TOP 2017: Theoretical Summary

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I summarize the theory talks presented at the TOP 2017 conference.

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1 Introduction

In contrast to almost all other participants of the TOP 2017 conference, I do not actively work on the top quark physics these days. Indeed, my last paper on top quark physics was published more than three years ago. Given the task of summarizing the theory talks at the TOP 2017 conference, there is both bad and good in this situation: bad, because my understanding and knowledge of certain things can be incomplete or outdated; good, because it becomes easier to notice and appreciate new developments that occurred during elapsed time and to reflect on the changes from a broader perspective.

In this respect, the week of TOP 2017 in Portugal offered many interesting observations that collectively point towards truly exciting progress that is happening in the top quark world. On the experimental side, it is the appearance of very large data samples that, potentially, offer many hidden gems if one knows where to look and which questions to ask. On the theory side, it is an emergence of high-precision predictions for many different processes with top quarks and a growing appreciation that many fundamental things can be learned by utilizing them in the right way.

These changes are driven by a lively community of physicists who have common goals, talk the same language and appreciate each others contributions to the exploration of the top quark physics. The close cooperation of theory and experiment leads to many interesting results, beyond traditional exclusion limits, that are based on a careful theoretical interpretation of precise measurements. These types of interactions seem to be the hallmark of the top quark physics but they can also be viewed as a model for how LHC physics will be done in the years to come. If TOP 2017 is any indication, high energy physics future is assured since there will be non-trivial problems to solve, interesting discussions to have and ambitious scientific goals to achieve, even if direct production of new particles at the LHC will remain out of reach.

The vitality of the top quark physics could be felt especially strongly at TOP 2017 since it offered a stark contrast to a somewhat gloomy perspective on the future of high energy physics driven by the fact that no BSM physics has been discovered so far at the LHC. The question that looms large over the horizon is how to move forward from here. One of the possible answers – if not *the only* possible answer – is that we have to start serious discussions about credible and verifiable ways to find subtle effects and small deviations from Standard Model predictions at hadron colliders or, said differently, about how to do precision physics at the LHC in a convincing way. From this perspective, a particular relevance of the LHC top quark physics program is that it has never been entirely focused on searches, since it *anyhow* had a new heavy particle to study, and studying this particle was, in fact, what was being done. As the result, when searches turned null results, the "precision mentality" was already in place in the top quark community and it was ready to take the lead.

Precision physics goes after phenomena that are not easy to see in hadron collisions. They may arise in many ways as their originators can be too heavy to be seen or they can blend into a background. No matter how subtle, one hopes to find a way to understand what they are. The success of this endeavor requires several things: i) superb experimentation; ii) good understanding of which questions to ask and a good eye for places where new things can hide and iii) an ability to describe hadron collisions from first principles with maximal attainable (and still sensible) precision. The cross-talk between experts in different theory areas and experts in experiment is crucial; it is precisely this cross talk that will allow us to move forward towards the common goal – finding



Figure 1: Top quark quantum numbers and three (!) masses from Review of Particle Physics.

physics beyond the Standard Model at the LHC either directly or through precision measurements. It was inspiring to see how efficiently this cross talk works in the top quark community. In fact, it appears that the ability to connect very different aspects of high-energy physics is driven by the very nature of the top quark, a particle that has something for everyone. Indeed, i) it is unusually heavy and interacts strongly with the Higgs boson; so strongly, in fact, that it can destabilize the electroweak vacuum [1, 2]; ii) it is part of a flavor puzzle but the role it plays is not apparent [1, 3, 4]; iii) it may be expected to talk directly to the Dark Side, but we do not know how and if at all [1, 5]; iv) it has a capacity to annoy those of us who do not care about the top by directly interfering with searches for other, "more interesting" things at the LHC; v) it is the only "free" colored particle that we can observe and whose properties we, therefore, can describe in great detail from first principles. In short, top quark is an interesting object to study and it can teach us a lot. This was the leitmotif of the many theory talks at the TOP 2017 conference that I attempt to summarize in the remainder of this contribution.

2 The top quark mass

How many parameters identify the top quark and define its physics? This is an interesting question to discuss [1] but, if in doubt, we can always consult the most learned resource that we have in our field – the Review of Particle Physics. The result is shown in Fig. 1 which reminds us about the electric charge of the top quark, its weak isospin and "topness", gives the value of the top quark width and, amazingly enough, lists *three* different top quark masses. Three masses is a puzzling feature as it appears that the top quark has three different *types* of masses that go under the following names: 1) mass from direct measurement, 2) mass from cross section measurements and 3) pole mass from cross sections measurements. Clearly, for those who still do not believe that the top quark is special, this is a very strong argument that in certain aspects this particle is truly unique!

Of course, "three top quark masses" is an indication of a problem that we run into when trying to understand what this important quantity means. For the sake of example, it is often said that the value of the top quark mass has important implications for the stability of electroweak vacuum. It is stated that the electroweak vacuum becomes stable if the *pole mass* of the top quark m_t is smaller than 171.18 GeV. Since the numerical value for m_t reported by ATLAS and CMS is 172.4(5) GeV, it appears to be precise enough to argue that Universe is not stable and that its lifetime is $10^{139^{+105}_{-51}}$



Figure 2: Dependence of the extracted value of the top quark mass on applied kinematic cuts.

years [1]. However, the problem with these discussions is that in both of these statements the mass parameter whose numerical value is quoted is not specified! This omission could be excused if not for the fact that the most natural definition of a mass parameter of a heavy particle – the pole mass – is ambiguous for a heavy quark by an amount proportional to $\Lambda_{\rm QCD} \sim \mathcal{O}(150 - 200)$ MeV. Moreover, although the experimental number is very precise, it is often questioned if it corresponds to the pole mass or to some other mass parameter such as e.g. the "Monte Carlo" mass.

Both of these issues were discussed at the conference by P. Nason [6]. He argued that the theoretical uncertainty in the pole mass of the top quark related to the asymptotic nature of perturbative series (infra-red renormalon) is $\mathcal{O}(100 - 200)$ MeV [6] and, therefore, is much smaller than the current experimental uncertainty on the top quark mass. Given that the error on the measurement is $\mathcal{O}(500)$ MeV and that it is unlikely to decrease significantly, the irreducible theory uncertainty in the value of the top quark pole mass is so small that it becomes irrelevant for *practical purposes* of the LHC physics. It is also argued in [6] that top quark mass measurements that provide the most precise values of the top quark mass and that are based on the reconstruction of kinematics of top quark decay products should be thought of as measurements of the pole mass. The issue to address is not which mass parameter is measured but whether or not all sources of systematic uncertainties, including proper treatment of non-perturbative effects, are accounted for.

It is interesting to mention that there is a way to verify this point to some extent. Indeed, there are early studies by the CMS collaboration that explore the dependence of the measured mass parameter on the event selection criteria, c.f. Fig. 2. The idea is that by doing so one can detect missed or poorly understood non-perturbative effects since they should affect different events samples in different ways. It was found that the measured value of the top quark mass is stable against modifications of kinematic cuts. However, the uncertainties in the top quark mass reported in that study were close to $\mathcal{O}(2)$ GeV and similar studies with a much higher precision should be performed in the future.

3 Simple processes

Theoretical description of processes where either a $t\bar{t}$ pair or a single top quark are produced are extremely advanced. Consider as an example the $t\bar{t}$ pair production at the LHC. The landmark

computations of NNLO QCD corrections to this process reviewed in Ref. [7] were recently combined with NLO electroweak corrections [8]. There are numerous phenomenological applications of these computations – from constraints on parton distributions functions, to the determination of top quark pole mass and the strong coupling constant, to a hunt for broad(ish) resonances that decay to top quarks and interfere with continuum top pair production, to the exclusion of elusive stops in the so-called stealth mass region.

One of the questions that seems to be heavily discussed in connection with these computations is the "right" choice of the renormalization and factorization scales [7] where what is right and what is wrong is decided by an accelerated convergence of the perturbative expansion for a particular observable. It is found, for example, that $\mu = M_T/2$ is an appropriate scale for certain transverse momenta distributions whereas $H_T/4$ is a better choice for other observables [7]. While these discussions are interesting, to my taste they are missing an underlying physics picture that should guide choices of scales in situations where NNLO calculations are not available. Clearly, a physical way to define proper scales must depend on kinematics and parton composition of a particular event. Approaches based on these considerations are well-known and are used e.g. in parton showers where strong coupling constants are evaluated at scales that correspond to daughter's transverse momenta in sequences of $1 \rightarrow 2$ branchings. It is also employed in MLM, CKKW and MINLO approaches that combine parton showers with matrix elements calculations. These connections between scales and kinematics are based on physics principles that theorists were able to understand so far and that, as a matter of fact, should be applicable in a broader context. Hopefully, studies of scale setting prescriptions described in [7] will either lead to a confirmation of this physical picture or to its extension and refinement.

An important next step in improving description of top quark pair production is the inclusion of top quark decays; this will enable computations of fiducial cross sections defined at the level of physical particles and jets. This can be done using the narrow width approximation that was welltested in NLO QCD computations. The technology to combine top quark production and decay with higher-order QCD computations is available and it is only a matter of time before these results will be produced. Once this happens, there will be a tool to directly confront theoretical predictions with experimental measurements and to study kinematic distributions of top quark decay products at the highest available level of precision. Recall that similar computations at NLO QCD allowed for precision studies of various spin observables in top quark decays at higher orders of QCD, led to constraints on possible stop contributions to cross sections and provided important theory input for estimating how well the top quark mass can be inferred from kinematic distributions of top quark decay products. Once the NNLO production and NNLO decays are combined, it will be possible to perform similar studies at the next level of precision. Although such results are not there yet, at TOP 2017 A. Papanastasiou described a computation [7] that combines approximate NNLO in the production with exact NNLO in the decay and it appears that even this approximate result improves the description of fiducial cross sections dramatically, see Fig. 3.

Clearly, inclusion of QCD corrections to top decays enables direct computations of fiducial cross sections. This is good but is it worth the effort? Indeed, is it likely that the QCD corrections to fiducial cross sections differ significantly from corrections to total cross sections? This question has the positive answer as the recent computation of NNLO QCD effects to single top quark production and decay shows [9]. Both NLO and NNLO QCD corrections to inclusive single top production cross section are known to be small, close to one percent. However, if one computes corrections



Figure 3: Fiducial cross sections computed using approximate NNLO for production and exact NNLO for decay [7].

to fiducial cross section that is defined by requiring two jets, one of which should be a *b*-jet, with $p_{\perp,j} > 40$ GeV and $|\eta_j| < 5$, and imposes some constraints on leptonic transverse momenta and rapidities, QCD corrections to cross sections become significant and reach $\mathcal{O}(-30\%)$ at NLO and $\mathcal{O}(-5\%)$ at NNLO. One of the interesting applications of the single top quark production is a constraint on the ratio of up and down PDFs that can be obtained from the ratio of single top and single anti-top cross sections or kinematic distributions. As discussed in [9] this ratio is stable against radiative corrections also for fiducial cuts, and seems to be predictable with high, $\mathcal{O}(1\%)$, precision at NNLO.

Another interesting recent development is the appearance of NLO QCD computations that go *beyond* the narrow width approximation [7]. Such computations work with physical final states and include both resonance and non-resonance contributions and their interferences. The very appearance of these computations is a testimony to a great progress that theorists achieved in computing radiative corrections to hard scattering processes; none of these computations would have been even remotely possible a decade ago, before the so-called NLO QCD revolution.

What is the virtue of the calculations that go beyond the narrow width approximation? I believe that quite often misleading answers to this question are given in that these calculations are attempted to be justified by arguing that there may be significant off-shell effects. As a rule, none are found, at least in kinematic regions associated with the $t\bar{t}$ production. Clearly, it can not be otherwise if the top quark samples are defined properly. Large off-shell effects are found in regions where production of two on-shell tops is kinematically unfavorable; to understand what these regions are, no NLO QCD computations are needed since the analysis can be done at leading order. This is exactly what experimentalists do when they design their selection cuts to obtain samples enriched with top quarks and this is why off-shell effects in top quark production cross sections and distributions are, typically, small.

Nevertheless, computations that go beyond the narrow width approximation are very valuable because they remove unphysical objects – top quarks – from the consideration and allow us to define "top quarks" operationally using kinematics of observable particles and jets and selection cuts. It is this feature that changes the quality of theoretical predictions, makes them infinitely closer to the real world and leads to theoretical computations that are capable of reproducing quite closely what is being done in experiments. These developments are further supported by an understanding



Figure 4: Left pane: expected constraints on the Wilson coefficients of the two operators in the extension of the Standard Model shown in Eq.(1). See [13] for details. Right pane: Comparison of fixed order (NLO) and matched predictions for the $b\bar{b}$ invariant mass spectrum in $pp \rightarrow t\bar{t}b\bar{b}$, see [15].

of how to combine these computations with parton showers through the resonance-aware matching algorithm [10] that will definitely contribute to making them accessible to experimentalists.

4 Top quark couplings

Couplings of top quarks to gauge bosons and the Higgs boson in the Standard Model are completely fixed (except for the CKM matrix elements that are largely arbitrary). However, if we consider the Standard Model as an effective low-energy approximation to a more complete theory, the Standard Model Lagrangian can be extended by a large number of higher-dimensional operators that may affect couplings of top quarks to other Standard Model particles.

Similar to precision electroweak or CKM fits, one can attempt to determine the Wilson coefficients of the many operators that appear in extensions of the Standard Model by fitting their predictions to available data [11, 12, 13]. This is non-trivial since the parameter space is large and the development of a careful strategy of how such a fit can be performed is required [12, 14]. While the discussion of the peculiarities of the full fit is beyond the scope of this talk, simple examples show that interesting things can be done. Indeed, imagine that the Standard Model is extended by two operators that describe a local HGG interaction vertex and the modified top Yukawa coupling

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{\rm SM} + \delta \mathcal{L}, \quad \delta \mathcal{L} = C_{\phi G} y_t^2 (\phi^+ \phi) G^a_{\mu\nu} G^{a,\mu\nu} + C_{t\phi} y_t^3 (\phi^+ \phi) (\overline{Q}t) \phi. \tag{1}$$

The two Wilson coefficients $C_{\phi G}, C_{t\phi}$ can be over-constrained [13] by studying contributions of effective operators in Eq.(1) to three production processes that involve the Higgs boson and the top quarks, e.g. $pp \to t\bar{t}H$, $pp \to H$ and $pp \to Hj$. As follows from the left pane in Fig. 4, this method allows a determination of the two Wilson coefficients with very high precision provided that 3000 fb⁻¹ of integrated luminosity are collected at the LHC.

Although direct measurements of the top Yukawa coupling is of great interest, it is a difficult measurement because of significant $t\bar{t}b\bar{b}$ background and a poor experimental resolution on the



Figure 5: Comparison of measured $pp \to ttZ$, $pp \to t\bar{t}W$ and $pp \to t\bar{t}\gamma$ with theoretical predictions.

invariant mass of a $b\bar{b}$ pair. It was expected that NLO QCD computations of $pp \rightarrow t\bar{t}b\bar{b}$ background would improve the quality of predictions for $b\bar{b}$ invariant mass distribution. Unfortunately, this did not happen since when the NLO QCD computations were matched to parton showers, significant differences relative to fixed order results were observed [15]. Indeed, gluon splittings into $b\bar{b}$ pairs in parton showers produce additional *b*-jets that increase the $m_{b\bar{b}}$ distribution in kinematic regions relevant for top Yukawa measurements by about thirty percent. It it not clear at this point if this effect is real or if it is an artifact of the matching. Further studies of this problem are definitely warranted.

Another way to overcome the challenge of measuring the top quark Yukawa coupling is to better understand the $pp \rightarrow t\bar{t}H$ signal. Since NNLO QCD computations for $2 \rightarrow 3$ processes are currently out of reach, one has to resort to approximate methods. In particular, as discussed by A. Ferroglia, it is possible to improve existing NLO QCD predictions for $pp \rightarrow t\bar{t}H$ process by considering the resummation of soft gluons through next-to-next-to-leading logarithmic accuracy [16].

Leaving the Yukawa coupling aside, it is useful to keep in mind that even top quark couplings to electroweak vector bosons, including photons, are not well known experimentally [14]. For example, there are still models consistent with experimental data that predict $\mathcal{O}(10\%)$ deviations in $Zt\bar{t}$ couplings. It is therefore exciting to see that experimental measurements of $\sigma_{t\bar{t}Z}$ are starting to get close to this precision, see Fig. 5. Precision, even marginal, requires that NLO-corrected predictions for cross sections and kinematic distributions are used; such computations both in the Standard Model and allowing for more general structure of the $t\bar{t}Z$ couplings are discussed in [14]. Similar measurements of the $t\bar{t}\gamma$ couplings are also getting quite precise, see Fig. 5. In this case it is essential to include proper theory predictions for photons emitted both in top production and top decay processes as they give similar contributions to fiducial cross section [14].

5 Conclusions

If the future of hadron collider physics is in a stronger emphasis on precision – as many null search results for physics beyond the Standard Model suggest – the top quark community is posed to lead the transition. Indeed, it is obvious that already now top physics combines precise measurements

with precise theory and BSM insights in an impressive and unique way.

Years of theoretical work led to enormous progress that allows us to connect the top quark signals at the LHC with the Lagrangian of the underlying quantum field theory, be it the Standard Model or one of its extensions. It is currently possible to provide reliable predictions for fiducial cross sections that can be directly compared with experimental measurements and use the results of these comparisons to search for physics beyond the Standard Model in a variety of clever ways. Technology has been developed to study BSM physics in the top sector in an agnostic way that, hopefully, will guide us through the dark ages and enable New Physics discovery at the end. The theory talks at the TOP 2017 conference provided a powerful testimony to just how far we got in our exploration of the top quark physics and charted a course for the future. Without a doubt, there will a lot of interesting physics to discuss and summarize at the TOP 2018.

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