Probing the top-quark width using the charge identification of *b* jets

Pier Paolo Giardino[1,*] and Cen Zhang[1,2,†]

[1]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

We propose a new method for measuring the top-quark width based on the on-/off-shell ratio of *b*-charge asymmetry in $pp \to Wbj$ production at the LHC. The charge asymmetry removes virtually all backgrounds and related uncertainties, while remaining systematic and theoretical uncertainties can be taken under control by the ratio of cross sections. Limited only by statistical error, in an optimistic scenario, we find that our approach leads to good precision at high integrated luminosity, at a few hundred MeV assuming 300–3000 fb^{-1} at the LHC. The approach directly probes the total width, in such a way that model-dependence can be minimized. It is complementary to existing cross section measurements which always leave a degeneracy between the total rate and the branching ratio, and provides valuable information about the properties of the top quark. The proposal opens up new opportunities for precision top measurements using a *b*-charge identification algorithm.

I. INTRODUCTION

As the heaviest elementary particle known to date, the top quark plays a unique role in revealing physics beyond the standard model (BSM). It is often said that the LHC has already moved the top-quark physics into a precision era. In fact, many key observables, such as mass and inclusive cross sections, are already measured at the percentage level [1]. However, the situation becomes much worse once the top-quark width, Γ_t, is taken into account. Since all the cross section measurements involve also the branching ratio to a given final state, our inadequate knowledge on the total width of the top quark prevents us from directly interpreting them as model-independent constraints on the top-quark couplings. Currently, direct measurement of the top-quark width is only possible through (partially) reconstructing the top-quark kinematics. The most recent limit from CMS [2] still allows for $\mathcal{O}(1)$ deviation from the standard model (SM) value. Indirect measurement using $\mathrm{Br}(t \to Wb)/\mathrm{Br}(t \to Wq)$ could give much more precise limits [3], however, they are based on strong assumptions including $\mathrm{Br}(t \to Wq) = 1$. As a result, BSM physics that enhances the major production mechanisms and at the same time increases the top-quark width, e.g. through undetectable decay channels, can still leave the measured cross sections unchanged, and will not be directly excluded by existing measurements.

To break this degeneracy, top-width measurements have been proposed at the future lepton colliders [4–9]. In this paper, instead of resorting to future colliders, we propose a new way to directly measure the width of the top quark at the LHC, by using the *b*-charge asymmetry. The approach probes the total width, including exotic channels, but is

approximately independent of BSM couplings, thus placing direct limits on Γ_t and resolving the degeneracy between top couplings and the total width. The main feature of this method is that the background is essentially removed by the asymmetry, while systematic and theoretical errors are largely canceled by taking the ratio of the asymmetries in on-/off-shell regions, therefore we expect this approach to reach a good precision at high integrated luminosity.

II. *b*-CHARGE ASYMMETRY

The basic idea is to probe the $bW^+ \to t \to bW^+$ resonance (see Fig. 1 left), which is sensitive to Γ_t, and compare with a different probe of the same amplitude that is not sensitive to Γ_t. One possibility is to measure the same process but in both on-/off-shell regions. This has been proposed as a way to constrain the Higgs width [10–15]. Another possibility is to measure the $\bar{b}W^+ \to \bar{b}W^+$ scattering amplitude, which is related to $bW^+ \to t \to bW^+$ by the crossing symmetry, as shown in Fig. 1 right. It tests the same amplitude, but is insensitive to Γ_t, as the top quark is now in the *t*-channel. At a hadron collider, the initial state *W* is emitted from the proton, so the full process of interest is $pp \to Wbj$, which contains both channels. However, unlike the Higgs-width measurement where the off-shell contribution gives roughly 20% of the total signal due to
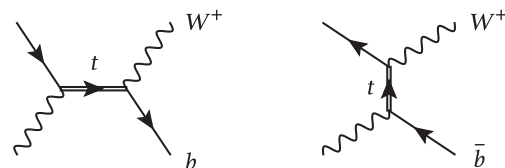

FIG. 1. $bW \to bW$ scattering amplitude in *s*- and *t*-channels. Top quark is represented by double lines.

*pgiardino@bnl.gov
†cenzhang@ihep.ac.cn

ZZ threshold [14], the top-resonance does not have this "high-tail" in its off-shell region. For this reason both measurements (off-shell and t-channel) are difficult due to overwhelming backgrounds from QCD and $t\bar{t}$ production.

We propose to measure the difference between s- and t-channel bW scattering, which essentially corresponds to a b-charge asymmetry, $\sigma^A = \sigma(b) - \sigma(\bar{b})$, and take its on-/off-shell ratio. The main reason is that, even though the b-charge is symmetric in the proton, in the signal the difference between s-/t-channels translates the W-charge asymmetry in the proton into a b-charge asymmetry, while in the background the b-charge remains symmetric to a good approximation. This makes σ^A an ideal observable to remove backgrounds. Let us consider the following background sources:

(i) *QCD.* The dominant contribution to Wbj final state comes from QCD production, where the W is emitted from a light quark, see Fig. 2(a). At the leading order (LO) this process is symmetric under the exchange of b and $\bar{b}$, due to the fact that the b-quark couples only to one gluon. The color charge carried by b transforms as $T^A \to -T^{A*}$, which means that δ^{AB} and f^{ABC} are even while d^{ABC} is odd under charge conjugation. Since the b color charge is present only as δ^{AB} at the LO, partonic cross section of this process is invariant under $b \leftrightarrow \bar{b}$. Given that $b/\bar{b}$ has the same PDF, $\sigma(bW^\pm)$ will be equal to $\sigma(\bar{b}W^\pm)$. This statement does not hold at the next-to-leading order (NLO) in QCD, because the box diagrams will induce a d^{ABC} in the b-quark current. However, with numerical simulation we will show that the resulting asymmetry is tiny. Note that under C or CP the process is not invariant due to a difference in the PDF of the initial state quark.

(ii) *$t\bar{t}$ production.* The $t\bar{t}$ production can mimic the signal if one of the W-bosons decays hadronically, see Fig. 2(b). Unlike the QCD background, they are not invariant under b-charge conjugation, but are invariant under CP (we assume $V_{tb} = 1$). For $gg \to t\bar{t}$ component we thus expect $\sigma(bW^\pm)$ to cancel

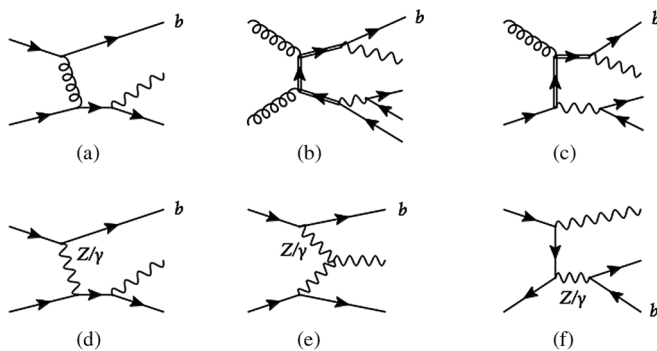$\sigma(\bar{b}W^\mp)$. The $q\bar{q}$ initial state gives a different boost to the center of mass frame under charge conjugation, leading to the $t\bar{t}$ charge asymmetry at the LHC. This could in principle result in a small $b\bar{b}$ asymmetry if cuts on rapidities are imposed. However, the top-quark charge asymmetry is only an NLO effect, at roughly ~1% at the LHC [16]. Given that our cuts will not be sensitive to the difference in rapidity between b and $\bar{b}$, this is again expected to be a tiny effect.

(iii) *tW production.* See Fig. 2(c). Similar to $t\bar{t}$ production, this process, with g and b in its initial state, is invariant under CP conjugation. We expect the resulting $b\bar{b}$ asymmetry to vanish up to NLO in QCD. The same argument applies also to WWb production.

(iv) *EW.* These consist of all the nontop diagrams in the $bW \to bW$ scattering amplitude. Even though we call them electroweak (EW) background, they actually belong to the same gauge group of the signal process, and in principle should be defined as part of the signal. We list them here because they do not probe the desired amplitudes in Fig. 1, and may lead to a model-dependence, for example, if the tbW coupling g_{tbW} deviates from the SM. Nevertheless, under the b charge conjugation only the $V - A$ interference could contribute. We will show that, after imposing kinematic cuts that suppress the unwanted topologies, the remaining asymmetry from EW production is at the 1% level for background and ~10% for the interference with signal.

In conclusion, the b-charge asymmetry $\sigma^A = \sigma(b) - \sigma(\bar{b})$ is almost free of background. Two comments are in order. First, from a 4-flavor scheme point of view the process is $pp \to Wb\bar{b}j$, which always gives the same number of b and $\bar{b}$. A nonzero σ^A arises because we measure only the charge of the b-jet with a higher p_T, which is more likely to have interacted with the W-boson from the other proton. Second, when defining σ^A we do not distinguish between W^+ and W^-, because $\sigma(bW^\pm) - \sigma(\bar{b}W^\pm)$ will cancel only the QCD (with part of EW) background, while $\sigma(bW^\pm) - \sigma(\bar{b}W^\mp)$ will cancel only the $t\bar{t}$ and tW backgrounds.

In order to measure σ^A, we need to identify the charge of the b jets. At the LHC, reconstruction of b-jet charge was already used (see, e.g., Refs. [17–20].) Recently, the ATLAS collaboration has developed a jet vertex charge (JVC) tagger, which also makes use of the reconstructed displaced vertices. While technical details can be found in Ref. [21], here we simply point out that by selecting a symmetric working point, where the correct tagging of a b-jet and a $\bar{b}$-jet are the same, the efficiency of charge tagging can reach $\epsilon \approx 65\%$, which implies that $2\epsilon - 1 = 30\%$ of the actual b-charge asymmetry will be measured.

FIG. 2. Background processes in $pp \to Wbj$ production, including QCD (a), $t\bar{t}$ (b), tW (c), and EW (d-f).

With the asymmetry we define an on-/off-shell ratio:

$$\mathcal{R} = \sigma^{\mathcal{A}}_{\text{off}}/\sigma^{\mathcal{A}}_{\text{on}} \qquad (1)$$

where $\sigma^{\mathcal{A}}_{\text{on,off}}$ represents the asymmetric cross section with the top being on-/off-shell, defined by some mass window cut. Both $\sigma^{\mathcal{A}}_{\text{on}}$ and $\sigma^{\mathcal{A}}_{\text{off}}$ probe the same amplitude, but $\sigma^{\mathcal{A}}_{\text{on}}$ is dominated by the s-channel and is thus inversely proportional to Γ_t, while $\sigma^{\mathcal{A}}_{\text{off}}$ is insensitive to Γ_t. Their ratio will be a direct probe of Γ_t.

Apart from removing backgrounds, there are several advantages of using the ratio between the asymmetric cross sections:

(i) Systematic uncertainties, such as uncertainties related to luminosity and tagging efficiency, *including the b-charge tagging efficiency*, are expected to cancel to large extent.

(ii) Theoretical uncertainties for the signal, due to radiative corrections should partly cancel. We will show that the ratio is stable under QCD corrections.[1]

(iii) Dominant model-dependence should cancel in the ratio.

III. SIMULATION

To find the relation between $\mathcal{R}$ and Γ_t, we simulate both the signal and the background processes using MADGRAPH5_AMC@NLO [22] and PYTHIA8 [23]. Given that the asymmetry in background could be induced by radiative corrections, we simulate our background processes at NLO in QCD with parton shower (PS), where results are obtained with NNPDF3.0 [24] and are matched by using MC@NLO [25]. For $t\bar{t}$ and tW background we use MADSPIN [26] to decay the top quarks. Signal processes are computed at LO + PS for various g_{tbW} and Γ_t including full off-shell effects. A K-factor computed under the SM assumption is applied.

We take $m_t = 173.2$ GeV and $\Gamma_t^{\text{SM}} = 1.37$ GeV. Renormalization and factorization scales are set to one half of the total transverse mass. Scale uncertainties are obtained by varying both scales independently by a factor of two in both directions. Jets are clustered with anti-k_T algorithm, as implemented in FASTJET [27], with $R = 0.4$ and a 25 GeV p_T cut. We require only one lepton in the final state. We assume perfect b jet-tagging and W-boson reconstruction. A more complete analysis could include errors due to mistagging and acceptance, etc., but is unlikely to change our result as these effects are expected to cancel in the $\mathcal{R}$ ratio.

Despite no contribution to the asymmetry, the absolute number of background events will contribute to the

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[1]We expect the EW corrections to be small. A complete computation would be necessary, but it is beyond the scope of this paper.

TABLE I. Total cross sections (σ) and b-charge asymmetry ($\sigma^{\mathcal{A}}$) at the LHC 13 TeV, in pb, from signal and background processes. The first column includes both signal and EW background, and their interference.

		Signal+ EW	EW only	QCD	$t\bar{t}$	tW
Off-shell	σ	5.08(2)	0.512(2)	4.68(3)	4.39(4)	1.04(1)
	$\sigma^{\mathcal{A}}$	1.40(1)	0.009(1)	−0.04(3)	0.02(3)	−0.005(6)
On-shell	σ	32.61(5)	0.135(1)	1.32(2)	12.47(9)	1.56(1)
	$\sigma^{\mathcal{A}}$	10.21(3)	0.002(1)	−0.02(1)	−0.07(8)	0.01(1)

statistical error. To reduce the background events, we apply the following kinematic cuts:

$$\eta(j_1) > 2.3, \quad \eta(j_{b1}) < 2.5,$$
$$p_T(j_{b1}) > 25\,\text{GeV}, \quad p_T(j_2) < 50\,\text{GeV}, \quad p_T(j_{b2}) < 50\,\text{GeV},$$
$$\eta(W) < 4.0, \quad p_T(W) < 120\,\text{GeV}, \quad m(Wj_1) > 140\,\text{GeV}.$$

Here $j_{1,2}$ ($j_{b1,2}$) represent the non-b (b) jets with the largest and the second largest p_T. We consider events with at least one b and one non-b jet, and at most two b and two non-b jets. Cuts on the first b-jet are to be consistent with the b-jet charge tagger simulation in Ref. [21]. On-/off-shell events are defined by a mass window cut of $m_t \pm 20$ GeV. If either $m(Wj_{b1})$ or $m(Wj_{b2})$ falls into the window, we consider the event as an on-shell event. We further smear $m(Wj_{b1,2})$ by a Gaussian with a 10 GeV width to account for possible errors in reconstructing the top. These cuts only serve as a simple way to suppress the background. A sophisticated signal/background discrimination is not strictly required, thanks to the charge asymmetry, but certainly helps to further reduce the statistical uncertainty. In particular, multivariate analysis based approaches have been widely used in single-top measurements (see, for example, Refs. [28–32]), and it is probably straightforward to apply them also to the off-shell region.

Our results for the total and asymmetric cross sections under the SM assumption are shown in Table I. As we have expected, the b-charge asymmetry removes nearly all of the background, while leaving about 30% of the signal.

IV. UNCERTAINTIES

The main feature of our approach is that systematic errors are expected to be negligible. The b-charge asymmetry is background free, so we have no error from background modeling; errors related to luminosity and tagging efficiency are expected to cancel out in the $\mathcal{R}$ ratio. While a complete study of systematic errors can be performed only by experimental collaborations, here we simply assign a 2% error to possibly uncanceled systematic effects. This estimate may be a bit optimistic, as we do not take into account possible contaminations from mistagged b-jets. The mistagging from a c-quark would not affect the

TABLE II. Approximate LO and NLO asymmetries for on-/off-shell cross sections and their ratio. Uncertainties shown in percentage come from scale variation.

	$\sigma^{\mathcal{A}}_{\mathrm{off}}$ [pb]	$\sigma^{\mathcal{A}}_{\mathrm{on}}$ [pb]	$\mathcal{R}$ ratio
LO	$1.32(2)^{+9\%}_{-12\%}$	$9.0(1)^{+9\%}_{-12\%}$	$0.146(3)^{+0.1\%}_{-0.1\%}$
NLO	$1.41(8)^{+6.2\%}_{-6.4\%}$	$9.8(1)^{+4.8\%}_{-5.1\%}$	$0.144(8)^{+1.3\%}_{-1.6\%}$

signal because $c\bar{c}$ is symmetric in a proton, but those from u- and d-quarks may lead to a charge asymmetry that is not negligible. However, we do not have enough information to assess how much of this asymmetry would survive the JVC charge tagger. In an optimistic scenario, these mistagged b-jets would not lead to an observable charge asymmetry, as the tagger uses the information from displaced vertices and soft muons from the b decay. For this reason, we will aim at providing the best possible scenario, keeping in mind that the mistagging-related errors should be determined by a full experimental analysis.

Another important source comes from perturbative QCD corrections. The Wb invariant mass distribution can be changed by additional gluon emission from both decay and production [33–36]. However, such effects are partly captured by PS simulation. Complete single-top production including off-shell and PS effects has shown that, when matched to PYTHIA8, NLO correction is at the level of $\lesssim 20\%$ and does not significantly change the shape [36] (see also Ref. [37]). To find out the radiative correction on the ratio $\mathcal{R}$, we simulate the Wbj production at the NLO matched to PYTHIA8. We approximate the W^+b and $W^-\bar{b}$ events by single tops produced on-shell and decayed by MADSPIN. This is a good approximation near the resonance [36], while in the off-shell region, we already see in Table I that neglecting the EW background has only a small effect on the asymmetry. On the other hand, for W^-b and $W^+\bar{b}$ production we compute the full process.

Our results are shown in Table II. As expected, the ratio partly reduces the scale uncertainties of individual cross sections. Given that the central value of the ratio seems stable under QCD correction, we believe that the remaining $\sim1.5\%$ scale uncertainty is a good estimate for our theoretical error.

Finally, we estimate the relative statistical error by $\delta = \sqrt{\sigma\mathcal{L}}/(2\epsilon - 1)\sigma^{\mathcal{A}}\mathcal{L}$, i.e. the fluctuation is given by the root of the total number of events (including background) while the central value is $2\epsilon - 1 \approx 30\%$ of the actual b-charge asymmetry.

TABLE III. One-sigma exclusion limit on Γ_t, expected at LHC 13 TeV.

Luminosity [fb^{-1}]	30	300	3000
Limits [GeV]	[0.40, 2.30]	[1.01, 1.73]	[1.14, 1.60]
Stat. error	11%	3%	1%

V. RESULTS

The exclusion limits on Γ_t are given in Table III for LHC 13 TeV, together with corresponding statistical errors. Our limit at 30 fb^{-1} is not as good as the current limits put by CMS, mainly because of the lower production rate of single-top process, but is already competitive. Moreover, the direct measurement in Ref. [2] has larger systematic uncertainties and will eventually become systematics-dominated at high luminosity, and further improvements beyond that point will be difficult. In contrast, our approach should scale better with luminosity, since it is limited mainly by statistical uncertainty, and therefore its precision is expected to improve quickly as the integrated luminosity increases. At HL-LHC we expect to reach a precision of roughly 250 MeV. We should also mention that, in any case, an independent new measurement on the same observable is always valuable as a consistency check.

We briefly discuss the model dependence of this approach. Assuming that BSM effects enter as a constant deviation in the coupling g_{tbW} from its SM value, we would expect the measurement on the width to be independent of g_{tbW}, as both the on- and off-shell cross sections scale as g^4_{tbW}. In practice, a small dependence remains, from the interference between the signal and the EW background (QCD background does not interfere), which scales as g^2_{tbW}. In Fig. 3 we show the expected limits on the (Γ_t, g_{tbW}) plane. We can see that the allowed region (represented by the green band), while mainly constraining Γ_t, is not exactly vertical. However, this remaining dependence on g_{tbW} can be taken under control, by imposing further kinematic cuts that suppress the interference. One possible way is to select only the transversely polarized component W_T, using the angular distribution of the decay products of W. To illustrate the idea, we simply assume that the transverse components can be perfectly identified.
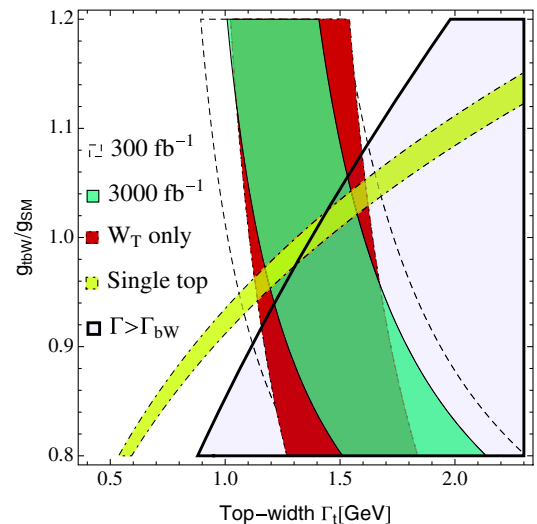

FIG. 3. Constraints on Γ_t and g_{tbW} at 68% confidence level.

The resulting constraint is given by the red band in Fig. 3, displaying a much smaller model-dependence.

A more reliable way is to combine this measurement with the single-top cross section measurement, which probes a different combination, g_{tbW}^4/Γ_t. The projected precision for t-channel single top is roughly 5% at the HL-LHC [38], given by the yellow band in Fig. 3. We see that the Γ_t and the single-top measurements nicely complement each other. Note also that under the same assumption we have $\Gamma_t > \Gamma(t \to bW) = \Gamma_t^{\mathrm{SM}} g_{tbW}^2/g^2$, which bounds Γ_t from below, as illustrated by the purple area in Fig. 3. By naively combining all constraints, we expect the following one-sigma limit at 3000 fb^{-1}:

$$1.31 \text{ GeV} < \Gamma_t < 1.57 \text{ GeV}. \tag{2}$$

Similar to the Higgs-width measurement case, a potential worry is that an energy-dependent coupling could generate additional model-dependence. The problem is less severe here, as $\sim$90% of the off-shell events do not go beyond $m_t \pm 40$ GeV. In addition, the off-shell contribution in g_{tbW} will be canceled by a contact $bbWW$ coupling required by gauge symmetry (see Ref. [39] for a similar case). Other momentum dependence could exist but is insensitive to on-/off-shellness, and only leads to less than a few percent deviation on $\mathcal{R}$.

We emphasize that the main purpose of this work is to present the idea of using b-charge asymmetry to probe Γ_t, and perform a first analysis to estimate its performance. Further improvements are possible, and deserve more investigations. For example, the precision level of this approach relies on the JVC tagging efficiency ϵ. If future developments improves ϵ, say from 65% to 80%, the precision on the width can be improved by a factor of two. In addition, using the charge information of the W could help. Even though $\sigma(bW^{\pm}) - \sigma(\bar{b}W^{\pm})$ is not completely free of background, it is interesting to see if one can gain further information by measuring/constraining the remaining background. Finally, in the current analysis we only distinguish between on-/off-shell events with a simple mass-window cut. In principle one could also consider dividing the $m(Wb)$ distribution into more bins, so that more information from the distribution can be used.

VI. SUMMARY

We proposed the on-/off-shell ratio of b-charge asymmetry from $pp \to Wbj$ as a direct probe of the top-quark width Γ_t. We pointed out that this asymmetry is virtually free of any background related uncertainties. Remaining systematic uncertainties are expected to cancel by taking the ratio of cross sections, and we also showed that theoretical uncertainties from QCD radiative corrections are under control. The approach is therefore dominated only by statistical error, which means good precision can be expected at high integrated luminosity. Using the state-of-the-art Monte Carlo tools, we found that in the optimistic scenario a 200–300 MeV precision can be expected at the HL-LHC, and we encourage the experimental collaborations to perform more detailed analyses to determine the final reach. The approach directly probes the total width, and is insensitive to BSM couplings.

We demonstrated that the b-charge tagging algorithm developed by ATLAS, even with only $\sim$65% efficiency, is already a powerful tool if used in a special way. In addition to improving the precision of top-width measurement, we also hope that the key idea of using the b-charge information will open up new opportunities for doing precision top physics.

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[1] C. Patrignani *et al.* (Particle Data Group Collaboration), Chin. Phys. C **40**, 100001 (2016).

[2] C. Collaboration (CMS), Report No. CMS-PAS-TOP-16-019, 2016.

[3] V. Khachatryan *et al.* (CMS Collaboration), Phys. Lett. B **736**, 33 (2014).

[4] M. Martinez and R. Miquel, Eur. Phys. J. C **27**, 49 (2003).

[5] A. Juste *et al.*, ECONF **C0508141**, PLEN0043 (2005).

[6] T. Horiguchi, A. Ishikawa, T. Suehara, K. Fujii, Y. Sumino, Y. Kiyo, and H. Yamamoto, arXiv:1310.0563.

[7] K. Seidel, F. Simon, M. Tesar, and S. Poss, Eur. Phys. J. C **73**, 2530 (2013).

[8] A. Arbey *et al.*, Eur. Phys. J. C **75**, 371 (2015).

[9] S. Liebler, G. Moortgat-Pick, and A. S. Papanastasiou, J. High Energy Phys. 03 (2016) 099.

[10] N. Kauer and G. Passarino, J. High Energy Phys. 08 (2012) 116.

[11] G. Passarino, J. High Energy Phys. 08 (2012) 146.

[12] G. Passarino, Eur. Phys. J. C **74**, 2866 (2014).

[13] N. Kauer, Mod. Phys. Lett. A **28**, 1330015 (2013).

[14] F. Caola and K. Melnikov, Phys. Rev. D **88**, 054024 (2013).

[15] J. M. Campbell, R. K. Ellis, and C. Williams, J. High Energy Phys. 04 (2014) 060.

[16] W. Bernreuther and Z.-G. Si, Phys. Rev. D **86**, 034026 (2012).

[17] G. Aad *et al.* (ATLAS), Phys. Rev. D **90**, 052007 (2014).

[18] G. Aad *et al.* (ATLAS), J. High Energy Phys. 11 (2013) 031.

[19] O. Gedalia, G. Isidori, F. Maltoni, G. Perez, M. Selvaggi, and Y. Soreq, Phys. Rev. Lett. **110**, 232002 (2013).

[20] M. Aaboud *et al.* (ATLAS), J. High Energy Phys. 02 (2017) 071.

[21] CERN Technical Report No. ATL-PHYS-PUB-2015-040, 2015, URL http://cds.cern.ch/record/2048132.

[22] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, J. High Energy Phys. 07 (2014) 079.

[23] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput. Phys. Commun. **178**, 852 (2008).

[24] R. D. Ball *et al.* (NNPDF), J. High Energy Phys. 04 (2015) 040.

[25] S. Frixione and B. R. Webber, J. High Energy Phys. 06 (2002) 029.

[26] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, J. High Energy Phys. 03 (2013) 015.

[27] M. Cacciari, G. P. Salam, and G. Soyez, Eur. Phys. J. C **72**, 1896 (2012).

[28] S. Chatrchyan *et al.* (CMS Collaboration), J. High Energy Phys. 12 (2012) 035.

[29] A. M. Sirunyan *et al.* (CMS Collaboration), arXiv:1610.00678.

[30] G. Aad *et al.* (ATLAS), Phys. Rev. D **90**, 112006 (2014).

[31] M. Aaboud *et al.* (ATLAS Collaboration), J. High Energy Phys. 04 (2017) 086.

[32] M. Aaboud *et al.* (ATLAS), arXiv:1702.02859.

[33] P. Falgari, P. Mellor, and A. Signer, Phys. Rev. D **82**, 054028 (2010).

[34] P. Falgari, F. Giannuzzi, P. Mellor, and A. Signer, Phys. Rev. D **83**, 094013 (2011).

[35] A. S. Papanastasiou, R. Frederix, S. Frixione, V. Hirschi, and F. Maltoni, Phys. Lett. B **726**, 223 (2013).

[36] R. Frederix, S. Frixione, A. S. Papanastasiou, S. Prestel, and P. Torrielli, J. High Energy Phys. 06 (2016) 027.

[37] T. Ježo and P. Nason, J. High Energy Phys. 12 (2015) 065.

[38] B. Schoenrock, E. Drueke, B. Alvarez Gonzalez, and R. Schwienhorst, arXiv:1308.6307.

[39] J. A. Aguilar-Saavedra, Nucl. Phys. **B804**, 160 (2008).