta = \sqrt{(v/v_t)^2 - 1}$ and $v_t \simeq O(60\text{–}100)$ GeV is the top-pion decay constant. An important feature is that the charged top pion $\pi_t^\pm$ mainly couples to the right-handed top (t_R) or charm (c_R) but not the left-handed top (t_L) or charm (c_L), in contrast to the standard W-t-b coupling which involves only t_L. Note that $\pi_t^\pm$ also has a topcolor-instanton induced coupling with t_L, of the strength $\sqrt{2}m_b^\star/v_t$ [1], which is much suppressed by $m_b^\star \le m_b \ll v_t$. The tiny left-handed rotation element $|K_{UL}^{tc}| = s \approx 2\%\text{–}4\%$ [cf. (3) and (4)] further makes the c_L-b_R coupling to $\pi_t^\pm$ negligible. Hence, the produced top quark from $\phi^\pm$-t-b interaction is close to 100% right-handed polarized, and measuring the top polarization in the single-top event provides further identification of the signal. Equation (7) suggests that the neutral top pion π_t^0 can be produced in association with the single top via charm-gluon fusion, i.e., $cg, \bar{c}g \to t\pi_t^0, \bar{t}\pi_t^0$. However, due to the limited Tevatron energy, the t-π_t^0 production is feasible only at the LHC. This is similar to a study [12] for the 2HDM, but a much larger signal rate for π_t^0 is expected because of the enhanced π_t^0 Yukawa coupling. Typically, for $m_{\pi_t^\pm} > m_t + m_b$ the main decay channels of $\pi_t^\pm$ are tb and cb. The total decay width and the branching ratios (BRs) of $\pi_t^\pm$ are shown in Fig. 3, separately, in which we have assumed that the tb and cb pairs are the only two available decay channels of $\pi_t^\pm$ up to 1 TeV, though the top pion is not expected to be very heavy. [Note that the mass splitting $m_{\pi_t^\pm} - m_{\pi_t^0}$ may be larger than M_W in a certain parameter region so that the $\pi_t^\pm \to W\pi_t^0$ channel can become important as well. This will make the pattern of BRs for $\pi_t^\pm$ decay similar to that of $H^\pm$ decay in the 2HDM [cf. Fig. 3(b).]] From Figs. 1 and 3, we can estimate the single-top event rates at various colliders. For the 1.8 and 2.0 TeV Tevatron (14 TeV LHC) with 0.1 and 2 (100) fb^{-1} luminosity and $m_\phi = 200$ (500) GeV, we find the numbers of single t and $\bar{t}$ events to be 153 and 4.5×10^3 (1.4×10^6), while for the 0.5 (1.0) TeV photon-photon ($\gamma\gamma$) LC with a 50 (500) fb^{-1} luminosity the rate becomes 2.9×10^3 (1.2×10^4) for $m_\phi = 200$ (500) GeV. (If top decays semileptonically, a branching ratio of 21% for $t \to bW(\to \ell\nu_\ell)$, with $\ell = e$ or μ, should be included.)

Flavor-mixing and charged Higgs production in 2HDM.—The 2HDM is the simplest extension of the SM and its supersymmetrization results in the popular minimal supersymmetric SM (MSSM). In contrast to the MSSM,

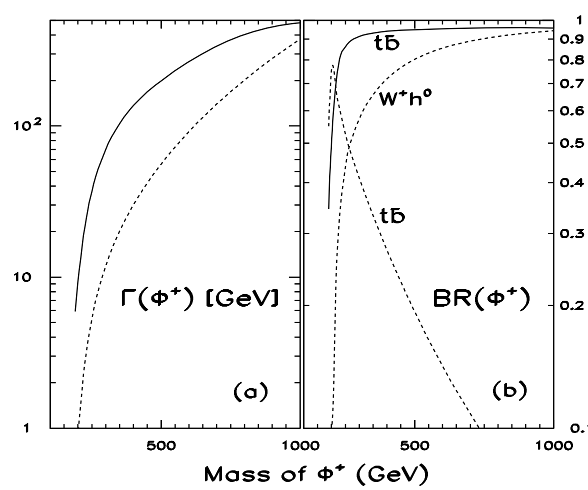

FIG. 3. Total decay widths (a) and branching ratios (b) of $\pi_t^\pm$ in the TopC model (solid curve), and of $H^\pm$ in the 2HDM (dashed curve) for the typical parameter choice in the text.

the general 2HDM has potentially dangerous tree-level flavor-changing neutral currents. Under the reasonable ansatz for the structure of the Higgs Yukawa couplings [cf. (10)], the pattern for the FM Yukawa couplings may be naturally generated from the quark-mass hierarchy, which sufficiently suppresses the FCNC for the light generations while predicting significant mixings between the charm and top quarks. The generic 2HDM considered here is called "type-III" [4,5], which does not make use of the *ad hoc* discrete symmetry [13]. The FM Yukawa couplings can be conveniently formulated under a proper basis of Higgs doublets such that $\langle\Phi_1\rangle = (0, v/\sqrt{2})^T$ and $\langle\Phi_2\rangle = (0,0)^T$. Thus, the diagonalization of the fermion mass matrix also diagonalizes the Yukawa couplings of Φ_1, and all the FM couplings are generated by Φ_2. The Yukawa interaction of the quark sector can be written as

$$-\mathcal{L}_Y^q = \frac{\sqrt{2}}{v}[M_{ij}^U \overline{Q_{iL}}\tilde{\Phi}_1 u_{jR} + M_{ij}^D \overline{Q_{iL}}\Phi_1 d_{jR}] + [Y_{ij}^U \overline{Q_{iL}}\tilde{\Phi}_2 u_{jR} + Y_{ij}^D \overline{Q_{iL}}\Phi_2 d_{jR}] + \text{h.c.} \quad (8)$$

Here the Higgs boson states are $(H_1^0, H_2^0, A^0, H^\pm)$ and the CP-even neutral states (H_1^0, H_2^0) rotate into the mass eigenstates (h^0, H^0), characterized by the mixing angle α. The t-b-$H^\pm$ and c-b-$H^\pm$ interactions are

$$H^+[\overline{t_R}(\hat{Y}_U^\dagger V)_{tb} b_L - \overline{t_L}(V\hat{Y}_D)_{tb} b_R] + H^+[\overline{c_R}(\hat{Y}_U^\dagger V)_{cb} b_L - \overline{c_L}(V\hat{Y}_D)_{cb} b_R] + \text{h.c.}, \quad (9)$$

where $\hat{Y}^{U(D)} = K_{U(D)L}^\dagger Y^{U(D)} K_{U(D)R}$ and V is the CKM matrix. The couplings $\hat{Y}_{ij}^{U,D}$ thus contain all new FM effects and exhibit a natural hierarchy under the ansatz [4,5]

$$\hat{Y}_{ij}^{U,D} = \xi_{ij}^{U,D}\sqrt{m_i m_j}/\langle\Phi_1\rangle \quad (10)$$

with $\xi_{ij}^{U,D} \sim O(1)$. Equation (10) shows that the t-c or c-t transition gives the largest FM coupling while the FMs without involving the top quark are highly suppressed by the light quark masses. Such a suppression is shown to persist at high energy scales according to a recent renormalization group analysis [14]. From (9) and (10), we deduce $(\hat{Y}_U^\dagger V)_{cb} \simeq \hat{Y}_{tc}^{U*}V_{tb} + \hat{Y}_{cc}^{U*}V_{cb} \simeq \hat{Y}_{tc}^{U*}$ and $(V\hat{Y}_D)_{cb} \simeq \hat{Y}_{sb}^D \ll \hat{Y}_{tc}^{U*}$. Therefore, the dominant FM vertex c-b-$H^\pm$ involves $c_R b_L$ but not $c_L b_R$. It was found [5] that low energy data allow $\xi_{tc}^U, \xi_{ct}^U \sim O(1)$ and require $m_{h,H} \le m_\pm \le m_A$ or $m_A \le m_\pm \le m_{h,H}$, where $m_\pm$ is the mass of $H^\pm$ and $m_{h,H,A}$ the masses of (h^0, H^0, A^0). (The Higgs mixing angle α is not constrained.) For $m_\pm > m_t + m_b$, $H^\pm$ can decay into the tb and cb pairs. If $m_\pm > M_W + m_h$ or $m_\pm > M_W + m_A$, then additional decay channels, such as $H^\pm \to W^\pm h^0, W^\pm A^0$, should also be considered. The total decay width and the branching ratios of $H^\pm$ for a typical parameter set of $(\xi_{tt}^U, \xi_{tc}^U) = (1, 1.5)$, $m_h = 120$ GeV, $m_A \ge m_\pm$, and $\alpha = 0$ are shown in Fig. 3, separately. [We have verified that the choice of $\xi_{tt}^U = 1$ is consistent with the current 3σ R_b bound for $m_\pm \ge 120$ GeV. Choosing a larger value of $\xi_{tt}^U > 1$ will simultaneously increase (reduce) the BR of the tb (Wh^0) mode.] At the 14 TeV LHC with a 100 fb^{-1} luminosity and for $m_\phi = 300$ (800) GeV, about 1.3×10^5 (384) single-top and 1.8×10^5 (4.1×10^3) Wh^0 events will be produced, while the 0.5 (1.0) TeV $\gamma\gamma$ LC with a 50 (500) fb^{-1} luminosity can produce about 52 (131) single-top and 73 (545) Wh^0 events for $m_\phi = 300$ (500) GeV. From Fig. 3(b), we note that the tb and the $W^\pm h^0$ decay modes are complementary in low and high mass ranges of $H^\pm$, though the details may depend on the values of (m_h, m_A) and α. Therefore, in this model it is possible to detect $H^\pm$ in either the single-top or the $Wh^0(\to b\bar{b}, \tau\tau)$ event.

In summary, the s-channel production mechanism proposed in this work provides a unique probe of the charged (pseudo)scalars at the hadron and electron/photon colliders. We focus on probing the s-channel charged scalar or pseudoscalar via single-top production (as well as Wh^0), which is generic for the TopC model and the type-III 2HDM. For other models (such as supersymmetric theories), the leptonic decay channel (e.g., $\tau\nu_\tau$ mode) may become significant as well, and thus should be included. At the upgraded Tevatron, we show that under the typical flavor-mixing pattern of the TopC models, the charged top-pion mass can be explored up to ~300–350 GeV, while the LHC can probe the charged Higgs mass up to $\sim O(1)$ TeV for the 2HDM. The linear colliders, especially the $\gamma\gamma$ collider, will be effective for this purpose even at its early phase with $\sqrt{S} = 500$ GeV. For the MSSM, supersymmetry forbids tree-level FCNCs, and the small FMCCs are described by the usual CKM mixings. However, a large FMCC may be induced at the loop level, depending on the soft-breaking parameters of the model. Work along this line is in progress.

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