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# NLOPS off-shell effects in precise determinations of the top-quark mass and width at the LHC

**Simone Amoroso**, [a,*] **Daniel Britzger**, [b] **Stefan Kluth** [b] **and Ludovic Scyboz** [c]

*Deutsches Elektronen Synchrotron DESY, 22761 Hamburg, Germany*
*Max-Planck-Institut für Physik, 80805 München, Germany*
*Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, University of Oxford, Oxford OX1 3PU, UK*

*E-mail:* simone.amoroso@desy.de

The precise measurement of the properties of the top quark are among the most important goals of the LHC. The signature of top quarks can only be measured through their decay products, which are almost exclusively a W-boson and a b-quark, and unbiased measurements of the top-quark pair production process are therefore performed in the final state of two W-bosons and two b-quarks (WWbb). However, the WWbb final state has further contributions from single-top production and even from channels without intermediate top-quarks. At next-to-leading order QCD, these channels interfere and cannot be calculated separately any more, and since the top quarks can be off their mass shell, also finite width effects become important. In this contribution, we exploit a measurement of the WWbb final state in the di-lepton decay channel from ATLAS at 13 TeV together with a next-to-leading order QCD prediction supplemented with parton shower in the Powheg-Box-Res framework (denoted "bb4l") for a determination of the top-quark mass and its width. We evaluate the impact of using the fully off-shell calculations, and study the correlation between the top quark mass and width. For the inference, we make use of a novel analytic parameter estimation ansatz, the Linear Template Fit, which will also be introduced briefly.

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## 1. Introduction

Precise measurements of the properties of the top quark are among the most important goals of the LHC physics program. Top quarks can be reconstructed through their decay products, almost exclusively a W-boson and a b-quark. Unbiased measurements of the top-quark pair production process are therefore performed in the final state of two W-bosons and two b-quarks (WWbb). Recent measurements of the top quark mass from top quark decays at the LHC have reached the astonishing accuracy of 370 MeV [1]. All of the measurements made so far make use of templates constructed from Monte Carlo prediction at NLO in the strong coupling in the limit of vanishing top quark width (Narrow Width Approximation). The WWbb final state, however, has further contributions from single-top production and even from channels without intermediate top-quarks. At next-to-leading order QCD, these channels interfere and cannot be calculated separately any more, and, since the top quarks can be off their mass shell, finite width effects also become important. In this contribution, we exploit a measurement of the WWbb final state in the di-lepton decay channel from ATLAS at 13 TeV [4] together with next-to-leading order QCD prediction supplemented with parton shower in the Powheg-Box-Res framework (thereafter denoted as "bb4l") [2, 3] for a simultaneous determination of the top-quark mass ($m_t$) and its width ($\Gamma_t$). We evaluate the impact of using the fully off-shell calculations, and study the correlation between the top quark mass and width. For the inference, we make use of a novel analytic parameter estimation ansatz, the Linear Template Fit, which will also be introduced briefly.

## 2. Data and theoretical predictions

The value of the top-quark mass ($m_t$) and its partial decay width ($\Gamma_t$) are determined in a template fit of differential cross section predictions from the bb4l MC event generator to data. We consider the cross section measurement of $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{lb}^{\mathrm{minimax}}}$ performed by the ATLAS collaboration using 36.1 fb$^{-1}$ of integrated luminosity collected in proton–proton collisions at a center-of-mass energy of 13 TeV [4]. The measurement is performed in the di-lepton channel (using both opposite- and same-flavor di-lepton events), and is corrected for detector resolution and efficiencies through an unfolding to the particle level. The observable $m_{lb}^{\mathrm{minimax}}$ is defined as

$$m_{lb}^{\mathrm{minimax}} = \min\left(\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\right) , \quad (1)$$

where the $b_i$ and $\ell_i$ represent the two $b$-jets and leptons, respectively. It exhibits a kinematic endpoint at $\sqrt{m_t^2 - m_{\mathrm{W}}^2} \simeq 150$ GeV sensitive to the value of the top quark mass. Above this endpoint the top quarks are off-shell, the distribution is sensitive to the interference between single- and double-resonant diagrams, and can provide a competitive direct measurement of the top quark width $\Gamma_t$ [5].

Theoretical predictions are generated using the bb4l code in POWHEG-BOX-RES. For all samples the factorisation and renormalization scales are set to $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \sqrt{m_t^2 + p_{\mathrm{T}}^2}$, the `hdamp` parameter is set to $h = m_t$ and the NNPDF31_nnlo_hessian PDF set [6] is used. The nominal value of the top quark mass and width are set to $m_t = 172.5$ GeV and $\Gamma_t = 1.33$ GeV, respectively. Additional templates are generated with $\Gamma_t = 0.66, 1.0, 1.66, 2.0$ GeV and $m_t = 170, 171.5, 173.5,$

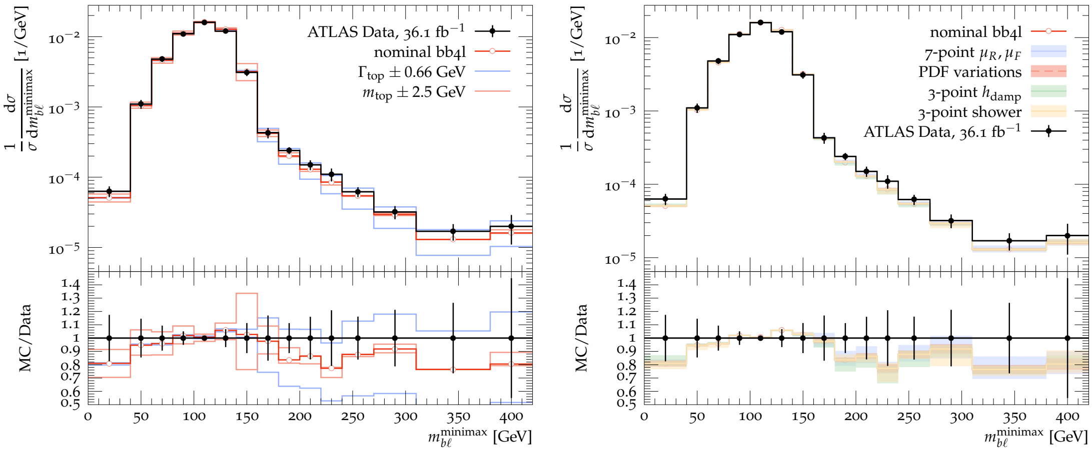


**Figure 1:** The ATLAS 13 TeV $m_{lb}^{\text{minimax}}$ distribution compared with theoretical predictions from the bb4l generator. The left plots illustrates the impact of variations of $m_t$ by 2.5 GeV (in light red) and of $\Gamma_t$ by 0.66 GeV (light blue). The right plot shows the size of the different source of theoretical uncertainties on top of the nominal bb4l prediction. In blue the envelope band of 7-point variations of $\mu_{\text{R}}$ and $\mu_{\text{F}}$. PDF variations are shown as a red band. Variations of the hdamp parameter by a factor of two are shown in green. Variations of the shower scales are shown in yellow.

175 GeV. The bb4l code does not include matrix-element for same-flavor lepton final states, which are dominated by the contribution of resonant diagrams with a Z boson exchange. The ATLAS analysis includes these final states, suppressing them by applying a veto on invariant di-lepton masses around the Z boson peak. We estimate them by relabeling the lepton flavor in the Les Houches events, after checkin using a LO sample that the missing diagrams have a negligible impact for the considered analysis. All bb4l events are then interfaced to Pythia8.307 [7] to include the effect of parton showering, underlying event and hadronisation. The matching is performed through vetoed showers as implemented in a dedicated Hook. They are finally passed through RIVET to reproduce the analysis distributions [8].

A comparison between the bb4l templates with different $m_t$ and $\Gamma_t$ and the ATLAS data for the $m_{lb}^{\text{minimax}}$ is shown in Fig. 1. In line with the theoretical expectation, it can be seen how the $m_t$ variations are the largest around 150 GeV, while variations of $\Gamma_t$ increase as $m_{lb}^{\text{minimax}}$ increases.

## 3. Fit methodology

The fit is performed by minimising a $\chi 2$ function between data and predictions using the Linear Template Fit program [9]. By approximating linearly the dependence on the parameters, and with the assumption of normal or log-normal probability distributions, the code can produce a fully analytic solution for the best parameter estimates. Experimental uncertainties are dominated by the theoretical modeling of the interference between single- and double-resonant diagrams, and the description of additional b-tagged jets. We additionally consider several sources of theoretical uncertainties on the templates. The statistical uncertainties in the templates are propagated to the linear . Uncertainties due to missing higher orders in the matrix-element are estimated from the envelope of 7-point variations of $\mu_{\text{R}}$and $\mu_{\text{F}}$. PDF uncertainties are derived from the NNPDF31

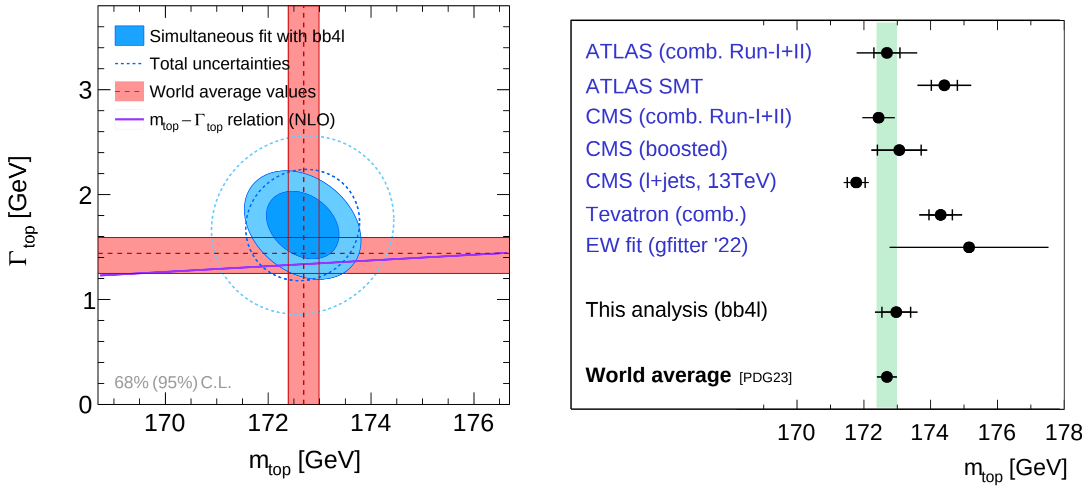


**Figure 2:** The left plot shows the one- and two-sigma contours in the $m_t$-$\Gamma_t$ plane resulting from this analsyis. The results are compared with the world averages for the individual measurements, as well as with the theoretical relation between the two parameters computed at NLO in QCD. The right plot compares the $m_t$ result of this analysis using bb4l with previous experimental determinations with the indirect determination from the global electroweak fit and with the world average.

eigenvector sets. Variations of the `hdamp` parameter by a factor two and a half are used to estimate an uncertainty on the NLOPS matching. Finally we consider uncertainties on the Pythia8 parton shower emissions. Those are evaluated following the approach of [10], by varying by a factor of two the scale at which the strong coupling is evaluated for each individual emission, and by additionally changing the the form of the splitting kernels in the non-singular limit. The impact of each source of uncertainty on the $m_{lb}^{\text{minimax}}$ distribution is shown in Fig. 1.

We observe an excellent agreement of the data with the post-fit bb4l predictions. In a simultaneous fit of $m_t$ and $\Gamma_t$ we obtain

$$m_t = 172.67 \pm 0.46_{(\text{exp})} \pm 0.57_{(\text{th})}\ \text{GeV} \tag{2}$$

$$\Gamma_t = 1.70 \pm 0.21_{(\text{exp})} \pm 0.27_{(\text{th})}\ \text{GeV}, \tag{3}$$

with a weak correlation between the two parameters of about -30%. The mass and width are consistent with previous determination. with uncertainties dominated dominated by the hdamp and parton shower variations. The one- and two-sigma contours in the $m_t$-$\Gamma_t$ plane are shown in Fig. 2, compared with the individual determinations for the two quantities and with the NLO relation as predicted by the SM.

We further perform an $m_t$ determination including the top-mass dependence in $\Gamma_t$. We obtain in this case the value

$$m_t = 172.97 \pm 0.43_{(\text{exp})} \pm 0.46_{(\text{th})}\ \text{GeV}. \tag{4}$$

The result shows a moderate reduction in the experimental and theoretical uncertainties and has a total uncertainty is competitive with that of other dedicated measurements.

## 4. Conclusions

We have presented the first simultaneous extraction of the top quark mass and width from LHC data. To this end we used a 13 TeV ATLAS measurement of the $m_{lb}^{\text{minimax}}$ distribution in di-leptonic top events together with theoretical predictions from the POWHEG bb4l Monte Carlo generator, including top decay, finite-width and off-shell effects up to NLO in QCD matched to the Pythia8 parton shower. The results are competetive with dedicated measurements and consistent with the world average and previous determinations. Top-quark mass effects in $\Gamma_t$ provide a small additional sensitivity to $m_t$ and help reduce the dominant model uncertainties. The proposed approach provides a promising avenue to improve the theoretical accuracy of $m_t$ and $\Gamma_t$ at the LHC.

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