Studying Same-Sign Top Pair Production in Flavor Changing Scalar Models at the HL-LHC

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(Dated: May 11, 2021)

We investigate the potential of the HL-LHC for discovering new physics effects via new strategies in the same-sign top pair signatures. We focus on the semi leptonic (electron and muon) decay of the top quarks and study the reach for a simplified model approach where top quark flavor changing could occur through a neutral scalar exchange. A relatively smaller background contribution and clean signature are the advantages of the leptonic decay mode of the same-sign W bosons in the same-sign production processes of top quark pairs. Assuming the FCNC between top quark, up type quark and scalar boson from the new physics interactions the branchings could be excluded of the order $O(10^{-4})$. We use angular observables of the same-sign lepton pairs and the top quark kinematics in the process which provide the possibility of separation of new physics signal from the SM backgrounds as well as distinguish the $tuH$ and $tch$ couplings. We find that the same-sign top quark pair production is quite capable of testing the top FCNCs at the HL-LHC.

I. INTRODUCTION

Among all fundamental fermions in the standard model (SM), top quark has the largest mass and causes the most serious hierarchy, and plays an essential role in the vacuum stability. Top quark is also the last corner stone of the family structure of SM with a huge mass gap with other members of quark content of SM. It is the most sensitive particle for TeV scale physics in SM with Higgs boson, therefore researching the interactions of top quark is a crucial part of BSM physics.

The flavor changing neutral currents (FCNCs) among the up or down sector quarks are not present at leading-order in both Yukawa and gauge interactions within the standard model (SM) framework. However, extremely small FCNC couplings could be generated from loop-level diagrams which are strongly suppressed due to the Glashow-Iliopoulos-Maiani (GIM) mechanism and it is one of the unique characteristics of SM. Besides it sets a new horizon for new researches.

The essence and importance of GIM mechanism’s veto effects and studying FCNC interactions lies in the decision of dropping or keeping the FCNC preventing unique feature of SM model to new physics. FCNC searches will deduce its ultimate fate without any doubt. If one can show its possibility, that would be a great progress at BSM researches.

The phenomenology of FCNC couplings has been discussed in many studies. There are scenarios within supersymmetry models and the two Higgs doublet models where the top quark FCNC processes could raise considerably because of the new loop level diagrams mediated by new particles. Then, top quark FCNCs could also show up in the processes through the exchange of a new neutral scalar.

A search for flavour changing neutral current processes in top quark decays have been presented by the ATLAS Collaboration from proton-proton collisions at the LHC with $\sqrt{s} = 13$ TeV. The observed (expected) upper limits are set on the $t \rightarrow cH$ branching ratio of $2.2 \times 10^{-3}$ ($1.6 \times 10^{-3}$) and on the $t \rightarrow uH$ branching ratio of $2.4 \times 10^{-3}$ ($1.7 \times 10^{-3}$) at the 95% confidence level. A search for flavor-changing neutral currents (FCNC) in events with the top quark and the Higgs boson is presented by the CMS collaboration. The observed (expected) upper limits at 95% confidence level are set on the branching ratios of top quark FCNC decays, $BR(t \rightarrow uH) < 4.7 \times 10^{-3}$ ($3.4 \times 10^{-3}$) and $BR(t \rightarrow cH) < 4.7 \times 10^{-3}$ ($4.4 \times 10^{-3}$), assuming a single non-zero FCNC coupling.

In recent years many new collider ideas such as HL-LHC/HE-LHC/FCC has been announced and technical design report of HL-LHC has been published. Most promising feature of that collider for BSM searches is increased COM energy (14 TeV) and especially its luminosity of $3 \, ab^{-1}$.

Development of such a new collider has notable effects on the BSM literature evidently since it to offer new possibilities for phenomenological studies and gives a large room for potential discoveries/exclusions. The researches based on new colliders started to making predictions about new physics scenarios and set new limitations. To be specific at HL-LHC for FCNC interactions, branching ratios are updated as $BR(t \rightarrow qH) < O(10^{-4})$ using various different analyses from different channels and processes; thus couplings are expected to go below $\eta_q = 0.04$ which is roughly below the known limits from experiments.

In this study, we would like to investigate the prob-
lem and seek for the new limits at HL-LHC. To do so, we restrict ourselves to production mechanisms of same sign $t\bar{t}tt$ pairs (signal processes $pp \rightarrow t\bar{t} \rightarrow W^+W^-bb \rightarrow l^+l^-bb + M_{ET}$, $pp \rightarrow t\bar{t} \rightarrow W^-W^-bb \rightarrow l^-l^-bb + M_{ET}$) including the exchange of Higgs boson at the HL-LHC. We introduce the kinematical variables to enhance the signal (S) and background (B) ratio. Angular separation of the two same sign leptons could indicate the new physics effects in $t\bar{t}$ production process, and separate the signal from background processes.

II. MODEL FRAMEWORK

The flavour changing neutral interactions of the top quark with other particles from the SM have been described in a general way as an extension \cite{14,15}. This provides a direct connection between experimental observables and the new anomalous couplings. The lagrangian describing FCNC $tqH$ interactions in model independent manner is given as

$$L_H = \frac{1}{\sqrt{2}} H \bar{t}(\eta^L q + \eta^R c) \bar{u} + h.c.$$  

where the $\eta^L/R$ couplings set the strength of the coupling between the top quark, the Higgs boson and up or charm quark, as well as the chirality of this coupling. They can be complex in general, however we take into account real parts of the couplings to reduce the free parameters. In literature that interaction can be seen as modeled without the constant $\frac{1}{\sqrt{2}}$, thus gives higher branchings precisely multiple of 4. We keep that constant here in order to make bounds more strict mean while keeping the conversion to other models in our mind. Note that it effects cross section too, thus makes analyzing signal processes even harder. The decay width for FCNC channels can be calculated as

$$\Gamma(t \rightarrow qh) = \frac{(\eta^2 q + \eta^2 h) (m_t^2 - m_h^2)^2}{64\pi m_t^2}$$  

and its numerical value depends on the coupling values related to $\Gamma(t \rightarrow qh) \simeq 0.1904(\eta^2 q + \eta^2 h) \text{ GeV}$. The
branching ratio to an FCNC channel can be expressed as $BR(t \rightarrow q\phi) = \Gamma(t \rightarrow q\phi)/\Gamma(t \rightarrow all)$. Since the dominant decay mode of top quark is $\Gamma(t \rightarrow Wb)$, this branching ratio mostly related to $(\eta^2_{qL} + \eta^2_{qR})$ factor especially for smaller coupling values.

The model framework can also be compared with the formalism assumed that the FCNC interactions occur via a weak sector. The relevant effective interaction Lagrangian including a new flavor changing scalar ($\phi$) is given

$$L_\phi = \phi \bar{q} (a_u + b_u \gamma^5) q + \phi \bar{q} (a_c + b_c \gamma^5) c + H.c.$$  \hspace{1cm} (3)

where the coupling parameters $a_{u,c}$ and $b_{u,c}$ denote the scalar and axial couplings between top quark and up-type light quarks ($u, c$) which proceeds through the exchange of a scalar $\phi$. To compare different formalism for the top-scalar FCNC we find the correspondence of the couplings $\eta_u = (\eta^2_{qL} + \eta^2_{qR})/2\sqrt{2}$ and $\eta_c = (\eta^2_{qL} - \eta^2_{qR})/2\sqrt{2}$. Assuming no specific chirality dependence (same value for left and right handed couplings) of the process we may set $a_u = \eta_u / \sqrt{2}$ and $b_u = 0$.

The parameters that appear in the topFNC_UFO model are complex numbers in general and their real and imaginary parts can be set manually. In this work, we restrict ourselves to real parameters in order to reduce the free parameters.

III. CROSS SECTIONS OF SIGNAL AND BACKGROUND

At the first step before event generation we calculate the cross section for FCNC processes including $tq\bar{q}$ vertices leads to same sign signal final state. Since the cross-section is proportional to the modulo quartic of the value of the anomalous couplings, i.e. the cross-section have same numerical value for the left-handed coupling and the right-handed coupling. In Figure 4 we can see due to precense of up type valance quarks in proton $pp \rightarrow t\bar{t}$ process is much more favorable than $pp \rightarrow t\bar{t}$. Although the contribution from the signal $pp \rightarrow t\bar{t}$ to same sign lepton signal compared to the signal from $pp \rightarrow t\bar{t}$ is nearly less than one order of magnitude, we also use that contribution to enhance the signal.

After setting model parameters the signal samples and background samples are generated with MadGraph5 (Signal process and backgrounds generated with 320,000 events.) 18. PYTHIA8 19 is used with shower and hadronisation processes and finally DELPHES 3 is used for detector level simulation [20]. Result files are analyzed with Root6 [21].

As mentioned before same sign lepton signal has relatively low background which is advantageous and many of the background processes fall into reducible background category which means although they are present due to similarities between signal process by applying proper analyze cuts their contributions can be well reduced. How-ever there still exist tough irreducible backgrounds. The contributions from various backgrounds are listed below.

![Figure 4. Estimated cross sections according to coupling constant of two same sign lepton signal in FCNC processes. As we can see main contribution comes from positively charged top pair due to higher parton distributions of valance quarks at proton which differs nearly one order of magnitude. Nevertheless we use negatively charged lepton pair to enhance the signal process. We assume all FCNC coefficients are the same and all channels are open (to state exactly we use $u + c \rightarrow \eta_u = \eta_c$ case).](image)

| Process | Cross section(pb) | Intermediate states |
|---------|-------------------|---------------------|
| $pp \rightarrow t\bar{t}$ | $8.037 \times 10^{-4}$ | $WWbb$ |
| $pp \rightarrow t\bar{t}W\pm$ | $1.647 \times 10^{-2}$ | $WWbb$ |
| $pp \rightarrow W^\pm W^\pm jj$ | $1.357 \times 10^{-2}$ | $WWjj$ |
| $pp \rightarrow W^+ W^- Z$ | $5.257 \times 10^{-4}$ | $WWZ$ |
| $pp \rightarrow t\bar{t}l^+l^-$ | $1.976 \times 10^{-5}$ | $WWbl$ |
| $pp \rightarrow ZZW\pm$ | $1.827 \times 10^{-4}$ | $WZZ$ |
| $pp \rightarrow ZZjj$ | $1.267 \times 10^{-4}$ | $ZZjj$ |

Characteristics of signal events are two jets (b-tagged if possible), two same sign leptons, and missing transverse energy. We choose our background processes by considering three fundamental features:
The processes \( pp \rightarrow W^{\pm}W^{\pm}jj \); \( pp \rightarrow t\bar{t}W^{\pm} \); \( pp \rightarrow t\bar{t}l^{\pm}l^{-} \); \( pp \rightarrow tW^{+}W^{-} \) with all leptonic decay modes which are most similar to our signal process are directly background to our signal process and they are all irreducible. Although they give same final state content with the signal, \( pp \rightarrow t\bar{t}W^{\pm} \) reconstruction region is slightly different. That process also gives similar products at final state. However its cross section is high. In the case \( pp \rightarrow W^{\pm}W^{\pm}jj \), on the one hand reconstruction region is significantly different, on the other hand its particle content is exactly the same. In addition to previous two discussions as an advantage for analysis \( pp \rightarrow t\bar{t}l^{\pm}l^{-} \) process has low cross section compared to other two. Nevertheless its reconstruction region is fairly same. \( pp \rightarrow tW^{+}W^{-} \) with leptonic decay modes directly produce signal content, however its reconstruction region noticeably distinct. Since its cross section is quite high. Similar arguments can easily be expanded to other backgrounds. Others are reducible backgrounds: even though their particle contents are similar to signal, either their cross sections are low and reconstruction region significantly different. In that regard they satisfy only one criterion while irreducible ones fulfill two or more.

Further we select decay channels of background events as such to give same sign \( 2\ell^{\pm} \) with \( 2j \) and MET. Jets at includes at least one b-tag jet. This ensures the maximum cross section for background and gives more contribution to histograms when we consider the detector effects such as misidentification and over counting of particles.

The mixing of signal and background processes are increased with misidentification of particles and loss of particles due to detector effects. These effects causes the fuzzing of characteristics of signal while imitating the features of signal for background processes. Moreover b-tag efficiency plays also an important role for analyzing the signal and background events. Since two b-tagged jets are a major property of signal. Nevertheless two b-tagged jets requirement is so strict for observability of signal while reducing background effects too. Therefore we confined ourselves to at least one b-tagged jet. Nonetheless, it makes the analyze harder to separate many of the backgrounds with signal. It is also important to note that there is no interference between signal and background at this level of calculation.

### Table II. Content of background groups:

Here we grouped backgrounds to increase clarity of our histograms. The most important feature of these backgrounds are four of them includes top pair as backbone, and others only bosons. Only \( pp \rightarrow t\bar{t}l^{\pm}l^{-} \) process is odd and left as own. That behaviour of backgrounds lead us the catagORIZATION of them in this table.

| Group Name | Processes | Definition |
|------------|-----------|------------|
| \( tt \) w/wo boson(s) | \( pp \rightarrow t\bar{t}W^{\pm} \) \( pp \rightarrow W^{+}W^{-}t\bar{t} \) \( pp \rightarrow t\bar{t}Z \) | Top pair with/without a boson or bosons |
| Bosons w/wo jets | \( pp \rightarrow W^{+}W^{+}jj \) \( pp \rightarrow W^{+}W^{-}Z \) \( pp \rightarrow ZZW^{\pm} \) \( pp \rightarrow ZZjj \) | Bosons with/without jets |

- Similarity of final state particles as much as possible with signal processes.
- High cross section compared to signal.
- Having same reconstruction inputs as for the signal.

Backgrounds given in Table II have at least one of this properties, besides some of them have two. As long as all processes have their own unique nature, they more or less differ at least one criterion or partly one or two criterion.

**IV. ANALYSIS**

At first stage we have started with the known limits from current LHC experiments that put a limit on the FCNC coupling constant values at around \( \eta_{c} = 0.15 \) and use that value as benchmark for upgrading HL-LHC detector to search for a possible FCNC signal outcome. Then we look forward to push the limits for \( \eta_{u+c} \), \( \eta_{u} \) and \( \eta_{c} \) separately.

We use the statistical significance \( SS_{\text{disc}} \)
SS_{disc} = \sqrt{2[(S + B) \ln(1 + S/B) - S]} \tag{4} 

and \(SS_{exc}\)

\[SS_{exc} = \sqrt{2[S - B \ln(1 + S/B)]} \tag{5}\]

for discovery and for exclusion as given in \[22, 25\]. For exclusion of a parameter value we are looking \(SS_{exc} > 1.645\) corresponding to a confidence level of 95\% CL. In order to make it complete we will give limits for discovery relation too. Both relations reduces to \(\frac{S}{\sqrt{B}}\) at large background limit, further we are dealing with an idealistic case to omit uncertainties we cannot intervene.

Here we will track exactly two positively/negatively charged leptons as same sign lepton pairs since we investigate the case \(W^{\pm} \rightarrow t^\pm \nu_t^\pm\) followed after \(t(\bar{t}) \rightarrow W^\pm b(\bar{b})\). Missing transverse energy is also an essential characteristics of the process too. We note that despite we have only two b-jets in our signal when we consider the nature of interaction, more jets must be generated and we need to distinguish them from bottom quarks to reconstruct two top quarks. That point needs a little bit attention when we think of backgrounds and to make it clear we would like to go deeper: as we know our background events have more particles, in addition the nature of interaction also dictates numerous jets which gives more hadronic transverse energy. When we consider both, a cut that is limiting the number of jets seem to be advantageous. The best choice is limiting jet number as two, so we conclude with exact event selection.

For lepton flavors we have 2 possibilities namely \(e^{\pm}\) and \(\mu^{\pm}\) for \(t^\pm\) case since \(\tau\) lepton disintegrates before reach the detector so its analysis is out of scope. In that respect we divide analysis region to three which includes three possibilities of same sign lepton pairs \((e^+ e^+, \mu^+ \mu^+, e^+ \mu^\pm, e^\pm \mu^\pm)\) with exactly two jets while at least one of them b-tagged and lastly presence missing transverse energy in events.

Decay of top quarks in their rest frame give rise to high \(p_T\) b-jets larger than about 80 GeV as a prediction in addition same happens for \(W^+\) bosons and daughter particles should have at least 40 GeV. These particles also carries momentum, thus we expect boosted behaviour at histograms for mother and daughter particles.

To sum up at the beginning of the analysis we have divided signal region to three analysis region with exact event selection, followed by simple cuts given in Table III. Here, the \(\eta\) cuts were choosen to work with the more sensitive regions of the detector. \(H_T\) defined as hadronic transverse energy as that scalar sum of \(p_T\) of all final state hadrons. \(H_T < 1000\) GeV cut applied since at that value signal events vanish. However as mentioned before it is not the case for background events. Here we give the kinematics of signal in figures below. Finally we present histograms showing the characteristics of jets produced and little comment on them. In Fig. 6 we see highest jet events stand at around 40-50 GeV which are obviously not coming from top quark decay, but instead they are the jets produced with top quarks residually. In that perspective we can understand their low \(p_T\). In addition, our signal sample has events containing up to nearly fifteen jets, hence we can understand their relative high number. After analysis region is selected to recognize the jets \(p_T^{jets} > 20\) GeV is fairly enough. Same is true for leptons with \(p_T^{l} > 10\) GeV and for \(MET > 20\) GeV respectively. As b-tagging has already been mentioned. Two b-tagged jets nearly suppress both signal and background and fade analyze improperly.

Next we move on our main analysis: We want to give some \(\Delta R\) distributions of signal after event selection and basic cuts. These histograms clearly gives us room to eliminate backgrounds by using discriminant cuts. In

| Event Selection and Basic Cuts |
|--------------------------------|
| \(N(jets) == 2\)            |
| \(N(t^\pm) == 2\)           |
| \(p_T^{jets} > 20\) GeV     |
| \(p_T^l > 10\) GeV          |
| \(MET > 20\) GeV            |
| \(|\eta^{ll}| < 2.5\)       |
| \(H_T < 1000\) GeV          |
| At least one b-tagged jet    |

Figure 6. For the signal process, lepton \(p_T\) distributions \(e^+ e^+, \mu^+ \mu^+, e^\pm \mu^\pm\) event regions: Histogram clearly shows that \(e^\pm \mu^\pm\) final state is more favorable. The \(e^\pm \mu^\pm\) pair comes from disintegration of \(W^\pm\) pairs which have about 80 GeV rest mass. Hence that energy plus momentum shared by final particles and gives a peak around 40 GeV with boosted behavior. However same flavor final states shows an asymmetry originates from the following reasons: Detector always discriminates lower and higher \(p_T\) particle which gives a gap between first and second highest \(p_T\) object. Nevertheless they all have boosted behavior and give peaks close to 40 GeV as well.
expecting peaks around and double top quarks, respectively. In this regard we are looking at the mass of single and double top quarks, respectively. Generally, we are more interested in the remaining background alone.

Coming from backgrounds, nicely eliminated except for irreducible ones. Further, the most significant contribution is coming from jets coming from leading and second leading jets which are in complete consistency with our expectations.

After these cuts we can reconstruct the objects that take place in interaction. Many contributions coming from backgrounds nicely eliminated except for irreducible ones. Further, the most significant contribution is coming from $pp \rightarrow t\bar{t}W^\pm$ which nearly constitutes whole remaining background alone.

In Fig. 12 - Fig. 19 we are reconstructing the transverse mass of single and double $W^\pm$ bosons and single and double top quarks, respectively. In this regard we are expecting peaks around $W$ boson mass, two $W$ bosons mass, top quark mass, two top quarks mass, respectively. However, all these objects are carrying high $p_T$, consequently their histograms boosted as expected and their peak region shifted accordingly.

V. RESULTS AND CONCLUSIONS

In this study we have searched for accessible limits for top-Higgs FCNC couplings using same sign lepton channel at the HL-LHC. This channel gives clean signal signature in addition to its low reducible/irreducible background. However, this channel suffers from two new physics vertices. Thus, these effects lower the cross section drastically which is a disadvantageous feature of this analysis. Keeping these in mind we can conclude that: simulation of this process with the same sign lepton channel turns into a laboratory for testing the mentioned sce-
narios in the text. In this respect this channel determines the upper limit for couplings and benefits exclusion limits rather than discovery.

In Table VI we summarize our results with the discovery and exclusion significance. As clearly seen from this table for $SS_{\text{disc}} \geq 2$, $u+c$ and only $u$ scenarios (95% confidence level for discovery relation, Eq. (4)) which state that results are consistent and even better than current LHC results. Which suggests to observe any top-Higgs FCNC interactions and exceed the excluded regions for couplings and branchings. We reach $\eta_q = 0.04$ value for these scenarios which sets the expected bound for couplings. While these limits are compatible with the expectations from HL-LHC, which enforce limitations for findings on other channels: Since on the one hand this channel gives its clean signal fingerprint, on the other hand even lower cross section, the same-sign lepton channel provides upper limits. These limits can also be combined with the other sensitive channels for similar scenarios.

\section*{ACKNOWLEDGMENTS}

The authors are grateful to Ulku Ulusoy for a careful reading of the manuscript. We wish to acknowledge the support of the AUHEP group, offering suggestions and encouragement. The numerical calculations reported in this paper were partially performed at TUBITAK ULAKBIM, High Performance and Grid Computing Center (TRUBA resources).

\begin{table}[h]
\centering
\caption{Cut efficiencies for signal and background processes.}
\begin{tabular}{lll}
\hline
Process & Region Selection & Precuts  \\
\hline
$pp \to tt(t\bar{t})$ & 0.213897 & 0.079799 \\
$pp \to t\bar{t}W^\pm$ & 0.111334 & 0.0637999 \\
$pp \to W^\pm W^\mp jj$ & 0.86062 & 0.0025144 \\
$pp \to W^+W^-Z$ & 0.0449469 & 0.0260029 \\
$pp \to ZZW^\pm$ & 0.146 & 0.003125 \\
$pp \to W^+W^-t\bar{t}$ & 0.0283281 & 0.0506827 \\
$pp \to t\bar{t}Z$ & 0.0448687 & 0.0263268 \\
$pp \to ZZjj$ & 0.0629156 & 0.000298018 \\
\hline
\end{tabular}
\end{table}

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Table V. Cut efficiencies for signal and background processes.

| Process           | AR Cuts | Total      |
|-------------------|---------|------------|
| $pp \to tt(t\bar{t})$ | 0.650677 | 0.0111062  |
| $pp \to t\bar{t}W^\pm$ | 0.308403 | 0.00219062 |
| $pp \to W^\pm W^\pm jj$ | 0.483871 | 0.001105   |
| $pp \to W^+ W^- Z$ | 0.347826 | 0.000116   |
| $pp \to t\bar{t}l^+l^-$ | 0.385027 | 0.000045   |
| $pp \to ZZW^\pm$ | 0.273973 | 0.000125   |
| $pp \to W^+ W^- t\bar{t}$ | 0.281938 | 0.0004     |
| $pp \to t\bar{t}Z$ | 0.357143 | 0.000421875|
| $pp \to ZZjj$ | 0.5 | $9.375 \times 10^{-6}$ |

Figure 14. Transverse mass reconstruction of leading $W^\pm$ boson.

Figure 15. Transverse mass reconstruction of second leading $W^\pm$ boson.

Figure 16. Transverse mass reconstruction of two $W^\pm$ bosons.

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Figure 17. Transverse mass reconstruction of leading top quark.

Figure 18. Transverse mass reconstruction of second leading top quark.

Figure 19. Mass reconstruction of two top quarks.

Figure 20. Signal significance ($SS_{\text{disc}}$) versus $\eta_q$ coupling parameter for three different scenarios.

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Table VI. Upper limits on $\eta_q$ parameter and corresponding branching ratio.

| Scenario $SS_{\text{disc}} \geq$ | $\eta_u = \eta_c$ | $\eta_u = \eta_c$ | $\eta_u = \eta_c$ |
|----------------------------------|-----------------|-----------------|-----------------|
|                                  | $\eta_c = \eta_u$ | $\eta_c = \eta_u$ | $\eta_c = \eta_u$ |
| $SS_{\text{disc}} \geq 2$       | 0.1206 $5.538 \times 10^{-3}$ | 0.1317 $3.302 \times 10^{-3}$ | 0.3015 $1.731 \times 10^{-2}$ |
| Only $\eta_u$                   | 0.1348 $6.920 \times 10^{-3}$ | 0.1474 $4.137 \times 10^{-3}$ | 0.3343 $2.128 \times 10^{-2}$ |
| Only $\eta_c$                   | 0.1540 $9.037 \times 10^{-3}$ | 0.1687 $2.845 \times 10^{-2}$ | 0.3795 $2.742 \times 10^{-2}$ |
| $SS_{\text{disc}} \geq 3$       | 0.04 $6.096 \times 10^{-4}$ | 0.04 $3.048 \times 10^{-4}$ | 0.1 $1.905 \times 10^{-3}$ |
| Only $\eta_u$                   | 0.04 $6.096 \times 10^{-4}$ | 0.04 $3.048 \times 10^{-4}$ | 0.1 $1.905 \times 10^{-3}$ |
| Only $\eta_c$                   | 0.1 $1.905 \times 10^{-3}$ | 0.1 $1.905 \times 10^{-3}$ | 0.1 $1.905 \times 10^{-3}$ |