

Extracting the Top-Quark Width from Nonresonant Production

Christian Herwig,^{1,*} Tomáš Ježo,^{2,†} and Benjamin Nachman^{3,‡}

¹*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

²*Physics Institute, Universität Zürich, CH-8006 Zürich, Switzerland*

³*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*



(Received 29 March 2019; published 14 June 2019)

In the context of the standard model of particle physics, the relationship between the top-quark mass and width (Γ_t) has been precisely calculated. However, the uncertainty from current direct measurements of the width is nearly 50%. A new approach for directly measuring the top-quark width using events away from the resonance peak is presented. By using an orthogonal dataset to traditional top-quark width extractions, this new method may enable significant improvements in the experimental sensitivity in a method combination. Recasting a recent ATLAS differential cross section measurement, we find $\Gamma_t = 1.28 \pm 0.30$ GeV (1.33 ± 0.29 GeV expected), providing the most precise direct measurement of the width.

DOI: 10.1103/PhysRevLett.122.231803

Introduction.—Even though the top quark was discovered over 20 years ago [1,2] and its mass has been measured with a subpercent precision [3], direct measurements of its width Γ_t have an uncertainty of 50% or worse [4–6]. Indirect measurements of Γ_t using single top-quark production are more precise, but also require additional modeling assumptions [7,8]. In the context of the standard model (SM), the relationship between the top-quark mass and Γ_t is known at next-to-next-to-leading order (NNLO) in the strong coupling constant with an uncertainty of a few percent [9–11]. Improving the precision of Γ_t can therefore provide a stringent test of the SM.

The current methods for measuring Γ_t perform template fits to invariant mass spectra that peak near the top-quark mass. Because of their cleaner event signatures, the lepton + jets and dilepton decays from $t\bar{t}$ production are used for the fits and the most sensitive observable is m_{lb} : the invariant mass of a charged lepton and a jet originating from a b quark (b jet). While the location of the m_{lb} peak is linearly sensitive to the top-quark mass, the measured width around the peak depends sublinearly on Γ_t . This is because the measured width is dominated by the unmeasured neutrino momentum and the fragmentation of the b quark, not by Γ_t .

We propose a new method for measuring Γ_t that is linearly sensitive to Γ_t [12]. The idea is motivated by recent proposals to measure the Higgs boson width from nonresonant production [17–20], which has interesting beyond

the standard model (BSM) sensitivity [21–28] and has led to measurements by the CMS [29–32] and ATLAS [33] Collaborations. Similarly, we propose to study the $WWbb$ cross section far from the $t\bar{t}$ resonance peak, using a method that can be linearly sensitive to Γ_t . Furthermore, this approach may be sensitive to BSM physics that only affects the nonresonant part of the spectrum. Such modifications could be due to interference effects from complex phases or from new decay channels that are kinematically inaccessible at the resonance peak.

Existing calculations and measurements.—Calculations of the top-quark width at next-to-leading order (NLO) in the strong coupling constant were first performed in Refs. [34–36]. More recently, the NNLO computation of the total width has been completed [9–11], followed by fully differential calculations of the decay rate [37,38]. At leading order (LO), the dependence of the width on the top-quark mass is given by

$$\Gamma_t^{\text{LO}} = \frac{G_F m_t^3}{8\sqrt{2}\pi} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right), \quad (1)$$

assuming $|V_{tb}| = 1$ and neglecting the b -quark mass [34]. For a top-quark mass of 172.5 GeV the predicted width is 1.322 GeV, including NNLO QCD, finite b -quark and W masses, and NLO electroweak corrections [37].

The width of the top quark has been measured at the Tevatron and the Large Hadron Collider (LHC) using several approaches. Direct measurements, based on the reconstructed top-quark mass distribution in events with top-quark pairs were made by the CDF [4], ATLAS [5], and CMS [6] Collaborations, with Ref. [5] obtaining the most precise value of $\Gamma_t = 1.76 \pm 0.33(\text{stat})_{-0.68}^{+0.79}(\text{syst})$ using this method. The D0 [7] and CMS [8] Collaborations have each determined the width indirectly, via a combination of

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

the t -channel single-top cross section and measurement of the branching fraction ratio $\mathcal{BR}(t \rightarrow Wb)/\mathcal{BR}(t \rightarrow Wq)$. The most precise estimate from Ref. [8] finds $\Gamma_t = 1.36 \pm 0.02(\text{stat})_{-0.11}^{+0.14}(\text{syst})$, with the restrictive assumption that $\mathcal{BR}(t \rightarrow Wq) = 1$.

Sensitivity of the ATLAS measurement.—Recently, the ATLAS Collaboration reported a differential cross section measurement of events with two charged leptons ($\ell = e, \mu$) and two b jets, in an observable sensitive to both top-quark pair ($t\bar{t}$) and single top-quark (tWb) production [39]. The measurement probed the interference between $t\bar{t}$ and tWb by comparing the data with state-of-the-art interference models [40–43]. The target observable was the minimax pairing of lepton-jet invariant masses $m_{b\ell}$,

$$m_{b\ell}^{\text{minimax}} = \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}, \quad (2)$$

where the labeling of leptons and b -tagged jets is arbitrary. For values of $m_{b\ell}^{\text{minimax}} > \sqrt{m_t^2 - m_W^2}$, the top-quark pair process at LO enters only through off-shell effects and tWb contributions become important. In this high- $m_{b\ell}^{\text{minimax}}$ region, the NLO calculation of $bb\ell^+\nu_\ell l^-\bar{\nu}_l b\bar{b}$ including interference effects [44–49] and parton showering [43], provides an excellent description of the data.

The advent of such calculations enables these data to constrain other properties of the top quark. Specifically, modifications to the top-quark width impact the $m_{b\ell}^{\text{minimax}}$ spectrum. The origin of this dependence is twofold.

First, the cross section of events with $m_{b\ell}^{\text{minimax}}$ considerably greater than $\sqrt{m_t^2 - m_W^2}$ has a contribution from top-quark pair production diagrams, where at least one of the top (anti-)quarks is produced far off shell. The width impacts the size of this contribution directly through the top-quark line shape, which can be described as a Breit-Wigner distribution:

$$\frac{d\sigma}{dm_{Wb}^2} \sim \frac{1}{(m_{Wb}^2 - m_t^2)^2 + m_t^2\Gamma_t^2}. \quad (3)$$

Integrating over both top-quark resonances, the fraction of off-shell events is found to be linearly dependent on the width [50].

Second, the “tail” cross section is also enhanced by tWb diagrams containing only one top-(anti-)quark propagator. While this is a smaller overall contribution than that of top-quark pairs, the W boson and b quark not originating from a top quark often satisfy $m_{Wb} > m_t$, so that a comparatively large fraction of such events have $m_{b\ell}^{\text{minimax}} > \sqrt{m_t^2 - m_W^2}$. For this reason, width variations affect the relative importance of these two classes of diagrams and thus the shape itself of the $m_{b\ell}^{\text{minimax}}$ observable.

In Ref. [39], the fractional contribution of $WWb\bar{b}$ events to 15 bins of $m_{b\ell}^{\text{minimax}}$ was reported, including many

measurements with $m_{b\ell}^{\text{minimax}} > \sqrt{m_t^2 - m_W^2}$. These data enable an extraction of the top-quark width, assuming that BSM effects modifying the width do not also modify nonresonant production. Despite the measurement not considering a width uncertainty, the unfolded result would only be impacted through migrations in the response matrix, and the effect is thus expected to be negligible. For comparison, the uncertainty due to unfolding with different interference schemes is $<5\%$ in most bins, despite the predictions leading to raw differences of 50% or more for large values of $m_{b\ell}^{\text{minimax}}$.

Signal models and event selection.—The primary calculation used to model the $W^+W^-b\bar{b}$ signal is the `B_BBAR_41` [43] generator implemented in `POWHEG BOX RES` [51]. It includes NLO QCD corrections and matching with the parton shower (PS) based on the `POWHEG` method [52,53]. The process is described in terms of exact matrix elements for $pp \rightarrow \ell^+\nu_\ell l^-\bar{\nu}_l b\bar{b}$, dominated by top-pair topologies with leptonic W -boson decays, with massive b quarks provided by the `OPENLOOPS` program [54]. The `B_BBAR_41` generator combines for the first time consistent NLO + PS treatment of top-quark resonances, including quantum corrections to top-quark propagators and off-shell top-quark decay chains; exact spin correlations at NLO, interference between NLO radiation from top-quark production and decays, full NLO accuracy in $t\bar{t}$ production and decays; NLO accuracy in b -quark kinematics; access to phase-space regions with unresolved b quarks and/or jet vetoes.

The nominal event sample was obtained using the `NNPDF30_nlo_as_0118` parton distribution function (PDF) set and the input top-quark mass value $m_t = 172.5$ GeV. Additional samples were generated with a range of top-quark widths $\Gamma_t \in \{0.66, 1, \Gamma_t^{\text{SM}}, 1.66, 2\}$ GeV (with $m_t = 172.5$ and $\Gamma_t^{\text{SM}} = 1.3328$ GeV) [55] to enable the extraction of the best-fit value from data, with a range of top-quark mass values $m_t \in \{171.5, 172.5, 173.5\}$ GeV (with $\Gamma_t = \Gamma_t^{\text{SM}}$) in order to estimate the uncertainty due to the top-quark mass, and a range of α_S values in the PDF $\alpha_S \in \{0.115, 0.118, 0.121\}$ (with $m_t = 172.5$ GeV and $\Gamma_t = \Gamma_t^{\text{SM}}$) to explore the uncertainty due to variation of scale of the shower evolution. The central renormalization and factorization scales are set to the geometric average of transverse masses of the top quark and antitop quark, and the value of `hdamp` is always set equal to the input value of the top-quark mass. The samples include all possible combinations of different family final state leptons (corresponding to the channel 7 setting). Events also feature additional weights due to standard 7-point scale variation and due to PDF variation. Up to three hardest emissions are kept with the `allrad 1` setting, one from the production process and one from each of the top-quark resonances, and matching to `PYTHIA 8.2` [56] makes use of both the `POWHEGHOOKS` and `POWHEGHOOKSBB4L` [57] vetoes, and `A14` set of tuned parameters [58]. In the samples with

$\alpha_S \in \{0.115, 0.121\}$ the SPACESHOWER:ALPHASVALUE parameter of shower evolution in PYTHIA 8.2 is set correspondingly.

In addition, a LO calculation of the $W^+W^-b\bar{b}$ process is examined, calculated by MADGRAPH5_AMC@NLO 2.6.4 (MG5_AMC@NLO) [59] with up to 2 extra jets, matched to a parton shower implemented in PYTHIA 8.240. This sample of events was simulated using the NNPDF23_nlo_as_0118 PDF set, the A14 set of tuned parameters, $m_t = 172.5$ GeV, and $\Gamma_t \in \{0.66, 1, 1.33, 1.66, 2\}$ GeV. Alternative samples were produced with α_S varied as described above, as well as with alternative top-quark mass hypotheses $m_t \in \{170, 175\}$ GeV.

Event samples are analyzed and compared to data using the selection criteria of Ref. [39] as implemented in the Rivet toolkit [60]. Briefly, leptons and jets are reconstructed at particle-level with selections based upon the acceptance of the ATLAS detector. Leptons are dressed with nearby photons and are required to have transverse momentum $p_T > 28$ GeV and pseudorapidity $|\eta| < 2.47$ (2.5) for electrons (muons). Jets are reconstructed with the anti- k_T algorithm using a radius parameter of $R = 0.4$ [61–63] and considered in the analysis only if $p_T > 25$ GeV and $|\eta| < 2.5$. They are b tagged if a B hadron with $p_T > 5$ GeV is found within the jet cone. Events are selected that have two leptons, two b -tagged jets, with same-flavor lepton events vetoed if the dilepton mass $m_{\ell\ell} < 10$ GeV or satisfies $|m_{\ell\ell} - m_Z| < 15$ GeV.

The B_BBAR_41 simulation produces events with different-flavor leptons and must be corrected to account for same-flavor contributions. The ee and $\mu\mu$ contribution is obtained by reweighting the generated $e\mu$ events that satisfy same-flavor $m_{\ell\ell}$ requirements. Good closure of this technique is found using the LO MG5_AMC@NLO simulation, which includes all leptonic decays of the W boson. Further, the contribution of di- τ events (with fully leptonic τ decays) is found to be negligible and is not considered.

Top-quark width extraction.—Using the experimental data of Ref. [39] and the signal models described above, the top-quark width is extracted by minimizing the following χ^2 statistic:

$$\chi^2 = \sum_{i,j} (d_i - m_i) V_{ij}^{-1} (d_j - m_j), \quad (4)$$

where d_i is the measured, normalized, differential cross section indexed by bins of $m_{b\ell}^{\text{minimax}}$ and m_i is the corresponding prediction. The covariance matrix V_{ij} gives the uncertainty on the unfolded data, including bin-to-bin correlations. The measurements with $m_{b\ell}^{\text{minimax}} < 160$ GeV are only weakly sensitive to variations in Γ_t and are thus excluded from Eq. (4).

For each systematic uncertainty, the differential cross section is computed separately for a set of test widths Γ_t . To interpolate between generated samples, the calculated yields are fit as a function of the top-quark width to obtain a

parametrized prediction $m_i = F_i(\Gamma_t)$, individually for each bin i . Choosing the functions F_i to be quadratic in Γ_t is found to fit the calculated predictions well for each bin of $m_{b\ell}^{\text{minimax}}$. Thus, given the data and choice of signal model, the statistic may be written explicitly as a function of the width $\chi^2 = \chi^2(\Gamma_t | d, m)$. By minimizing this function with respect to Γ_t , the best-fit value of the width may be extracted.

Uncertainties.—Uncertainties stemming from the precision of the experimental measurement, from choices in signal modeling, and from the limited number of generated events are each considered. Pseudoexperiments are used to assess the experimental uncertainty, where pseudodata are drawn from a multivariate Gaussian distribution with mean and covariance matrix given by d_i and V_{ij} . For each pseudoexperiment a random dataset d_i^{pseudo} is drawn from this distribution and a new value of Γ_t is extracted by minimizing $\chi^2(\Gamma_t | d_i^{\text{pseudo}}, m_i)$. The experimental uncertainty is calculated as the 1σ range of extracted widths from the pseudoexperiment distribution.

Theoretical uncertainties are assessed on the B_BBAR_41 signal model by generating event samples with alternative input parameters. The nominal simulated sample with alternative weight sets is used to estimate the uncertainty due to the choice of PDF as well as renormalization and factorization scales. The PDF uncertainty is assessed as the standard deviation of widths extracted over the set of 100 eigenvector variations of the NNPDF30_nlo_as_0118 PDF set. The scale uncertainty is the maximum pairwise difference between the widths extracted with the nominal and varied scales.

For top-quark mass and α_S variations, independent samples of events are generated. To minimize the impact of statistical variations across samples and make optimal use of all generated events, the systematic uncertainty dependence is extracted in a fit, writing

$$m_i(\alpha_s, m_t) = \hat{m}_i(\alpha_s^{\text{SM}}, m_t^{\text{SM}}) + \hat{a}_i(\alpha_s - \alpha_s^{\text{SM}}) + \hat{b}_i(m_t - m_t^{\text{SM}}). \quad (5)$$

Further, the fitted coefficients \hat{a}_i, \hat{b}_i are constrained to vary quadratically in $m_{b\ell}^{\text{minimax}}$ to reduce unphysical, statistical fluctuations. The postfit yields for m_t and α_s variations are then used to reweight the nominal $m_{b\ell}^{\text{minimax}}$ spectra for each value of the top-quark width and to extract the χ^2 -minimizing value for each variation.

An uncertainty due to the finite number of simulated events is estimated from an ensemble of pseudoexperiments where the predicted yields for all bins of each value of the top-quark width are varied within their uncertainties. A width is obtained for each trial to assess the impact on the final extracted parameter.

For the MG5_AMC@NLO signal model, an identical set of uncertainties are assessed, employing the same estimation methods, with the following modification: the

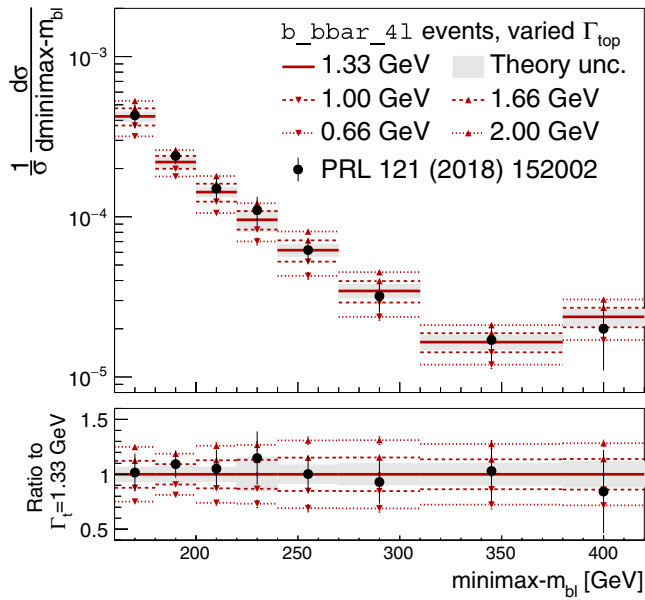


FIG. 1. The $m_{b\ell}^{\text{minimax}}$ spectrum predicted using $B_{\text{BBAR}}41$ is shown for various values of the top-quark width. Data from the unfolded ATLAS measurement are included for comparison. The gray band shows the theoretical uncertainty for the simulated sample corresponding to the predicted SM value of the width.

NNPDF23_nlo_as_0119 PDF set is used as the nominal value for this sample. The top-quark mass uncertainty is assessed using samples with $m_t = 170, 175$ GeV, interpolating to obtain the same 1 GeV variations as used above.

The nominal $B_{\text{BBAR}}41$ prediction is compared to ATLAS data in Fig. 1. Predictions for alternate values of the top-quark width are also shown, as well as the theoretical uncertainty on the nominal estimate. A summary of the uncertainties on the width extracted using both signal models is presented in Table I. Changes to the top-quark width are found to produce larger variations in the relative fraction of events in the $m_{b\ell}^{\text{minimax}}$ tail for samples generated using $MG5_AMC@NLO$ than $B_{\text{BBAR}}41$. As a result, the impact of uncertainties on the extracted width parameter is generally smaller when using the LO simulation, despite the impact on the normalized

TABLE I. Uncertainty on the top-quark width extracted for data, with individual contributions shown from experimental, theoretical, and statistical sources.

Uncertainty [GeV]	$B_{\text{BBAR}}41$	$MG5_AMC@NLO$
Experimental	+0.27/ - 0.26	± 0.20
Theory		
PDF	± 0.06	± 0.04
Scale	± 0.10	± 0.06
m_t	± 0.03	± 0.03
α_s	± 0.06	± 0.04
Combined	± 0.14	± 0.10
Simulation Stats.	± 0.04	± 0.04
Total	± 0.30	± 0.22

differential cross section being similar. This effect leads to a smaller uncertainty due to scale variations, among others, in the LO sample than in the more accurate $B_{\text{BBAR}}41$ calculation.

Results.—Using the $B_{\text{BBAR}}41$ signal description, a top-quark width of 1.28 ± 0.30 GeV is extracted (1.33 ± 0.29 GeV expected), as shown in Fig. 2. A width is also extracted using the leading order $MG5_AMC@NLO$ simulation, obtaining 1.18 ± 0.22 GeV (1.33 ± 0.23 GeV expected). These measurements are more precise than the previously most precise direct measurement of ($1.76^{+0.86}_{-0.76}$ GeV) [5].

These results can also be interpreted into a limit on the BSM decays of the top-quark through the relation

$$\mathcal{BR}(t \rightarrow \text{BSM}) < \frac{\Gamma_{\text{ext}}^{+95\%} - \Gamma_{t \rightarrow bW}^{\text{SM}}}{\Gamma_{\text{ext}}^{+95\%}}, \quad (6)$$

where $\Gamma_{t \rightarrow bW}^{\text{SM}}$ is the SM partial width for $t \rightarrow Wb$ and $\Gamma_{\text{ext}}^{+95\%}$ is the (one-sided) upper limit on the top-quark width at the 95% confidence level. The limit is $\mathcal{BR}(t \rightarrow \text{BSM}) < 29\%$ using the $B_{\text{BBAR}}41$ model (30% expected) and 18% using the $MG5_AMC@NLO$ model (26% expected). Model-specific BSM constraints are also possible for processes which have a significant effect in the off-shell region defined by high $m_{b\ell}^{\text{minimax}}$. For example, a charged Higgs H^+ produced via its btH^+ coupling and then decaying via $\tau\nu$ would preferentially enhance this region. However, limits from this measurement are not as strong as direct searches [64–66] because of the penalties from the τ decay to e/μ .

Conclusions.—In conclusion, we present a novel method to directly measure the top-quark width and have provided a first estimate using the technique based on a recent measurement of top-quark properties by the ATLAS Collaboration. The estimate of 1.28 ± 0.31 GeV obtained using the POWHEG BOX RES calculation is in good agreement with the standard model prediction of 1.32 GeV and more precise than existing direct measurements. Future measurements with more data and in combination with

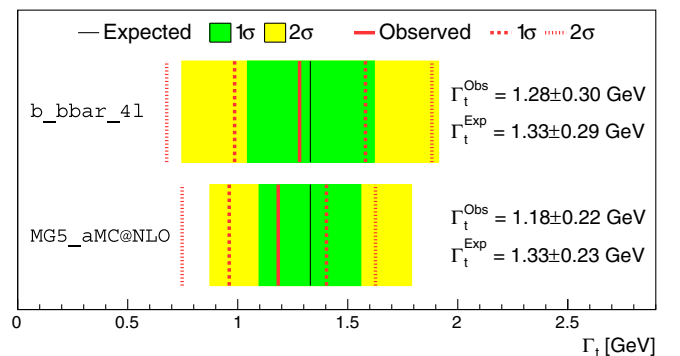


FIG. 2. Observed and expected top-quark widths for the $B_{\text{BBAR}}41$ and $MG5_AMC@NLO$ signal models.

other extractions will be able to provide robust constraints on the top sector of the SM.

We would like to thank Till Eifert, Silvia Ferrario Ravasio, Jay Howarth, Elliot Lipeles, and Stefano Pozzorini for careful reading and suggestions on the manuscript. We would also like to thank Stefan Prestel for a clarifying conversation about the PYTHIA treatment of resonances. B. N. is supported by the DOE under Contract No. DE-AC02-05CH11231. C. H. is supported by the DOE under Contract No. DE-SC0007901. The work of T. J. is supported in part by the University of Zürich under the Contract No. K-72319-02-01 and in part by the Swiss National Science Foundation under Contract No. BSCG10-157722.

*herwig@sas.upenn.edu

†tomas.jezo@physik.uzh.ch

‡bpnachman@lbl.gov

- [1] F. Abe *et al.* (CDF Collaboration), Observation of Top Quark Production in $\bar{p}p$ Collisions, *Phys. Rev. Lett.* **74**, 2626 (1995).
- [2] S. Abachi *et al.* (D0 Collaboration), Observation of the Top Quark, *Phys. Rev. Lett.* **74**, 2632 (1995).
- [3] ATLAS, CDF, CMS, and D0 Collaborations, First combination of Tevatron and LHC measurements of the top-quark mass, [arXiv:1403.4427](https://arxiv.org/abs/1403.4427).
- [4] T. Aaltonen *et al.* (CDF Collaboration), Direct Measurement of the Total Decay Width of the Top Quark, *Phys. Rev. Lett.* **111**, 202001 (2013).
- [5] M. Aaboud *et al.* (ATLAS Collaboration), Direct top-quark decay width measurement in the $t\bar{t}$ lepton + jets channel at $\sqrt{s} = 8$ TeV with the ATLAS experiment, *Eur. Phys. J. C* **78**, 129 (2018).
- [6] CMS Collaboration, Bounding the top quark width using final states with two charged leptons and two jets at $\sqrt{s} = 13$ TeV, Report No. CMS-PAS-TOP-16-019, 2016.
- [7] V. Abazov *et al.* (D0 Collaboration), An Improved determination of the width of the top quark, *Phys. Rev. D* **85**, 091104 (2012).
- [8] V. Khachatryan *et al.* (CMS Collaboration), Measurement of the ratio $\mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$ in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Lett. B* **736**, 33 (2014).
- [9] A. Czarnecki and K. Melnikov, Two-loop qcd corrections to top quark width, *Nucl. Phys.* **B544**, 520 (1999).
- [10] K. G. Chetyrkin, R. Harlander, T. Seidensticker, and M. Steinhauser, Second order qcd corrections to $\Gamma(t \rightarrow wb)$, *Phys. Rev. D* **60**, 114015 (1999).
- [11] I. Blokland, A. Czarnecki, M. Ślusarczyk, and F. Tkachov, Heavy-to-Light-Quark Decays with Two-Loop Accuracy, *Phys. Rev. Lett.* **93**, 062001 (2004).
- [12] Similar ideas were recently discussed in Refs. [13–15]. The key difference with respect to this analysis are that these studies (I) were performed at the parton-level only, (II) do not propose a physical observable for measuring the cross section, and (III) do not extract any results with LHC data (and in the case of Ref. [13], are for e^+e^-). A related idea using b -jet charge asymmetries in pp collisions was proposed in Ref. [16]. While a promising proposal, this latter study does not yet include reconstruction effects.
- [13] S. Liebler, G. Moortgat-Pick, and A. S. Papanastasiou, Probing the top-quark width through ratios of resonance contributions of $e^+e^- \rightarrow W^+W^-b\bar{b}$, *J. High Energy Phys.* **03** (2016) 099.
- [14] A. Baskakov, E. Boos, and L. Dudko, Model independent top quark width measurement using a combination of resonant and non resonant cross sections, *Phys. Rev. D* **98**, 116011 (2018).
- [15] A. Baskakov, E. Boos, and L. Dudko, On the top-quark width measurement using a combination of resonant and non resonant cross sections, Proceedings of the 23th International Workshop on High Energy Physics and Quantum Field Theory (QFTHEP 2017): Yaroslavl, Russia, EPJ Web Conf. 158, 04007 (EDP Sciences, Les Ulis Cedex, 2017).
- [16] P. P. Giardino and C. Zhang, Probing the top-quark width using the charge identification of b jets, *Phys. Rev. D* **96**, 011901(R) (2017).
- [17] N. Kauer and G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, *J. High Energy Phys.* **08** (2012) 116.
- [18] F. Caola and K. Melnikov, Constraining the Higgs boson width with ZZ production at the LHC, *Phys. Rev. D* **88**, 054024 (2013).
- [19] J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC using full analytic results for $gg \rightarrow e^-e^+\mu^-\mu^+$, *J. High Energy Phys.* **04** (2014) 060.
- [20] J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC: Complementary results from $H \rightarrow WW$, *Phys. Rev. D* **89**, 053011 (2014).
- [21] C. Englert and M. Spannowsky, Limitations and opportunities of off-shell coupling measurements, *Phys. Rev. D* **90**, 053003 (2014).
- [22] G. Cacciapaglia, A. Deandrea, G. D. LaRochelle, and J. B. Flament, Higgs Couplings: Disentangling New Physics with Off-Shell Measurements, *Phys. Rev. Lett.* **113**, 201802 (2014).
- [23] A. Azatov, C. Grojean, A. Paul, and E. Salvioni, Taming the off-shell Higgs boson, *J. Exp. Theor. Phys.* **120**, 354 (2015).
- [24] M. Ghezzi, G. Passarino, and S. Uccirati, Bounding the Higgs width using effective field theory, Proceedings of the 12th DESY Workshop on Elementary Particle Physics: Loops and Legs in Quantum Field Theory (LL2014): Weimar, Germany, 2014, *Proc. Sci.*, LL2014 (2014) 072.
- [25] M. Buschmann, D. Goncalves, S. Kuttimalai, M. Schonherr, F. Krauss, and T. Plehn, Mass effects in the Higgs-Gluon coupling: Boosted vs off-shell production, *J. High Energy Phys.* **02** (2015) 038.
- [26] J. S. Gainer, J. Lykken, K. T. Matchev, S. Mrenna, and M. Park, Beyond Geolocating: Constraining higher dimensional operators in $H \rightarrow 4\ell$ with off-shell production and more, *Phys. Rev. D* **91**, 035011 (2015).
- [27] C. Englert, Y. Soreq, and M. Spannowsky, Off-shell Higgs coupling measurements in BSM scenarios, *J. High Energy Phys.* **05** (2015) 145.
- [28] D. Goncalves, T. Han, and S. Mukhopadhyay, Off-Shell Higgs Probe of Naturalness, *Phys. Rev. Lett.* **120**, 111801 (2018); Erratum, *Phys. Rev. Lett.* **121**, 079902(E) (2018).
- [29] V. Khachatryan *et al.* (CMS Collaboration), Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs, *Phys. Lett. B* **736**, 64 (2014).

- [30] V. Khachatryan *et al.* (CMS Collaboration), Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width, *J. High Energy Phys.* **09** (2016) 051.
- [31] V. Khachatryan *et al.* (CMS Collaboration), Limits on the Higgs boson lifetime and width from its decay to four charged leptons, *Phys. Rev. D* **92**, 072010 (2015).
- [32] A. M. Sirunyan *et al.* (CMS Collaboration), Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **11** (2017) 047.
- [33] M. Aaboud *et al.* (ATLAS Collaboration), Constraints on off-shell Higgs boson production and the Higgs boson total width in $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states with the ATLAS detector, *Phys. Lett. B* **786**, 223 (2018).
- [34] M. Jeżabek and J. H. Kühn, QCD corrections to semileptonic decays of heavy quarks, *Nucl. Phys.* **B314**, 1 (1989).
- [35] A. Czarnecki, QCD corrections to the decay $t \rightarrow Wb$ in dimensional regularization, *Phys. Lett. B* **252**, 467 (1990).
- [36] C. S. Li, R. J. Oakes, and T. C. Yuan, Qcd corrections to $t \rightarrow W^+ + b$, *Phys. Rev. D* **43**, 3759 (1991).
- [37] J. Gao, C. S. Li, and H. X. Zhu, Top Quark Decay at Next-to-Next-to Leading Order in QCD, *Phys. Rev. Lett.* **110**, 042001 (2013).
- [38] M. Brucherseifer, F. Caola, and K. Melnikov, $\mathcal{O}(\alpha_s^2)$ corrections to fully-differential top quark decays, *J. High Energy Phys.* **04** (2013) 059.
- [39] M. Aaboud *et al.* (ATLAS Collaboration), Probing the Quantum Interference Between Singly and Doubly Resonant Top-Quark Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector, *Phys. Rev. Lett.* **121**, 152002 (2018).
- [40] S. Frixione, E. Laenen, P. Motylinski, C. D. White, and B. R. Webber, Single-top hadroproduction in association with a W boson, *J. High Energy Phys.* **07** (2008) 029.
- [41] W. Hollik, J. M. Lindert, and D. Pagani, NLO corrections to squark-squark production and decay at the LHC, *J. High Energy Phys.* **03** (2013) 139.
- [42] F. Demartin, B. Maier, F. Maltoni, K. Mawatari, and M. Zaro, tWH associated production at the LHC, *Eur. Phys. J. C* **77**, 34 (2017).
- [43] T. Ježo, J. M. Lindert, P. Nason, C. Oleari, and S. Pozzorini, An NLO + PS generator for $t\bar{t}$ and Wt production and decay including non-resonant and interference effects, *Eur. Phys. J. C* **76**, 691 (2016).
- [44] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, and M. Worek, Complete off-shell effects in top quark pair hadroproduction with leptonic decay at next-to-leading order, *J. High Energy Phys.* **02** (2011) 083.
- [45] A. Denner, S. Dittmaier, S. Kallweit, and S. Pozzorini, NLO QCD Corrections to WWbb Production at Hadron Colliders, *Phys. Rev. Lett.* **106**, 052001 (2011).
- [46] A. Denner, S. Dittmaier, S. Kallweit, and S. Pozzorini, NLO QCD corrections to off-shell top-antitop production with leptonic decays at hadron colliders, *J. High Energy Phys.* **10** (2012) 110.
- [47] G. Heinrich, A. Maier, R. Nisius, J. Schlenk, and J. Winter, NLO QCD corrections to $W^+W^-b\bar{b}$ production with leptonic decays in the light of top quark mass and asymmetry measurements, *J. High Energy Phys.* **06** (2014) 158.
- [48] R. Frederix, Top Quark Induced Backgrounds to Higgs Production in the $WW^{(*)} \rightarrow ll\nu\nu$ Decay Channel at Next-to-Leading-Order in QCD, *Phys. Rev. Lett.* **112**, 082002 (2014).
- [49] F. Cascioli, S. Kallweit, P. Maierhöfer, and S. Pozzorini, A unified NLO description of top-pair and associated Wt production, *Eur. Phys. J. C* **74**, 2783 (2014).
- [50] N. Kauer and D. Zeppenfeld, Finite width effects in top quark production at hadron colliders, *Phys. Rev. D* **65**, 014021 (2001).
- [51] T. Ježo and P. Nason, On the treatment of resonances in next-to-leading order calculations matched to a parton shower, *J. High Energy Phys.* **12** (2015) 065.
- [52] P. Nason, A New method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* **11** (2004) 040.
- [53] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with Parton shower simulations: The POWHEG method, *J. High Energy Phys.* **11** (2007) 070.
- [54] F. Cascioli, P. Maierhofer, and S. Pozzorini, Scattering Amplitudes with Open Loops, *Phys. Rev. Lett.* **108**, 111601 (2012).
- [55] The value of Γ_t^{SM} is the NLO top-quark width calculated by `b_bbar_41` from all the other input values.
- [56] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [57] S. Ferrario Ravasio, T. Ježo, P. Nason, and C. Oleari, A theoretical study of top-mass measurements at the LHC using NLO + PS generators of increasing accuracy, *Eur. Phys. J. C* **78**, 458 (2018).
- [58] ATLAS Collaboration, ATLAS Run 1 Pythia 8 tunes, Report No. ATL-PHYS-PUB-2014-021, 2014.
- [59] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [60] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth, J. Monk, H. Schulz, and F. Siegert, Rivet user manual, *Comput. Phys. Commun.* **184**, 2803 (2013).
- [61] M. Cacciari, G. P. Salam, and G. Soyez, The anti- k_r jet clustering algorithm, *J. High Energy Phys.* **04** (2008) 063.
- [62] M. Cacciari and G. P. Salam, Dispelling the N^3 myth for the k_r jet-finder, *Phys. Lett. B* **641**, 57 (2006).
- [63] M. Cacciari, G. P. Salam, and G. Soyez, FastJet User Manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [64] M. Aaboud *et al.* (ATLAS Collaboration), Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu_\tau$ in the $\tau + \text{jets}$ and $\tau + \text{lepton}$ final states with 36 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS experiment, *J. High Energy Phys.* **09** (2018) 139.
- [65] M. Aaboud *et al.* (ATLAS Collaboration), Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **11** (2018) 085.
- [66] V. Khachatryan *et al.* (CMS Collaboration), Search for a charged Higgs boson in pp collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **11** (2015) 018.