Precise photoproduction of the charged top-pions at the LHC with forward detector acceptances

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Abstract We study the photoproduction of the charged top-pion predicted by the top triangle moose (TTM) model (a deconstructed version of the topcolor-assisted technicolor TC2 model) via the processes \( pp \to p\gamma p \to \pi^\pm t + X \) at the 14 TeV Large Hadron Collider (LHC) including next-to-leading order (NLO) QCD corrections. Our results show that the production cross sections and distributions are sensitive to the free parameters \( \sin \omega \) and \( M_{\pi^\pm} \). A typical QCD correction value is \( 7^{−11} \% \) and this does not depend much on \( \sin \omega \) as well as the forward detector acceptances.

1 Introduction

The top quark is the heaviest known elementary particle, which makes it an excellent candidate for new physics searches. The origin of its mass might be different from that of the other quarks and leptons; a top quark condensate \( \langle t\bar{t} \rangle \), for example, could be responsible for at least part of the mechanism of electroweak symmetry breaking (EWSB). An interesting model involving a role for the top quark in dynamical EWSB is known as the topcolor-assisted technicolor (TC2) model [1–3]. Higgsless models [4] have emerged as a novel way of understanding the mechanism of EWSB without the presence of a scalar particle in the spectrum. Recently, combing Higgsless and topcolor mechanisms, a deconstructed Higgsless model was proposed, called the top triangle moose (TTM) model [5,6]. In this model, EWSB results largely from the Higgsless mechanism, while the top quark mass is mainly generated by the topcolor mechanism. The TTM model alleviates the tension between obtaining the correct top quark mass and keeping \( \Delta \rho \) small that exists in many Higgsless models, which can be seen as the deconstructed version of the TC2 model. The new physics models belonging to the topcolor scenario generally have two sources of EWSB and there are two sets of Goldstone bosons. One set is eaten by the electroweak (EW) gauge bosons \( W \) and \( Z \) to generate their masses, while the other set remains in the spectrum, which is called the top-pions \( \pi^0 \) and \( \pi^\pm \). The topcolor scenario also predicts the existence of the top-Higgs \( h^0 \), which is the \( t\bar{t} \) bound state. The possible signals of these new scalar particles have been extensively studied in the literature, however, most studies have been done in the context of the TC2 model. A phenomenological analysis of the top-pions and top-Higgs predicted by the TTM model [5–7] is necessary.

The Large Hadron Collider (LHC) generates high-energetic proton–proton \( (pp) \) collisions with a luminosity of \( \mathcal{L} = 10^{34} \) cm\(^{-2}\) s\(^{-1}\). It provides high statistics data at high energies. On the other hand hadronic interactions generally involve serious backgrounds. A new phenomenon called exclusive production was observed in the measurements of CDF collaboration including exclusive lepton pair production [8,9], photon–photon production [10], dijet production [11], exclusive charmonium \( (J/\psi) \) meson photoproduction [12], etc. Complementary to \( pp \) interactions, studies of exclusive production of leptons, photons, and heavy particles might be possible and this opens a new field of studying very high-energy photon–photon \( (\gamma\gamma) \) and photon–proton \( (\gamma p) \) interactions.

Following the experience from HERA and the Tevatron, new detectors are proposed to be installed in the LHC tunnel as an additional upgrade of the ATLAS and CMS detectors. There is a program of studying forward physics with extra detectors located in a region nearly 100–400 m from the interaction point [13–17]. Technical details of the ATLAS Forward Physics (AFP) projects can be found, for example, in Ref. [18]. This forward detector equipment allows one to detect intact scattered protons after the collision. There-

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fore the processes which spoil the proton structure can easily be discerned from the exclusive photoproduction processes. By the use of forward detector equipment we can eliminate many serious backgrounds. This is one of the advantages of exclusive photoproduction processes.

A brief review of the experimental prospects for studying high-energy $\gamma\gamma$ and $\gamma p$ interactions is discussed in Ref. [19] and cross sections are calculated for many EW and BSM processes. Many phenomenological studies of photon-produced processes are summarized here, involving: standard model productions [20–22], supersymmetry [23–28], extra dimensions [29–31], unparticle physics [32], gauge boson self-interactions [33–42], neutrino electromagnetic properties [43–45], top quark physics [21,22,46–48], and triplet Higgs production [49], etc.

Photoproduction of the charged top-pion at leading order (LO) has been studied in Refs. [50,51], which proceeds via the subprocess $\gamma c \to \pi_t^+b$ mediated by the flavor changing couplings and through $\gamma b \to \pi_t^+t$ at the large hadron-electron collider (LHeC) [52]. At the LHC, in a general $pp$ collision, the charged top-pion can be produced in association with a top quark through bottom–gluon fusion, $gb \to t\pi_t^-$, and through gluon–gluon fusion, $gg \to bt\pi_t^-$, phenomenologically similar to a charged Higgs boson in a two-Higgs-doublet model with low tan $\beta$. A related NLO study can be found in Ref. [53]. On the other hand, $\pi_t^\pm t$ associated production at the $\gamma p$ collision LHC will be very clean or at least with backgrounds easy going, thus leading to a good chance to be detected. It can be a complementary process to be studied in addition of $gb \to t\pi_t^-$. In this paper, we present this production at the $\gamma p$ collision assuming a typical LHC multipurpose forward detector. Accurate theoretical predictions including higher order QCD corrections are included. This paper is organized as follows: in Sect. 2 we present a brief introduction to the calculation framework including the TTM model description, EPA implementation, and LO and NLO cross section calculations. Section 3 is arranged to present numerical checks and results of our studies. Finally we summarize the conclusions in the last section.

2 Calculation framework

2.1 The essential features of the TTM model

The detailed description of the TTM model can be found in Refs. [5,6], and here we just briefly review its essential features which are related to our calculation. The EW gauge structure of the TTM model is $SU(2)_L \times SU(2)_R \times U(1)_{X}$. The nonlinear sigma field $\sum_{01}$ breaks the group $SU(2)_0 \times SU(2)_1$ down to $SU(2)$ and field $\sum_{12}$ breaks $SU(2)_1 \times U(1)_2$ down to $U(1)$. To separate top-quark mass generation from EWSB, a top-Higgs field $\Phi$ is introduced to the TTM model, which couples preferentially to the top quark. To ensure that most of EWSB comes from the Higgsless side, the VEVs of the fields $\sum_{01}$ and $\sum_{12}$ are chosen to be $(\sum_{01}) = (\sum_{12}) = F = \sqrt{2}v\cos\omega$, in which $v = 246$ GeV is the EW scale and $\omega$ is a new small parameter. The VEV of the top-Higgs field is $f = (\Phi) = v\sin\omega$.

From the above discussions, we can see that, for the TTM model, there are six scalar degrees of freedom on the Higgsless sector and four on the top-Higgs sector. Six of these Goldstone bosons are eaten to give masses to the gauge bosons $W^\pm$, $Z$, $W'^\pm$ and $Z'$. The others remain as physical states in the spectrum, which are called top-pions ($\pi_t^\pm$ and $\pi_t^0$) and top-Higgs ($h_t^0$). In this paper, we will focus our attention on photoproduction of the charged top-pions via $\gamma p$ collisions at the LHC. The couplings of the charged top-pions $\pi_t^\pm$ to ordinary particles, which are related to our calculation, are given by Ref. [6]:

$$\mathcal{L}_{\pi_t^{\pm}b} = i\lambda_t \cos \omega \left\{ 1 - \frac{x^2[a^4 + (a^4 - 2a^2 + 2)\cos 2\omega]}{8(a^2 - 1)^2} \right\} \times \pi_t^\pm \bar{t}_R b_L + \text{h.c.,}$$

(1)

with

$$\lambda_t = \frac{\sqrt{2m_t}}{v\sin\omega} \left[ \frac{M_D^2(\epsilon_t^2 + 1) - m_t^2}{M_D^2 - m_t^2} \right],$$

$$a = \frac{v\sin\omega}{\sqrt{2}M_D}, \quad x = \sqrt{2}\epsilon_t = \frac{2\cos\omega M_W}{M_{W'}}.$$  

(2)

Here we assume the CKM matrix to be the identity and we omit the light quark masses. $M_D$ is the mass scale of the heavy fermion and $M_{W'}$ is the mass of the new gauge boson $W'$. Since the top quark mass depends very little on the right-handed delocalization parameter $\epsilon_t$, we have set $\epsilon_t = 0$ in Eq. (1). The parameter $\epsilon_L$ describes the degree of delocalization of the left-handed fermions and is flavor universal, the parameter $x$ represents the ratio of the gauge couplings. The relationship between $\epsilon_L$ and $x$, which is given in Eq. (2), is imposed by ideal delocalization.

Reference [54] has shown that $M_{W'}$ should be larger than 380 GeV, as demanded by the LEPII data and smaller than 1.2 TeV by the need to maintain perturbative unitarity in $W_tW_L$ scattering. It is obvious that the coupling $\pi_t^{\pm}b$ is not very sensitive to the parameters $M_{W'}$ and $M_D$. Thus, the production cross sections of the subprocesses $\gamma b \to t\pi_t^-$ and $\gamma b \to t\pi_t^+$ are not strongly dependent on the values of the mass parameters $M_{W'}$ and $M_D$. In our following numerical calculation, we will take the illustrative values $M_{W'} = 500$ GeV and $M_D = 400$ GeV. In this case, we have $[M_D^2(\epsilon_t^2 + 1) - m_t^2]/(M_D^2 - m_t^2) \approx 1$ and Eq. (1) can be approximately written as

$$\mathcal{L}_{\pi_t^{\pm}b} \approx i\frac{\sqrt{2}m_t}{v} \cot \omega \pi_t^\pm \bar{t}_R b_L + \text{h.c.}$$

(3)
with
\[ C = 1 - \frac{x^2[a^4 + (a^4 - 2a^2 + 2) \cos 2\omega]}{8(a^2 - 1)^2}. \]

It is obvious that the constant C is not sensitive to the value of \( \sin \omega \) and its value is close to 1. The parameter \( \sin \omega \) indicates the fraction of EWSB provided by the top condensate. The top-pion mass \( M_\pi \) depends on the amount of top-quark mass arising from the extended technicolor (ETC) sector and on the effects of EW gauge interactions [55, 56], and thus its value is model-dependent. In the context of the TTM model, Ref. [6] has obtained the constraints on the top-pion mass via studying its effects on the relevant experimental observables. Similarly to Refs. [6, 57], we will assume it as a free parameter.

2.2 Equivalent photon approximation (EPA)

In \( \gamma p \) collisions, the quasi-real photons are emitted from protons with very low virtuality so that it is a good approximation to assume that they are on-mass-shell. These quasi-real photons are scattered with small angles and low transverse momentum. At the same time, protons emitting photons remain intact and are not spoilt. Intact protons thus deviate slightly from their trajectory along the beam path without being detected by central detectors. Deflected protons and their energy loss will be detected by the forward detectors with a very large pseudorapidity. Photons emitted without being detected by central detectors. Deflected protons and their energy loss will be detected by the forward detectors with a very large pseudorapidity. Photons emitted with small angles by the incoming proton beam, which is related to the quasi-real photon energy by \( E_\gamma = \xi E \), and \( M_p \) is the mass of the proton. \( \xi = (|p| - |p'|)/|p| \), where \( p \) and \( p' \) are the momenta of incoming protons and intact scattered protons, respectively. \( \mu_p^2 = 7.78 \) is the magnetic moment of the proton. \( F_E \) and \( F_M \) are functions of the electric and magnetic form factors.

In this case, if both incoming emitted protons remain intact, that provides the \( \gamma \gamma \) collision and it can be cleaner than the \( \gamma p \) collision; however, \( \gamma p \) collisions have higher energy and effective luminosity with respect to \( \gamma \gamma \) interactions.

2.3 The cross sections up to NLO

We denote the parton level process as \( \gamma (p_1)b(p_2) \to \pi^-_t(p_3)t(p_4) \) where \( p_i \) are the particle four momenta. The hadronic cross section at the LHC can be converted by integrating \( \gamma b \to \pi^+_t \) over the photon \( (dN(x, Q^2)) \) and quark \( (G_{bp}(x, \mu_f)) \) spectra:

\[
\frac{d\sigma}{d\Phi} = \int \int d\Phi \rho. \]
Fig. 2 The QCD one-loop Feynman diagrams for the partonic process $\gamma b \rightarrow \pi^- t t$ (a–h). Counterterm diagrams corresponding to Fig. 1 are not shown here.

Fig. 3 Some the tree level Feynman diagrams for the real gluon/light-(anti)quark emission subprocess $\gamma b \rightarrow \pi^- t g$ related to the first process in Eq. 7 (a–f) and $\gamma g \rightarrow \pi^- t \bar{t}$ related to the second process in Eq. 7 (g, h).

fields as $\psi_{q,L,R}^{0} = (1 + \delta Z_{\psi_{q,L,R}}) \frac{1}{2} \psi_{q,L,R}$. In the modified minimal subtraction ($\overline{MS}$) renormalization scheme the renormalization constants for the massless quarks, and massive top quark (defined on shell) are expressed as

$$
\delta Z_{\psi_{q,L,R}} = -\frac{\alpha_s}{4\pi} C_F (\Delta_{UV} - \Delta_{IR}), \delta Z_{\psi_{q,R}} = -\frac{\alpha_s}{4\pi} C_F (\Delta_{UV} - \Delta_{IR}), \delta m_t = \frac{3}{16\pi} [3\Delta_{UV} + 4], \Delta_{UV,IR} = \frac{1}{\epsilon_{UV,IR}} \Gamma(1 + \epsilon_{UV,IR})(4\pi)^{\epsilon_{UV,IR}}
$$

referring to the UV and IR divergences, respectively. By adding a renormalization part to the virtual corrections, any UV singularities are regulated leaving soft/collinear IR singularities untouched. These IR singularities will be removed by combining the real emission corrections. Singularities associated with initial state collinear gluon emission are absorbed into the definition of the parton distribution functions. We adopt TCPSS to isolate the IR singularities by introducing two cutoff parameters $\delta_s$ and $\delta_c$. An arbitrary small $\delta_s$ separates the three-body final state phase space into two regions: the soft region ($E_5 \leq \delta_s \sqrt{\hat{s}}/2$) and the hard region ($E_5 > \delta_s \sqrt{\hat{s}}/2$). The quantity $\delta_c$ separates the hard region into the hard collinear (HC) region and hard noncollinear (HN) region. The criterion for separating the HC region is described as follows: the region for real gluon/light-(anti)quark emission with $\hat{s}_{ij} < \delta_c \hat{s}$ is called the HC region. Otherwise it is called the HN region which in our case is related to

$$
\gamma(p_1)b(p_2) \rightarrow \pi^- (p_3)t(p_4)g(p_5),
\gamma(p_1)g(p_2) \rightarrow \pi^- (p_3)t(p_4)\bar{b}(p_5), \quad (7)
$$

corresponding to real gluon emission and real light-(anti)quark emission partonic processes, respectively. After combining all these contributions, the UV and IR singularities in $\sigma_{total} = \sigma_{Born} + \sigma_{loop} + \sigma_{S} + \sigma_{HC} + \sigma_{HN}$ are exactly canceled. The dependence on the arbitrary small cutoff parameters $\delta_s$ and $\delta_c$ then vanishes. These cancelations can be verified numerically in our numerical calculations.
3 Numerical results and discussions

We use FeynArts, FormCalc, and our modified LoopTools (FFL) [62–64] packages to perform the numerical calculation. We use CT10 [65] for the parton distributions for collider physics and BASES [66,67] to do the phase space integration. We use CT10 [65] for the parton distributions for col-

• Scenario 1: \(M_D = 400 \text{ GeV}, \sin \omega = 0.5, M_W = 500 \text{ GeV}, M_{\pi_t} = 400 \text{ GeV}\); 
• Scenario 2: \(M_D = 400 \text{ GeV}, \sin \omega = 0.2, M_W = 500 \text{ GeV}, M_{\pi_t} = 200 \text{ GeV}\),

corresponding to high (low) \(M_{\pi_t}\) regions, respectively. The detected acceptances are chosen to be [69,70]:

• \(\xi_1\): CMS-TOTEM forward detectors with \(0.0015 < \xi < 0.5\);
• \(\xi_2\): CMS-TOTEM forward detectors with \(0.1 < \xi < 0.5\);
• \(\xi_3\): AFP-CMS forward detectors with \(0.0015 < \xi < 0.15\).

Before presenting the numerical predictions, several checks should be done. First, The UV and IR safeties are verified numerically after combining all the contributions at the QCD one-loop level. We display random phase space points as well as the cancelation for different divergent parameters with the help of OneLoop [71] to compare with our modified LoopTools. Second, when doing the phase space integration, we use Kaleu [72] to cross check especially for the hard emission contributions. Third, since the total cross section is independent of the soft cutoff \(\delta_s = \Delta E_{X}/E_{X}, E_{X} = \sqrt{s}/2\) and the collinear cutoff \(\delta_c\), trivial efforts should be made to check such independence. Fourth, the scale \(\mu\) dependence should be reduced after considering the NLO corrections. Indeed, our results show that the scale uncertainty can be reduced significantly. Choosing the input scenario 1 as an example, if \(\mu\) varies from \(1/8\mu_0\) to \(\mu_0\), the LO cross section varies from 3.2 to 6 fb, while NLO predictions stay much flatter between 5.5 and 6.4 fb. For more details, see Fig. 4, where we show the scale \(\mu\) dependence of the LO and NLO QCD loop-corrected cross sections for \(pp \rightarrow p\gamma p \rightarrow \pi^- t + X\). In the further numerical calculations, we fix \(\delta_s = 10^{-4}\), \(\delta_c = \delta_s/50\) and choose \(\mu = \mu_0 = M_t\).

3.1 Cross sections and distributions

In Fig. 5 we present the cross sections (the left panel) for NLO predictions and the K-factor (the right panel) defined as \(K = \sigma^{\text{NLO}}/\sigma^{\text{LO}}\) for \(pp \rightarrow p\gamma p \rightarrow \pi^- t + X\) as functions of different values of the input parameters in the TTM model. One is \(\sin \omega\) and the other is the top-pion mass \(M_{\pi_t}\). Here we choose the detector acceptance as 0.0015 < \(\xi < 0.5\). The other parameters related to the TTM model are chosen to be \(M_D = 400 \text{ GeV}\) and \(M_W = 500 \text{ GeV}\). The total cross section is sensitive to the input parameter \(\sin \omega\). When \(\sin \omega\) becomes larger, the cross sections reduce obviously. The same behavior can be found for the charged top-pion mass \(M_{\pi_t}\). When the mass becomes heavier, the phase space of the final states is suppressed, thus leading lower cross sections. The right panel presents the K-factor dependence on \(\sin \omega\) and \(M_{\pi_t}\). No matter how \(\sin \omega\) changes, the K-factor does not change much.
Fig. 5 Cross sections (the left panel) for NLO predictions and K-factor (the right panel) defined as $\sigma^{NLO}/\sigma^{LO}$ for $pp \to p\gamma p \to \pi^- t + X$ as functions of different values of the parameters in TTM models at 14 TeV LHC. Here we choose $0.0015 < \xi < 0.5$. The other parameters related to TTM models are chosen to be $M_D = 400$ GeV, $M_{\gamma'} = 500$, with $\sin \omega$ varying from 0.2 to 0.8 and $M_{\pi^-}$ from 200 to 400 GeV, respectively, and the other TTM model input parameters are chosen to be as in scenario 2.

Fig. 6 Cross sections for LO and NLO predictions for $pp \to p\gamma p \to \pi^- t + X$ as functions of the different values of the $\xi$ detector acceptances at the 14 TeV LHC. Here we fix $\xi_{min} = 0.0015$ and take $\xi_{max}$ as a running parameter from 0.15 to 1. The left panel is in units of fb with a fixed top-pion mass. While for $M_{\pi^-}$ becoming larger from 200 to 400 GeV, the K-factor grows up step-by-step, however, not very much, we see, from 1.07 to 1.1, leading to NLO QCD corrections up to around 7–11 % within our chosen parameters.

To see how the cross sections depend on the detector acceptances, in Fig. 6 we fix $\xi_{min} = 0.0015$ and take $\xi_{max}$ as a running parameter. Cross sections for the two input scenarios are presented as $\xi_{max}$ running from 0.15 to 1. The left panel presents results for scenario 1 with dotted and dot-dotted lines for LO and NLO, while the right panel is for scenario 2 with solid and dashed lines for LO and NLO predictions, respectively. From these panels, we can see, for $\xi_{max} < 0.5$, that the cross section enhances rapidly when the $\xi$ acceptances become larger. The case is different for $\xi_{max} > 0.5$ where few contributions contribute. Furthermore, no matter how the detector acceptances change, the ratio of $\sigma^{NLO}$ to $\sigma^{LO}$ does not change much. Typical values of the K-factor equal to 1.09 for scenario 1, and 1.07 for scenario 2 lead to the NLO QCD loop corrections up to 9 and 7 % and keep unchanged as functions of running $\xi$. However, to avoid misleading ideas, we show Fig. 6 in order to see the dependence on $\xi_{max}$ with fixed $\xi_{min}$. If we change the choice of $\xi_{min}$, for example, from 0.0015 to 0.1, the results, i.e., the cross section of the signal at LO and NLO, the K-factor, will change to other values.

We present the transverse momentum ($p_T$) and rapidity ($y$) distributions for the charged top-pion in Fig. 7. For $p_T^{\pi^-}$, the NLO predictions can clearly enhance the LO distributions around the peak range and the same behavior can be found for the $p_T^{\pi^-}$ distributions. It will be interesting to see $y^{\pi^-}$ where the NLO corrections can shift the LO rapidity obviously in the way of moving the position where $y^{\pi^-}$ peaked. Take 0.0015 $< \xi < 0.5$ as an example, the distribution $y^{\pi^-}$ peaked at $y = -0.18$ for LO while the NLO predictions move the LO $y^{\pi^-}$ peak to $y = -0.42$ but there is no obvious enhancement to the LO predictions.
3.2 Signal background analysis and parameter sensitivity

Now let us turn to the signal and background analysis. From Ref. [6] we see that, for $M_{H_t} \geq 300$ GeV and $M_{\ell}\leq 600$ GeV, the charged top-pions $\pi^-_t$ dominantly decay into $\overline{t}b$ and we have $Br(\pi^-_t \rightarrow \overline{t}b) > 90\%$. As for the mass of $M_{H_t}$ to become higher, the validity of this statement is no longer independent of the mass of, for example, the top-Higgs, $M_{H_t}$. However, for each value of $\sin \omega$, a specific range of masses for the top-Higgs is excluded by the Tevatron data. For example, taking the illustrative value $\sin \omega = 0.5$, the data implies that the mass range $140$ GeV $< M_{H_t} < 195$ GeV is excluded. Here we concentrate on the case where $M_{H_t} \geq 350$ GeV. Even though, as the mass $M_{\ell}\leq 600$ GeV, the decay mode $\pi^\pm \rightarrow W^\pm H_t$ becomes more and more competitive, where the assumption of a branching ratio $Br(\pi^-_t \rightarrow \overline{t}b) < 90\%$ should be considered. We concentrate on the $\pi^-_t \rightarrow \overline{t}b(\pi^-_t \rightarrow \overline{t}b)$ decay modes in this case. In this case, photoproduction of the charged top-pion associated with a top quark can easily be transferred to the $\overline{t}b$ final state through

$$pp \rightarrow p\gamma p \rightarrow \pi^-_t t \rightarrow \overline{t}bW^+ b \rightarrow W^--\overline{b}bW^+ b \rightarrow \ell^+ \ell^- \overline{b}b E_T$$

and thus gives rise to the $\ell^+ \ell^- \overline{b}b E_T$ signature via $\gamma b$ collisions at the LHC.

The backgrounds appear in two kinds of processes. The first, called irreducible background, comes from photoproduction with a very similar final state as the signal. The second has the same final state but occurs through different processes induced by partonic interactions and is called a reducible background. The key difference between photoproduction and partonic interactions at the LHC lies in the absence of color exchange on the photon side. This causes an important zone of rapidity to be completely devoid of hadronic activity; it is called a large rapidity gap (LRG) and it is a natural way to distinguish photoproduction and partonic backgrounds. In the framework of EPA, emitted quasi-real photons from the protons have a low virtuality and are scattered with small angles from the beam pipe. Therefore when a proton emits a quasi-real photon it should also be scattered with a small angle. Hence, intact scattered protons exit the central detector without being detected. This causes a decrease in the energy deposit in the corresponding forward region compared to the case in which the proton remnants are detected by the calorimeters. Consequently, for any reaction like $pp \rightarrow p\gamma p \rightarrow pX$, one of the forward regions of the central detector shows a significant lack of energy. The region with a lack of energy (or equivalently lack of particles) defines a forward LRG. Backgrounds from the usual $pp$ deep inelastic processes can be rejected by applying a selection cut on this quantity.

In addition, another tagging method based on the same physics properties of photoproduction events is to place an exclusivity condition on the reconstructed particle tracks on the gap side which can obviously reduce partonic backgrounds [73]. Even if both conditions are used and the partonic background is reduced to a level that does not allow for proper signal extraction, elastic photon emission can be tagged using a very forward detector (VFD) [74] placed hundreds of meters away from the interaction point. For instance, the case for which VFD stations would be put at 220 and 420 m from the interaction point is mandatory in order to retain low partonic backgrounds [75]. Indeed, when an intact proton is scattered with a large pseudorapidity it escapes detection from the central detectors. But since its energy is
lower than the beam energy, its trajectory decouples from the beam path into the very forward region. Forward detectors can detect particles with a large pseudorapidity. The detection of final state intact protons by the forward detectors provides a characteristic signature. Backgrounds from usual DIS processes can detect particles with a large pseudorapidity. The detection beam path into the very forward region. Forward detectors lower than the beam energy, its trajectory decouples from the related background processes going easier than in the case considering the fake b-tagging efficiency, leading to such gauge bosons $W$, nature provided by the forward detectors.

Table 1 The TTM parameters $\sin \omega$ and $M_{\pi}$ sensitivities on the signal background ratio $S/\sqrt{B}$. $5\sigma$ for the discovery boundary and $3\sigma$ for the excluding boundary. The detector acceptance here is chosen to be $0.0015 < \xi < 0.5$

| $M_{\pi}$ [GeV] | $\mathcal{L} = 1 fb^{-1}$ | $\mathcal{L} = 10 fb^{-1}$ | $\mathcal{L} = 100 fb^{-1}$ |
|-----------------|-----------------|-----------------|-----------------|
|                 | $5\sigma$       | $3\sigma$       | $5\sigma$       | $3\sigma$       | $5\sigma$       | $3\sigma$       |
| 300             | 0.594           | 0.693           | 0.800           | 0.865           | 0.922           | 0.950           |
| 400             | 0.450           | 0.544           | 0.671           | 0.761           | 0.851           | 0.901           |
| 500             | 0.340           | 0.422           | 0.542           | 0.641           | 0.757           | 0.832           |
| 600             | 0.256           | 0.326           | 0.431           | 0.525           | 0.650           | 0.742           |
| 700             | 0.181           | 0.230           | 0.307           | 0.385           | 0.500           | 0.598           |
| 800             | 0.135           | 0.171           | 0.231           | 0.291           | 0.387           | 0.477           |
| 900             | $< 0.1$         | 0.130           | 0.173           | 0.220           | 0.292           | 0.370           |
| 1000            | $< 0.1$         | $< 0.1$         | 0.131           | 0.162           | 0.221           | 0.281           |
| 1100            | $< 0.1$         | $< 0.1$         | $< 0.1$         | 0.121           | 0.164           | 0.207           |
| 1200            | $< 0.1$         | $< 0.1$         | $< 0.1$         | $< 0.1$         | 0.122           | 0.148           |

When $M_{\pi} > 900$ GeV, the heavy final state strongly suppresses the phase space. The signal becomes much smaller and makes it more a challenge to detect. In this case, a higher luminosity is needed to make the discovery possible and push the discovery boundary larger. Two ways can be used in order to constrain the parameters or the excluding boundary more strictly: one is, as we see, to enhance the luminosity which can expand the related parameter space, see Table 1, while the other one is to take more kinematical cuts to improve the ratio $S/\sqrt{B}$. In our case for example, if a $p_T^{jet}$ cut is taken to be larger than 200 GeV, this can strongly suppress the $t\bar{t}j$ backgrounds and thus lead to better $S/\sqrt{B}$ in parts of the TTM parameter space.
4 Summary

In this work, we present the precise produced charged top-pion $\pi_T^\pm$ production associated with a top through $pp \rightarrow p\gamma p \rightarrow \pi_T^\pm + X$ at the 14 TeV LHC at NLO QCD loop level. We find that the cross sections are sensitive to the TTM parameters, and the smaller the sin $\omega$ or the lighter the top-pion $\pi_T^\pm$ is, the larger the cross sections will be. The typical QCD correction value is 7–11 %, which does not depend much on the TTM parameter sin $\omega$ as well as the detector acceptances $\xi$. We also present the $\sigma_T$ discovery and $\sigma_T$ excluding boundaries as functions of the TTM parameters for three values of the luminosity at the future LHC.

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