The s-Channel Single Top Quark Production as a Constraint for $W'$ Boson Contribution

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Abstract—An analysis is performed to constrain the $W'$ boson production using the measurement of the s-channel single top quark production cross section. Both phenomenological and statistical approaches are examined and results are presented. In the best case, $W'$ bosons that interact only to the right-handed fermions are excluded below 1390 GeV. To our knowledge, it is the first time that the measured cross section of the s-channel single top quark production from the colliders is used to rule out a part of the phase space of the $W'$ boson.

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1. INTRODUCTION

The existence of a new massive charged gauge boson, known as $W'$ boson, is proposed by many new physics scenarios. The minimal extension of the Standard Model (SM) gauge group incorporating $W'$ is known as $SU(2) \times SU(2) \times U(1)$ (G(221)) models [1]. The Kaluza-Klein excitations of the SM $W$ boson in extra dimension models is another famous example [2]. In this paper, a general description of this new massive charged particle interactions is considered, without constraining the couplings to a special model.

The general Lagrangian describing the fermionic interactions of $W'$ boson can be written as:

$$\mathcal{L} = \frac{V'_{ij} g_W}{2\sqrt{2}} f_i \bar{\nu}_j (a_R (1 + \gamma^5) + a_L (1 - \gamma^5)) W'^i f_j + \text{H.c.}$$

(1)

As for the notations, we follow the definitions of the [3, 4] with small modifications, where $V'_{ij}$ is a $3 \times 3$ identity matrix for leptons or the CKM matrix for quarks, $g_W = e / \sin(\theta_W)$ is the SM weak coupling constant and $a_{R, L}$ are the strengths of the right and left couplings. Through this work, $a_{R, L}$ are assumed to be real values.

There have been many direct searches for $W'$ in the high energy particle colliders, but up to now, all of them have failed. The searches include the fully left-handed $W'$ ($a_R = 0$) when $a_L$ is not constrained or when $a_L = 1$, known as the Sequential SM (SSM) [5]. The CMS experiment at the CERN LHC [6] has excluded the SSM $W'$ with masses below 4.1 TeV [7] at 95% confidence level (CL) by looking at the tail of the transverse mass distribution of a lepton which comes from the decay of a $W'$ associated with missing transverse energy coming from a neutrino. The search uses 2.3 fb$^{-1}$ of proton–proton (pp) collisions in the center of mass energy of 13 TeV. The ATLAS experiment [8] in a similar search uses 36.1 fb$^{-1}$ of data and rules out the SSM $W'$ below 5.1 TeV [9]. Another class of the searches, consider the fully right-handed $W'$ ($a_L = 0$), where decay to leptons are either closed or highly suppressed due to introduction of heavy right-handed neutrinos [10, 11]. Search for decay of $W'$ to light jets suffers from the high level of the QCD multijets backgrounds, but if $W'$ is heavier than 180 GeV, it can decay to a pair of top and bottom quarks ($tb = \bar{t}b$ or $\bar{t}b$) which has a distinguished signature due to the possibility of tagging the jets originating from the $b$ quarks. Both CMS and ATLAS experiments have looked at this final state in different center-of-mass energies. The most recent result from the ATLAS experiment is for $\sqrt{s} = 8$ TeV that excludes the $W'$ with masses below 1.92 TeV in 95% CL [11]. The CMS experiment rules out the right-handed $W'$ lighter than 3.6 TeV [12], by using up to 35.9 fb$^{-1}$ of 13 TeV data, in the same channel. The previous limit from the CMS experiment, in this channel, was 2.6 TeV based on 2.6 fb$^{-1}$ of 13 TeV data [13].
When $W'$ decays to $tb$, the final state is very similar to the final state of the $s$-channel single top production, where $W'$ boson is the off-shell mediator to produce top and bottom quarks. If $W'$ exists, it can affect the cross section of the SM $s$-channel single top production, so measuring this cross section can constrain the $W'$ contribution. The contribution of $W'$ boson to $s$-channel single top production is discussed in some other papers also [14–17], but it is the first time that the measured cross section of $s$-channel single top is used to constrain the $W'$ contribution. The idea is to present a new method which is simple and can be used to constrain the new physics by using the existing experimental measurements, when the final states are similar. In another approach, one can use the reported experimental measurements, when the final states are considered [21]. The horizontal line depicts SM prediction for the process. The shadow cyan area shows the allowed bound which is consistent with the ATLAS measurement. As it is seen in Eq. (3), for $a_L = 0$ and non-zero $a_R$, effect of $W'$ exchange can be destructive. To better show this effect in Fig. 1b, we zoom in the high $W'$ mass region, where this effect can be important. In Fig. 1a, there exists a peak at areas which square of center of mass energy is close to the squared total mass of top and bottom quarks.

In Fig. 2, we have shown the effect of $W'$ exchange for $a_L = 0$ and nonzero $a_R$ on single top quark production. As it is expected, with increasing $M_{W'}$, deviation from SM cross section decreases. Figures 1 (2) shows that the effect of presence of $W'$ for $M_{W'} < 1160$ GeV ($M_{W'} < 1390$ GeV) can be larger than the ATLAS measurement. This means left-handed (right-handed) $W'$ have been excluded for $M_{W'} < 1160$ GeV ($M_{W'} < 1390$ GeV). Figure 3 demonstrates this effect in the $W'$ parameter space. Scatter points depict regions in $(a_L, (b, a_R)$ and the $M_{W'}$ plane which are excluded by ATLAS measurement. To make these plots, the idea used in [23] and [24] is followed that the cross section is proportional to power 4th of either $a_L$ or $a_R$ and the effect of the couplings on the $W'$ width is ignored. According to Fig. 1a (Fig. 2), the best exclusion limit on $M_{W'}$ for $a_L = 1$ and $a_R = 0$ ($a_R = 1$ and $a_L = 0$) is 1160 GeV (1390 GeV). As an alternative approach in

\[
\hat{\sigma} = \frac{\sum \pi \alpha_w^2}{6} |V_{tb}|^2 |V_{qq'}|^2 \left( \frac{s - M^2}{\hat{s}^2 + M^2} \right) \times \left[ \frac{1}{(\hat{s} - m_W^2) + \Gamma_W^2 M_W^2} + \frac{2a_L^2 ((\hat{s} - m_W^2)(\hat{s} - M_{W'}^2) + \Gamma_W^2 M_W^2)}{(\hat{s} - m_W^2)^2 + \Gamma_W^2 M_W^2} \right] \]

where $\Gamma_W$ is the width of $W$ boson, $\alpha_w = g_w^2/(4\pi)$ and $\hat{s} = x_1 x_2 S$ is the parton center of mass energy while $S$ is the $pp$ center of mass energy. Width of the $W'$ is given in [14].

As it is mentioned, the most precise measurement of single top production has been achieved by the ATLAS collaboration [21]. In Fig. 1a, we display the total cross section of $pp \rightarrow tb$ versus $M_{W'}$ for several values of $a_L$ while $a_R = 0$. To calculate $\sigma(pp \rightarrow tb)$, the symbolic expression is implemented in a private Mathematica code. We have used the CTEQ6.6M parton distribution function [22] and set $\sqrt{s} = 8$ TeV. A SM cross section of 5.61 pb for the $\sigma(pp \rightarrow tb)$ is considered [21]. The horizontal line depicts SM prediction for this process. The shadow cyan area shows the allowed bound which is consistent with the ATLAS measurement. As it is seen in Eq. (3), for $a_L = 0$ and non-zero $a_R$, effect of $W'$ exchange can be destructive. To better show this effect in Fig. 1b, we zoom in the high $W'$ mass region, where this effect can be important. In Fig. 1a, there exists a peak at areas which square of center of mass energy is close to the squared total mass of top and bottom quarks.

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\[
\sigma(pp \rightarrow tb) = \sum_{qq'} \int dx_1 dx_2 q(x_1)\overline{q}(x_2) \hat{\sigma}(qq' \rightarrow tb),
\]
the next section, we use a statistical method to constrain the $W'$ phase space.

3. STATISTICAL ANALYSIS

In this study, we use the reported event yields by the experiments in search for $s$-channel single top production and find the upper limit on the contribution of the $W'$ boson. In this part, the interference is neglected even for the left-handed $W'$ boson. The data used in this study include the following categories:

| Category             | CMS $\mu$ 7 TeV | CMS $\mu$ 8 TeV | CMS electron 8 TeV | ATLAS 8 TeV |
|----------------------|-----------------|-----------------|-------------------|------------|
| Single top $s$-channel | 129 ± 5        | 452 ± 16        | 347 ± 12          | 540 ± 160  |
| SM Backgrounds       | 1920 ± 110      | 7060 ± 370      | 6240 ± 320        | 14670 ± 180|
| Observed data         | 1883            | 7023            | 6301              | 14677      |

More data is available [26–28], but it was tested and confirmed that adding them can not improve the results. It is also checked that the used categories of data are important and removing any of them can decrease the exclusion power. Table 1 summarizes the data used for this analysis. The quadratic sum of the statistical and systematic uncertainties are reported as the total uncertainty. The main part of the systematic uncertainty comes from the uncertainty on the jet energy scale.
For statistical calculations, the tools provided by the ROOT [29] data analysis framework are used. They use a Likelihood ratio semi-bayesian method to find the 95% CL upper limit on the contribution of the new physics. The efficiency of event reconstruction and selection for the events from $W'$ contribution is assumed to be the same as the efficiency of the $s$-channel events. The SM cross section of the $s$-channel single top production in different data categories is taken from the corresponding analysis. The cross section of $W'$ production with $tb$ final state can be found in [4]. The cross sections are provided up to next-to-leading order (NLO) of QCD precision. The relative uncertainty of the signal yield is assumed to be 30% for all categories which is a conservative value. Trying other values like 20 or 40% do not affect the final exclusions.

Figure 4a shows the 95% CL upper limit on the contribution of the $W'$ to the production cross section of the $s$-channel single top quark, when the $W'$ is fully left-handed with the couplings similar to those of the SM W boson. It can be seen that $W'$ boson with masses below 1290 GeV are excluded by the data. The expected value of the exclusion is 1255 GeV. The ±1 $\sigma$ of the expected limits are shown as a green band. In Fig. 4b, the same information is presented for the fully right-handed $W'$ boson, where the new boson does not couple to leptons. The expected (observed) limit on the mass of $W'$ in this model is 1325 (1360) GeV. The results can be compared to the CMS limits based on 8 TeV data in the similar final state which is 2.15 TeV [30].

In Fig. 5, the observed 95% CL upper limit is shown for different categories of data, separately. Although the ATLAS result is the most precise measurement for the $s$-channel single top production, but the main power for exclusions comes from “CMS $\mu$ 8 TeV”. For the SSM $W'$, using this category alone can rule out the $W'$ lighter than 1180 GeV. The power of the CMS results come from the detailed values for different channels, but the ATLAS experiment has reported only the sum of the yields of the electron and muon channels. In Table 2 the expected and observed limits are shown for different categories of data, in pure left-handed or right-handed scenario. The data from $pp$ collisions at $\sqrt{s} = 7$ TeV give the worst limit and data from 8 TeV collisions have improved the limits significantly. One can hope that when the data from
pp collisions at $\sqrt{s} = 13$ TeV are available, the limits can be improved even more, keeping in mind that the volume of the new data is much more than the previous data also.

The same analysis can set limits on the coupling versus $W'$ mass. In this part also, $W'$ is either fully right-handed or fully left-handed and the mixture is not allowed. Figure 6 shows the region in the $W'$ mass versus the coupling that can be excluded in 95% CL. It can be seen that varying the $a_L$ ($a_R$) from 0.4 to 1.8 can exclude the $W'$ mass between 600 and 1900 (2000) GeV. The main assumption here is the $(V-A)$ nature of $W'$ and couplings are free to change. Figure can be compared to Fig. 3, where the scattered points show the part of the phase space that produce the cross sections inconsistent with the measured cross section of the $s$-channel single top production from the ATLAS experiment.

4. CONCLUSIONS

The heavy partner of $W$ boson, known as $W'$ boson, can contribute to $s$-channel production of the single top quark. In this analysis, for the first time, the measured cross section of the $s$-channel single top quark is

| Dataset          | Left-handed |          | Right-handed |          |
|------------------|-------------|----------|--------------|----------|
|                  | expected    | observed | expected     | observed |
| CMS $\mu$ 7 TeV  | 1000        | 1020     | 1050         | 1070     |
| CMS $\mu$ 8 TeV  | 1150        | 1180     | 1220         | 1250     |
| CMS electron 8 TeV | 1090      | 1110     | 1160         | 1170     |
| ATLAS 8 TeV      | 1045        | 1045     | 1110         | 1120     |

Table 2. The expected and observed limits driven by different categories of data.
used to constrain the contribution of $W'$ boson. In a phenomenological approach, the part of the parameter space which is excluded by the measurement of the cross section is found. In an alternative approach, the reported yields from the experiments used to measure the cross section are statistically analyzed to set the upper limit on the yields of the $W'$ boson events. The latter analysis rules out the right-handed $W'$ boson with masses below 1.36 TeV, while the former can push the limit up to 1.39 TeV. The limits for a left-handed $W'$ boson are 1.16 and 1.29 TeV from the phenomenological and statistical analysis, respectively. In both approaches, the excluded region in the plane of the coupling versus the $W'$ boson mass is reported.

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