Model independent top quark width measurement using a combination of resonant and non resonant cross sections.

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Though top quark was discovered more than twenty years ago, measurement of its width is still challenging task. Most measurements either have rather low precision or they are done in assumption of the SM top quark interactions. We consider model independent parametrization of the top quark width and provide estimations on achievable accuracy using a combination of fiducial cross sections in double, single and non-resonant regions.
I. INTRODUCTION

The top quark is the heaviest known elementary particle. This fact makes it along with the Higgs boson the most promising window to physics Beyond of Standard Model (BSM). Measurements of the top quark properties and parameters are crucial for testing deviations from the Standard Model (SM) predictions. While the top quark mass was measured directly with an accuracy at the percentage level [1] the direct measurements of the top quark width give much worse precision of about 50% mainly because of experimental resolution [2]. Recent results of direct measurements of the width presented by CMS and ATLAS collaborations are of $0.6 < \Gamma_t < 2.5 \text{ GeV}$ [3] and $\Gamma_t = 1.76 \pm 0.33 \text{(stat.)}^{+0.79}_{-0.68} \text{(syst.) GeV}$ [4]. The indirect top quark width measurements have reached an accuracy of about ten percent [5, 6]. However the top quark width was measured indirectly only under certain SM assumptions, particularly assuming only the SM decay modes.

The accuracy of the direct top quark width measurement is expected to be improved by the analysis of the b-charge asymmetry with $W^+bW^-\bar{b}$, $W^-bW^+\bar{b}$ final states for the s-channel top, anti-top quark resonant contribution and with $W^-b$, $W^+\bar{b}$ final states for non-resonant top quark contribution [7].

In this paper we discuss another method of setting model independent limits on the top quark width in a complete gauge invariant way by fitting fiducial cross sections of $W^+bW^-\bar{b}$ production in certain phase space regions called double-resonant, single-resonant, and non-resonant. Similar method for the case of $e^+e^-$ collisions has been discussed in [8]. The idea of the method was illustrated on a simple $2 \rightarrow 3$ example for the process $gg \rightarrow tW^-\bar{b}$ in [9]. This work is a generalization of that study.

The idea of the width measurement from the comparison of rates in on- and off-shell regions was previously proposed for the Higgs boson [10] [11]. In corresponding measurements the Higgs boson width is extracted from $pp \rightarrow ZZ$ production above the threshold and from $pp \rightarrow H \rightarrow ZZ^*$ production below the threshold in the $ZZ^*$ mass region close the Higgs boson mass. This approach can not be directly applied to the top quark. The Higgs boson is much more narrow resonance than the top quark. This fact allows to calculate separately amplitudes for $pp \rightarrow ZZ$ and $pp \rightarrow H \rightarrow ZZ^*$ processes in a gauge invariant way. In case of the off-shell top quark production with its subsequent decay to $Wb$ one can not make calculations of diagrams involving the top quark pair and the single top separately in a gauge invariant way. Therefore we perform the computation of the complete gauge invariant set of diagrams and investigate a sensitivity of fiducial cross sections to deviations from the SM caused by the top quark width and related $Wtb$ coupling. This approach enables to
put model independent and fully gauge invariant constrains on the top quark width.

A. Study of the process $pp \rightarrow W^+W^-b\bar{b}$

We consider complete tree-level set of Feynman diagrams for the process $pp \rightarrow W^+W^-b\bar{b}$, in which both top quarks are off-shell. As well known, the main contribution comes from the gluon fusion subprocess [12], however, we take into account the contributions from all partonic subprocesses. The CompHEP generator [13] with MSTW2008 PDF [14] is used for the calculation. The computations are performed for a certain value of the top quark mass, for a definiteness it was taken to be $m_t = 172.5$ GeV, and for various values of the top quark width with the corresponding rescaling of the Wtb coupling.

Hadronization and fragmentation effects, as well as backgrounds impact are postponed to the next more realistic analysis, not to distract from the main idea of this research. Realistic estimations of this effects will be included in systematic uncertainty estimations.

The NLO QCD corrections for the process $pp \rightarrow W^+W^-b\bar{b}$ were computed [15] showing an impact on various kinematic distributions and making results more stable with respect to the QCD scale variation. The NLO corrections to the complete $2 \rightarrow 6$ process involving off-shell W bosons were calculated [16] and the k-factor for 13 TeV LHC energy was found to be 1.16. At this stage of our analysis, which aims to show the main effect caused by the width change, the complete leading order contributions have been taken into account, and the impact of the NLO corrections has been included in the assumed systematic uncertainties, as will be explained below.

The boundaries of fiducial double-resonant, single-resonant and non-resonant regions are expressed in terms of the SM value of the top quark width in the following way.

Double-resonant region (DR),

\begin{align*}
(m_t - n \cdot \Gamma_t^{SM} \leq M_{W^-b} & \leq m_t + n \cdot \Gamma_t^{SM}) \quad \text{and} \quad (m_t - n \cdot \Gamma_t^{SM} \leq M_{W^+b} & \leq m_t + n \cdot \Gamma_t^{SM})
\end{align*}

Single-resonant region (SR),

\begin{align*}
(m_t - n \cdot \Gamma_t^{SM} \leq M_{W^-b} & \leq m_t + n \cdot \Gamma_t^{SM}) \quad \text{and} \quad (M_{W^+b} \leq m_t - k \cdot \Gamma_t^{SM} \text{ or } m_t + k \cdot \Gamma_t^{SM} \leq M_{W^+b})
\end{align*}

or

\begin{align*}
(m_t - n \cdot \Gamma_t^{SM} \leq M_{W^+b} & \leq m_t + n \cdot \Gamma_t^{SM}) \quad \text{and} \quad (M_{W^-b} \leq m_t - k \cdot \Gamma_t^{SM} \text{ or } m_t + k \cdot \Gamma_t^{SM} \leq M_{W^-b})
\end{align*}
Non-resonant region (NR).

\[
\left( M_{W-b} \leq m_t - k \cdot \Gamma_t^{SM} \text{ or } m_t + k \cdot \Gamma_t^{SM} \leq M_{W-b} \right)
\]
and

\[
\left( M_{W+b} \leq m_t - k \cdot \Gamma_t^{SM} \text{ or } m_t + k \cdot \Gamma_t^{SM} \leq M_{W+b} \right)
\]

Here \( M_{W+b} \) and \( M_{W-b} \) are the invariant masses, \( n \) and \( k \) are integer numbers with obvious requirement \( n \leq k \) to have no overlapping regions.

One can parametrize the total top quark width as follows

\[
\Gamma_t = \xi^2 \cdot \Gamma_t^{SM} + \Delta,
\]
(2)
reflecting that the top quark width may differ from its SM value either by a modification of the Wtb coupling (e.g. see [17]) or by a presence of additional non-SM decay modes (e.g. see [18, 19]). In Eq. 2 the parameter \( \xi \) simultaneously changes the top quark width and rescales the Wtb coupling. The parameter \( \Delta \) affects the only top quark width. One should note the production cross section times branching ratio remains unchanged with variation of the parameter \( \xi \) in case of \( \Delta = 0 \). It is useful to parametrize the deviation \( \Delta \) also in terms of the SM top quark width as \( \Delta = \delta \cdot \Gamma_t^{SM} \). The parameters \( \xi \) and \( \delta \) have different origin, affect the matrix element in a different way, and therefore can not be combined in a single parameter.

In the SM \( \xi = 1 \) and \( \delta = 0 \). In order to study deviations of the top quark width from its SM value it is more convenient to have two parameters equal to zero in the SM and introduce the parameter \( \epsilon \) instead of \( \xi \) as follows.

\[
\epsilon = \xi^2 - 1.
\]
(3)

Current experimental data [2–6] indicate that deviations from the SM for the top quark width should be small. Not to contradict with this we will study dependencies of fiducial cross sections from two small parameters \( \epsilon \) and \( \delta \). As demonstrated in [9], it is reasonable to select integer parameters \( n \) and \( k \) in the interval from 10 to 20 for boundaries between resonant and non-resonant regions Eq. 1. For definiteness we take the values \( n = k = 15 \) at which 98% of the Breit-Wigner integral concentrated around the pole position [20]. The results of the computation of the fiducial cross sections at the 14 TeV collision energy in the defined DR, SR, and NR regions as a function of \( \epsilon \) and \( \delta \) parameters are shown in Fig. 1. In numerical computations the LO value of the top quark width was taken to be \( \Gamma_t^{SM} = 1.49 \) GeV.

As one can see, the surfaces of the three regions have significantly different shapes. The cross-section in the DR region is practically insensitive to simultaneous changes in the upper quark
coupling and width by the $\epsilon$ parameter, since its effect disappears when the amplitude numerator and the denominator change, respectively.

At the same time the parameter $\delta$ affects only the amplitude denominator and leads in the DR region to an inverse polynomial quadratic dependence of the cross section on it. These properties can be easily understood from the Breit-Wigner resonant behavior. In contrast, the cross section in the non-resonant region practically does not depend on the top quark width, and therefore depends very weakly on the parameter $\delta$. In turn, the cross section in the NR region depends quadratically on the parameter $\epsilon$ via the coupling constant in the amplitude numerator. One resonance region combines dependence on both types of parameters.

The fiducial cross sections in DR, SR, and NR regions are significantly different. The rate in the DR region exceeds by about one order of magnitude the rate in the SR region and by two order of magnitude the rate in the NR region. The boundaries variation within $10 \div 20$ SM top quark width does not have a significant impact on the cross section rate. NR region has the best sensitivity to the $\epsilon$ parameter but the smallest rate. The DR region has the sensitivity mostly to the direct width modification by the $\delta$ parameter.

For the collision energies of 28 TeV and 100 TeV the total rates are substantially higher but the surface shapes are very similar to the case of 14 TeV, the plots are given in Figs. 4, 5 in Appendix IV.

Precision measurements of the fiducial cross sections of the top quark production play a crucial role. Experimental analysis precision is limited by systematic uncertainties of jet energy scale, b-tagging and luminosity [21]. Statistical uncertainties are below percent level today and will decrease further with high luminosity updates [22]. We assume feasible accuracy of 10%, 8% and 5% for 14, 28 and 100 TeV collision energies including theoretical uncertainties at NLO, NNLO and, possibly, higher level by the time when new high energy machines will be realized.

Using the standard $\chi^2$ method ($\chi^2(\sigma) = \left( \frac{\sigma^{SM} - \sigma}{\Delta \sigma} \right)^2$) and requiring that the SM and modified cross sections are within one or two standard deviations from each other, we derive upper limits on $\epsilon$ and $\delta$ at 68 and 95% confidence level Fig. 2. Similar plots for 28 TeV and 100 TeV are in Appendix IV Figs. 6, 7. Combinations of all regions are presented in Fig. 3. From the limits on the parameters $\epsilon$ and $\delta$ one gets achievable constrains on the top quark width using Eq. 2. Model independent constrains on the top quark width are estimated to be from 23% to 12% for the energies from 14 to 100 TeV with assumed experimental accuracy of fiducial cross section measurements from 10% to 5%.
Gauge invariant estimation of deviations of the top quark width from its SM value is obtained in different kinematic regions. It is shown that top quark production cross section in the double resonant (DR) region is mostly sensitive to the $\delta$ parameter, which modifies only the top quark width. The fiducial cross section in the non-resonant (NR) region has sensitivity to $\epsilon$ parameter, which modifies top quark width and the Wtb coupling simultaneously. Single resonant (SR) region has comparative sensitivity to both parameters. Significant difference in dependence of fiducial cross sections in DR, SR and NR regions on $\epsilon$ and $\delta$ parameters one of the main observation of this study. This fact allows to put combined limits on $\delta$ and $\epsilon$ parameters simultaneously, and using these limits obtain constrains on the top quark. Achievable constrains in the model independent way on the top quark width are estimated to be from 23% to 12% for corresponding experimental accuracy from 10% to 5%. These results are achieved using simplified approach, all effects such
FIG. 3. Combined constraints on the $\epsilon$ and $\delta$ parameters for DR, SR and NR regions for different collision energies. Green and yellow arias correspond to exclusion limits at 68% and 95% CL on $\epsilon$ and $\delta$.

as hadronization and fragmentation, detector response as well as an impact of backgrounds are beyond the scope of current simply study demonstrating the main idea. Study of mentioned effects is postponed to the next more realistic analysis.

III. ACKNOWLEDGMENTS

The work was supported by grant 16-12-10280 of Russian Science Foundation.

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IV. APPENDIX
FIG. 4. Fiducial cross section dependencies from $\epsilon$ and $\delta$ parameters for the 28 TeV collision energy, $n = k = 15$.

FIG. 5. Fiducial cross section dependencies from $\epsilon$ and $\delta$ parameters for the 100 TeV collision energy, $n = k = 15$.

FIG. 6. Constraints on the $\epsilon$ and $\delta$ parameters for 28 TeV collision energy, $n = k = 15$ boundary for DR, SR and NR regions. Green and yellow arias correspond to exclusion limits at 68% and 95% CL on $\epsilon$ and $\delta$ for the CS measured with 8% uncertainty.
FIG. 7. Constraints on the $\epsilon$ and $\delta$ parameters for 100 TeV collision energy, $n = k = 15$ boundary for DR, SR and NR regions. Green and yellow arias correspond to exclusion limits at 68% and 95% CL on $\epsilon$ and $\delta$ for the CS measured with 5% uncertainty.