PROCEEDINGS OF SCIENCE

Theoretical results in top quark physics

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A summary of recent developments in the theoretical understanding of top quark physics is given.

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1. Introduction

The goal of this talk is to summarize the recent theoretical work in top quark physics, focusing mostly on its Standard Model aspect. I will discuss the issue of the top quark mass determination at hadron colliders, the recent progress in theoretical understanding of simple processes with top quarks, physics that we learn from extending next-to-leading (NLO) QCD computations to complex processes with top quarks and how Effective Field Theory (EFT) methods and precision QCD computations can be combined to study physics beyond the Standard Model (BSM) in top production and decay. The choice of topics is clearly subjective and reflects my personal interests and preferences.

Let us start by listing several well-known reasons that make top quark an interesting object to study. First, top quark is the Standard Model (SM) particle with the strongest coupling to Higgs boson. For this reason, it is considered quite plausible that top quarks play an important role in keeping the Higgs boson mass at its "unnaturally small" value and in ensuring stability - or lack of it – of the electroweak vacuum. Second, the top quark is the heaviest SM particle with a short lifetime and a particular decay signature; for this reason processes with top quarks provide important backgrounds to searches for physics beyond the Standard Model. Third, because of the top quark properties, top quark physics provides an important playground for preparing to detailed studies of BSM signals both in theory and experiment. Fourth, top quark interactions with neutral electroweak gauge bosons, such as Z's and photons, are among the least known in the Standard Model. The fifth reason is that the top quark is the only "free" quark that we can access in Nature.

I will elaborate on the last point since its understanding is crucial for the way we think about the top quark physics at colliders. Indeed, the top quark physics is different from physics of any other quark because most of the time top quarks are produced as free on-shell quarks that decay well before they are affected by non-perturbative long-distance QCD effects. The smallness of the top quark width relative to its mass, $\Gamma_t \ll m_t$, allows us to treat processes with top quarks in the narrow width approximation, neglecting radiative effects that connect production and decay stages. Another important point is that hadronization effects do not affect top quark polarization; as the result, one should apply the narrow widths approximation at the amplitude level and keep all the spin correlations of produced top quarks and their decay products.

These features are important because they open up a way to study complex processes with top quarks in higher orders of perturbative QCD, such as associated production with vector bosons or jets, or NNLO QCD corrections to top quark pair production, that include proper description of top quark decays. Of course, the quality of the on-shell approximation depends on the selection criteria for the final state particles since at the LHC an invariant mass of a top quark is not accurately reconstructed from its decay products. It is therefore important to check that the on-shell approximation actually works well for the realistic selection criteria that are used to identify the top quark pairs at the LHC. To this end, one can compare calculations of top quark pair production supplemented with decays to Wb final states in the narrow width approximation and the production of $W^+W^-b\bar{b}$ final states that includes both resonance and non-resonance contributions [2]. Such comparison shows that for the selection criteria used by the LHC experiments, the difference between the two computations is about 1% and that it does not depend on the order in perturbation theory. The agreement becomes worse at the corners of the available phase space where production of two on-shell tops becomes kinematically disfavored. For the realistic selection criteria at the LHC these regions contribute little to the observed top quark pair production cross section so that their effects remain marginal.

The remainder of the paper is organized as follows. In the next Section we discuss the issue of the top quark mass. In Section 3 we describe the recent theoretical progress with understanding top quark pair production and single top quark production cross sections. In Section 4 we discuss a few examples of how progress on the theory side helps with understanding physics of complex processes with top quarks. In Section 5 we discuss how Effective Field Theories and perturbative QCD are used to constrain BSM contributions to top quark physics. We conclude in Section 6.

2. The top quark mass

Among the basic features of the top quark, its mass definitely stands out in significance. Indeed, the top quark mass determines the top quark Yukawa coupling and plays a central role in the current discussion of the stability of electroweak vacuum [1]. The top quark mass is claimed to be measured very precisely. In fact, the relative precision of the top quark mass measurements is higher than of any other quark. However, there are continuous discussions about the meaning of these results since numerical differences between top quark masses defined in different renormalization schemes are known to be large. To say this differently, before we can make use of the very precise measurements of the top quark mass parameter at the LHC, we need to know the perturbative scheme in which this parameter is defined. Unfortunately, this information is not easy to deduce from the majority of the top quark mass measurements by both ATLAS and CMS.

The current line of reasoning is as follows. Since parton shower event generators are used in the analyses, the measured top quark mass is a “Monte-Carlo” mass whose relation to conventionally defined quark masses is obscure. However, the notion of the Monte-Carlo mass is unclear for many reasons. For example, there is quite a number of different parton shower event generators that are used in the analyses by the LHC collaborations. They attempt to address the same physics but they are clearly not identical. In this situation, should we be talking about HERWIG mass, PYTHIA mass and, perhaps, the SHERPA mass? What about different non-pertubative tunes that experimentalists use in their parton showers? Do they lead to different definitions of the top quark masses? Finally, what does a Monte-Carlo mass mean at the first place if parton showers do not include the mass counter-terms by construction? The list of questions above should convey the following message – although the theory community has correctly emphasized that what has been extracted recently by the CMS and ATLAS collaborations is ‘something that is closely related to the top quark mass”, we need to define precisely what this “something” is and why do we feel uncomfortable with the current experimental procedures and practices. Simply calling the measured quantity “the Monte Carlo mass” does not help us to understand the real issue.

To have a more structured discussion, I believe that it is convenient to separate the issue of the top quark measurement into two parts: a) the need to have a short-distance definition of the top quark mass and b) the impact of non-perturbative QCD effects on the top quark mass extraction from hadron collider data. We will first discuss the short-distance definition of the top quark mass. The perturbative instabilities of the pole mass of a quark are known for a long time; the pole mass is not well-defined to all orders in perturbation theory [3, 4]. On the other hand, if one works to a fixed order in perturbation theory, the pole mass is well-defined and the on-shell renormalization scheme is a perfectly valid scheme for fixed order computations. However, in B-physics the on-shell renormalization scheme is often discarded since the use of the pole mass in perturbative computations leads to large numerical shifts from one order of perturbation theory to the other; these shifts are compensated by *different numerical values that one needs to use for the quark pole mass in calculations in different orders of perturbation theory.* This is possible but not very convenient in practice so that, if we do not want to deal with the shifts at the first place, we switch to a different, "short-distance", mass definition.

I would like to stress that the above story reflects our experience with b-physics and, although it must apply to all heavy quarks as a matter of principle, the top quark physics seems to be somewhat different. In fact, we do not observe large corrections when we use the top quark *pole mass* in perturbative computations. For example, the recently computed four-loop relation between the short-distance $\overline{\mathrm{MS}}$ mass and the pole mass [5] shows that up to four loops in perturbative QCD the series seem perfectly convergent and there is no sign of their asymptotic nature. As an illustration, here is the equation which gives the value of the pole quark mass for a fixed (hypothetical) value of the $\overline{\mathrm{MS}}$ top quark mass

$$m_{t,\mathrm{pole}} = (163.643+7.557+1.617+0.501+0.195)\ \mathrm{GeV}. \tag{2.1}$$

The successive terms in brackets show $\mathcal{O}(\alpha_s^0), \mathcal{O}(\alpha_s), \ldots$ perturbative contributions.

Equation (2.1) shows that, as long as we are interested in the value of the top quark mass with the uncertainty that exceeds $\mathcal{O}(200)$ MeV, the *pole* mass of the top quark seems to be an absolutely adequate concept to be used for the description of the LHC data. A similar behavior – absence of large perturbative corrections when the result is written in terms of the pole mass – is seen in the perturbative expansion of the top quark width computed in Refs. [6, 7]

$$\Gamma_t = \frac{G_F m_{t,\mathrm{pole}}^3}{8\sqrt{2}\pi} |V_{\mathrm{tb}}|^2 \left(1-0.09+0.02\right). \tag{2.2}$$

Of course, the reason for the absence of large corrections is a smaller value of the strong coupling constant $\alpha_s(m_t)$ that delays the impact of the factorial growth of perturbative coefficients in $m_{t,\mathrm{pole}}$ and Γ_t to really high orders in perturbation theory. This is a simple reason but it leads to important and not so much appreciated conclusion that the top quark pole mass can be used *in practice* as a useful parameter to be determined at the LHC as long as the achieved precision is lower than $\mathcal{O}(200\ \mathrm{MeV})$.

On the other hand, it should be emphasized that, similar to any other observable studied at a hadron collider, the top quark mass gets affected by non-perturbative effects that are *unrelated to its proper definition*. Therefore, the question about non-perturbative effects affecting the extraction of the top quark mass exists *even* if a short distance mass is used consistently in theoretical calculations and experimental analyses. Indeed, let us imagine an idealized situation where parton shower is not needed for the extraction of the top quark mass from a particular observable. We choose a short-distance mass definition and write a prediction for an observable in perturbative QCD. However, *any* prediction of perturbative QCD is only accurate *up to power correction* that scale as some unknown power of $\Lambda_{\rm QCD}$ over the hard scale which we assume to the the top quark mass. We find

$$\frac{{\rm d}\sigma}{{\rm d}M} = T(M, m_t, \alpha_s)\left[1 + c\left(\frac{\Lambda_{\rm QCD}}{M}\right)^n\right]. \tag{2.3}$$

It is easy to see that these power correction lead to systematic uncertainties in the top quark mass determination that are different for different observables. One finds

$$\delta m_t \sim \frac{cT}{\partial T/\partial m_t}\left(\frac{\Lambda_{\rm QCD}}{m_t}\right)^n \sim \frac{cm_t}{k}\left(\frac{\Lambda_{\rm QCD}}{m_t}\right)^n, \tag{2.4}$$

where we assumed that $M = m_t$ is the solution of the perturbative version of this equation for the top quark mass, and that $\partial T/\partial m_t \sim T/m_t$ Since $n = 1$ can not be excluded for even the simplest observables, we should expect that the top quark mass can not be extracted with the precision that is better than $\Lambda_{\rm QCD}$ *even when the properly defined top quark mass is used.*[1] On the other hand, if a particular observable is sensitive to the top quark mass and *does not* receive power corrections with $n = 1$, it becomes ideal for the top quark mass determination. Therefore, the only way to improve the existing practices of the top quark mass determination is to study observables that are used for this purpose and either fully understand the power corrections *or* argue that they are small for a particular reason.[2]

What is the role of parton showers in this discussion? I believe their role is to provide estimates of non-perturbative corrections in a situation when the actual theory of power corrections to hadron collider observables is absent. Such estimates, necessarily, depend on hadronization models implemented in parton shower even generators. These models, on average, properly describe large amounts of data but they are, of course, heuristic. For this reason, estimates of power corrections may or may not be correct; if they are not, many determinations of the top quark mass are systematically biased.

To counter this concern, CMS performed an interesting study [8] where they checked the dependence of the extracted value of the top quark mass on the event selection criteria and the event kinematics. This is interesting since if power corrections are functions of event kinematics, they might show up as incompatible values of the top quark masses extracted from different types of events. CMS does not find significant kinematic biases but the precision of those studies is so far relatively poor [8]. It will be instructive to keep checking the (in)dependence of the extracted top quark mass on the event selection with a much higher statistics that will be available at the Run II.

Ultimately, to significantly improve the top quark mass extraction from the LHC data, we need to find an observable that is both a) sensitive to the top quark mass and b) is subject to negligible non-perturbative effects. Developing such understanding requires advances in the theory of power corrections in hadron collisions. Clearly, this is a long term goal but I think it is the only way to make high-precision determinations of the top quark mass from the LHC both credible and consistent with the underlying theoretical understanding of QCD.

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[1] We note that in semileptonic decays of heavy mesons, the choice of short-distance quark masses removes *all* $\mathcal{O}(\Lambda_{\rm QCD}/m_q)$ non-perturbative contributions to the width. There is no similar statement for heavy quark observables at a hadron collider, however.

[2] By choosing observables which exhibit $\partial T/\partial m_t \gg T/m_t$, which is what typically happens at the kinematic edges, one can decrease the importance of power corrections.

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

Figure 1: Theory predictions for top pair production cross section, from Ref. [10].

3. Simple processes with top quarks

Simple processes with top quarks, such as the top quark pair and single top quark production, play an important role in the LHC physics program. We will discuss the recent theoretical advances in the description of these processes in this Section.

We begin with the top quark pair production. Calculation of the NLO QCD corrections to top quark pair production is a classic computation in perturbative QCD performed for the first time almost thirty years ago [9] and then refined many times after that. A few years ago these NLO QCD results were extended to NNLO in perturbative QCD [10]. This landmark calculation of QCD corrections to one of the basic processes at the LHC signaled the advent of an era of the NNLO QCD hadron collider phenomenology that, as we have seen in the past year, is becoming a reality.

The NNLO QCD computation of the top quark pair production resulted in a few interesting observations. First, theoretical predictions for $t\bar{t}$ cross section and the experimental measurements compare quite well, both at the Tevatron and the LHC. Second, the situation with the theory of $t\bar{t}$ production after the NNLO QCD calculation is quite peculiar. Indeed, theoretical prediction exhibits very small residual scale variation uncertainty, of the order of 4% (see Fig.1). Also, all other sources of theoretical uncertainties - such as the top mass quark mass uncertainty, the PDF uncertainty etc. are similar to the scale variation uncertainty. Therefore, we have reached an interesting milestone in precision studies of the top quark pair production since it implies that further progress in top quark pair production will require *coherent improvements in all aspects of hadron collider physics theory*, not only further advances in technology of perturbative computations.

A precise theoretical prediction for a well-studied observable should have many interesting spin-offs and, indeed, this is what happens with the NNLO QCD computation of the top quark pair production cross section. So let me discuss a few of them. One of such spin-offs concerns the top quark forward-backward asymmetry at the Tevatron. It is well-known (see recent review [11] and reference therein) that measurements of the forward-backward asymmetry by CDF and D0 collaborations caused quite an excitement in recent years. Indeed, experimental and theoretical results showed persistent tension, especially for large rapidities of top quarks and large invariant masses of $t\bar{t}$ pairs. These discrepancies were explored in the context of physics beyond the Standard Model but no convincing explanation consistent with other data appeared so far.

The Standard Model predictions for the asymmetry were scrutinized as well. Unfortunately,

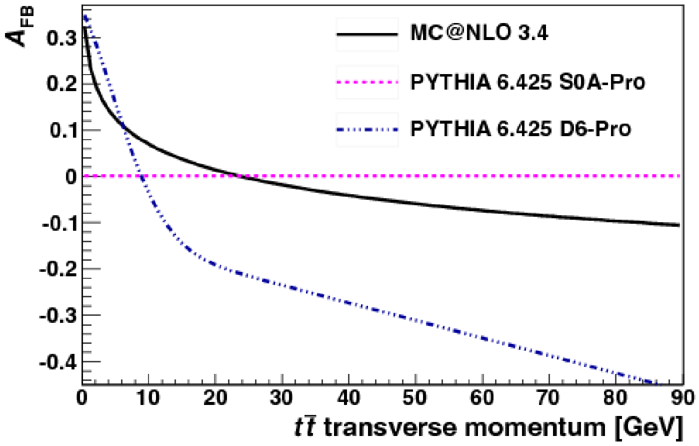

Figure 2: Asymmetries produced by different parton shower event generators as a function of the transverse momentum of the $t\bar{t}$ pair, see Ref. [13] for more details.

sources of potentially large radiative effects that can explain the disagreement were not identified. A few interesting observations, however, were made. For example, it was observed that parton shower Monte-Carlo event generators produce an asymmetry, c.f. Fig. 2. This was very surprising since asymmetry requires either one-loop virtual corrections or interference of real emissions by initial and final states. None of these effects is supposed to be included in "canonical" parton shower Monte Carlos that are constructed around collinear approximation. The reason that asymmetries are generated is the so-called color-coherence effect in parton showers that, in an approximate way, accounts for the interferences [12]. However, parton shower results for the asymmetry are essentially random in a sense that they differ significantly between different parton showers and even between different tunes of the same parton shower, see Fig. 2. The fact that these issues have not affected earlier comparisons of theoretical and experimental results for the asymmetry looks like a miracle at first sight but it is explained by the fact that parton showers matched to exact NLO QCD predictions were used for the analysis of data, so that the matching was forcing the asymmetry to follow the NLO predictions.

Another interesting observation was related to the asymmetry in final states with top pairs and a jet [14]. The asymmetry in this case is generated already at the tree level from the interference of gluons emitted by initial and final state. The corrections to this asymmetry were calculated and found to be close to $\mathcal{O}(-100)$ percent [14]. However, it was also argued [15] that these large effects are particular to $t\bar{t}j$ final state and nothing similar is possible for the inclusive asymmetry.

In spite of all the indications that large QCD corrections to the asymmetry are unlikely, it was very important to compute them explicitly. This was recently done [16]. The NNLO QCD corrections turned out to be moderate; they indeed increase the NLO QCD prediction for the asymmetry, move it closer to experimental results and reduce the scale-uncertainty. The "agreement" between theory and experiment remains at the level of $\mathcal{O}(1.5-2)$ standard deviations especially if results of the most recent measurements are taken into account. However, the dependence of the asymmetry on the invariant mass and on the rapidity differences of t and $\bar{t}$ still does not look good (see

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

Figure 3: Theory predictions for the single top production cross section with the cut on the top quark transverse momentum at different orders in perturbation theory (from Ref. [18]).

Ref. [16]); the resolution of this issue will have to wait further and, given the fact that analyses of the Tevatron data slowly wind down may, unfortunately, never happen.

Another interesting spin-off of the NNLO QCD computation of the top quark pair production is the observation that $\sigma_{t\bar{t}}$ can be used to constrain contributions of yet undiscovered particles to the "top pair production" cross section. As a particular example consider supersymmetric partners of top quarks, the stops. If stops and tops are quasi-degenerate in mass and stops decay to tops with little missing energy, the resulting final states are kinematically indistinguishable from top quarks except for spin correlations. However, stop contributions increase the top quark production cross section by about fourteen percent. Therefore, if we know the top cross section precisely, we can detect the excess! As we just discussed, the recent NNLO QCD computation reduces the residual uncertainty on the cross section to just about four percent; this improvement allows us to constrain the stop contribution to top pair production cross section and to exclude stops with masses close to the top quark mass [17].

We will now turn to the discussion of the single top quark production. Similar to the top quark pair production, theory of the single top quark production in the t-channel was recently extended to NNLO QCD [18]. The calculation is approximate in that N_c is assumed to be large which allows us to neglect the cross-talk between the two different incoming quark lines in the process $qb \to tq'$. It is well known that the total cross section of the t-channel single top production receives very small NLO QCD corrections suggesting that NNLO QCD computations are not needed. A more careful look, however, reveals that these small corrections are the result of significant cancellation between sizable corrections to different channels, making the NNLO QCD computations quite desirable.

Similar to the top quark pair production case, the results for t-channel single top production cross sections agree well with the results of CMS and ATLAS measurements. Theoretical predictions, in dependence on the cut of the transverse momentum of the top quark are shown in Fig. 3. The NLO QCD corrections depend strongly on the transverse momentum cut; the NNLO QCD corrections, on the other hand, are always small. The residual uncertainty in the predictions for all values of the $p_\perp$ cut is close to about a percent [18].

There are immediate physics implications of a precise knowledge of the single top production cross section. Indeed, one of the quantities that can be extracted from the single top quark cross section is the CKM matrix element V_{tb} (more generally, one can study the anomalous tbW couplings). The above results show that, at least on the theory side, the extraction of the V_{tb} from the measurement of the single top production cross section with the $\mathscr{O}(1\%)$ precision should be possible.

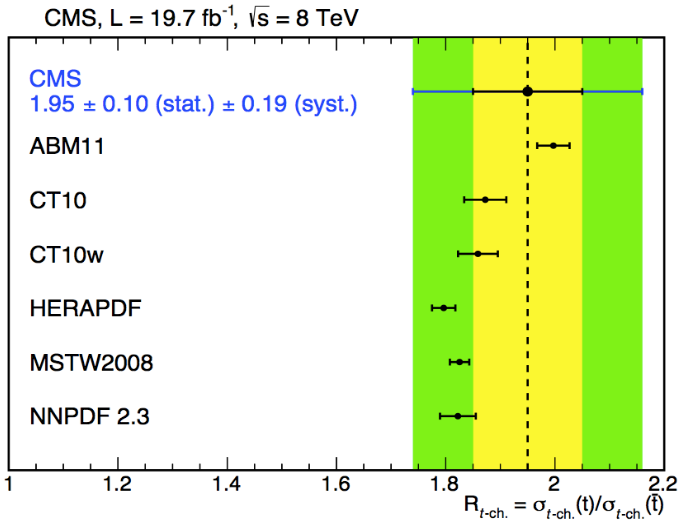

Figure 4: Comparison of theoretical predictions for $\sigma_t/\sigma_{\bar{t}}$ production cross sections for different sets of parton distribution functions and the experimental result, see Ref. [19] for more detail.

Another interesting observable related to the single top production cross section is the ratio of single top and single anti-top production cross sections. This ratio is very stable against higher order QCD corrections [18] *but* it depends very strongly on parton distribution functions, see Fig. 4. Further improvements in experimental measurements will allow us to use the ratio of single top to single anti-top production cross sections to constrain ratios of up and down quarks in the proton at relatively large values of the Bjorken x (see Ref. [20] for a recent discussion).

Another emergent "precision frontier" in top quark physics is related to the top quark decays and the measurement of the W-helicity fractions. W-boson helicity fractions determine angular distributions of leptons in $t \to Wb$ decays in the rest frame of the W-boson. The z-axis is taken to be along the direction of the W-boson in the top rest frame. The theory predictions are known to NNLO QCD and the residual uncertainty on the prediction is about one percent [21]. In terms of precision, the experimental results were always far behind but this seems to be changing. Indeed, recent CMS measurements started approaching a $\mathcal{O}(5\%)$ precision benchmark for the longitudinal- and minus-one helicity fractions [22]; hopefully, this trend will continue and we will soon be able to utilize the precision of the theory results in full to e.g. constrain potential BSM contributions to top quark decays (see Section 5 for more details). We note, however, that earlier calculations of helicity fractions were inclusive, while experimental measurements are definitely not. This, however, is not a problem since available fully differential NNLO QCD computations for top quark decay [23, 24] can and, perhaps, should be eventually used for a more detailed comparison between theoretical and experimental results.

4. Complex processes with top quarks

We will next discuss complex processes with top quarks. The increased ability to describe top-like final states with a high degree of realism, including next-to-leading order corrections (QCD and

EW), matching to parton showers and merging of different jet-multiplicity samples is another very impressive development that occurred in recent years. This effort is spearheaded by such groups as POWHEG, aMC@NLO, OpenLoops and Sherpa.

To illustrate the calculations that can currently be performed with the NLO QCD accuracy, I will discuss processes that involve top quarks and jets. For $pp \to t\bar{t}+0$ jets, one can avoid using the narrow width approximation and compute the NLO QCD corrections to $WWbb$ final state with massive b-quarks [29, 27]. For $pp \to t\bar{t}j$ this is already not possible. One can include radiative corrections to the production and decay, as well as spin correlations, but in the narrow width approximation [15, 28]. Note that, as explained in the Introduction, the accuracy of this approximation is expected to be better than one percent, almost independent of the kinematics. The production of $t\bar{t}$ pair in association with two jets is known for stable top quarks [26]. The situation with the associated production of a top pair and gauge or Higgs boson is similar. The $pp \to t\bar{t}+V$ is available in the narrow width approximation, including the NLO QCD corrections to the production and decay [36, 31, 33, 32]. The production of $t\bar{t}H$ was recently computed at NLO by studying $bWbWH$ final state [25]. All the computations listed above can be matched to parton showers.

There are many examples of interesting physics insights that we have learned thanks to the NLO QCD computations for complex processes. I will discuss one example here. We consider production of $WbWb$ final state that includes contributions from intermediate $t\bar{t}$ pairs but also from non-resonant diagrams [34]. The b-quarks are massive and the calculation can be performed in the four-flavor scheme. Loose requirements on the number of b-jets lead to larger off-shell contributions to the final result than in the case of top quark pair production cross section. However, these off-shell contributions can be identified with the single top quark production process, the associated tW production.

This observation has important consequences. Indeed, it was pointed out long ago [35] that a simple separation of top production process into a pair and single top production becomes unphysical at NLO QCD if top decays are allowed. The technical ability to describe the “meta”-process $pp \to WbWb$ at NLO exactly, forgoing simplifications offered by the narrow width approximation, makes it possible to define the relevant processes (top pairs, tW, t-channel single top) through kinematic selection requirements rather than through their partonic content. Achieving this would have been impossible without great progress with the automation of NLO QCD computations achieved in recent years.

When we talk about NLO QCD computations for complex processes, we think about improved predictions for QCD backgrounds. But quite often signal processes that we need to understand to study interesting things are also quite complex. It is therefore important to emphasize that theoretical developments in NLO QCD computations that occurred in recent years allow us to make advanced predictions for *both* backgrounds and signals at the same time. A good example of how such predictions are used together is the NLO QCD description of the di-photon production in association with a top quark pair at the LHC. This cross section receives contributions from the prompt process $pp \to t\bar{t}+2\gamma$ as well as from the associated production of the Higgs boson $pp \to t\bar{t}H$ followed by the decay $H \to \gamma\gamma$. The results of these calculations are shown in Fig. 5; the drawback is that decays of top quarks and the radiation of photons in top decays are not included in these computations although this effect is known to be significant for photons with moderate

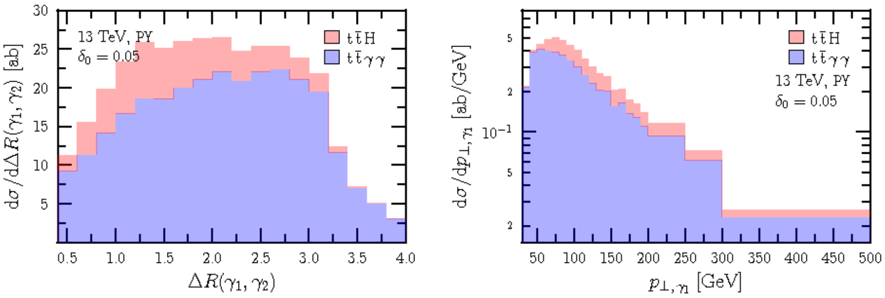

Figure 5: Di-photon production in association with top quarks, including prompt and $H \to \gamma\gamma$.

transverse momentum [36].

5. Effective field theories for physics beyond the Standard Model in top production and decay

The final topic that I would like to discuss is the BSM physics in top production and decay. This is an enormous topic since there are many different models of physics beyond the Standard Model that affect the top quark physics at the LHC. One may then wonder if a robust approach exists that allows us to describe large classes of BSM effects without resorting to specific models of New Physics. Indeed, such opportunity arises if we focus on those scenarios of BSM physics where new particles are relatively heavy; integrating them out, we describe their effects by local higher-dimensional operators whose contributions are suppressed by some high energy scale. In the context of top quark physics, the utility of this approach was strongly emphasized in Ref. [37].

Consider, as an example, the top quark decay [38]. If all quarks, except the top quark, are treated as massless, there exist just two dimension-six operators $\mathscr{O}_{\phi q}^{(3)} = i(\phi^+ \tau^i D_\mu \phi)(\bar{q}\gamma^\mu \tau^i q) +$ h.c. and $\mathscr{O}_{tW} = \bar{q}\sigma_{\mu\nu}\tau^i t\tilde{\phi} W_i^{\mu\nu}$ that affect the SM prediction for the top quark decay rate and for the W-boson helicity fractions [37]. Since both of these observables are well-measured and are computed to high orders in perturbative QCD, it is possible to use them to constrain ratios of Wilson coefficients to the scale of physics beyond the Standard Model. One finds [38]

$$\frac{C_{\phi q}^{(3)}}{\Lambda^2} = 0.3^{+1.4}_{-1.2}\ \mathrm{TeV}^{-2}, \quad \frac{C_{tW}}{\Lambda^2} = 0.088^{+0.44}_{-0.45}\ \mathrm{TeV}^{-2}. \tag{5.1}$$

Of course, such constraints are only meaningful if SM predictions for relevant quantities are sufficiently precise. The energy scale of new physics that can eventually be determined in any precision measurement is limited by one over uncertainty in the Standard Model prediction; this implies that reducing uncertainties in Standard Model predictions is absolutely crucial for the success of this research program.

One can exploit enhancements in kinematic distributions that occur because one deals with higher-dimensional operators, but it is not always clear if large effects obtained in this way are consistent with the applicability of effective field field theory description at the first place. For example, suppose we modify the Standard Model by adding to it a dimension-five operator that

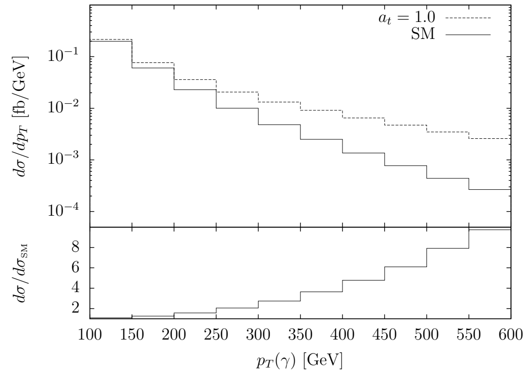

Figure 6: Spectrum of photons in the process $pp \to t + \gamma$ at the LHC, from Ref. [39]. The anomalous magnetic moment of the photon causes much harder spectrum of the emitted photons.

describes the top quark anomalous magnetic moment $\mathscr{L}_{t\bar{t}\gamma} = -a_t \frac{Q_t e}{4m_t}\bar{t}\sigma_{\mu\nu}tF^{\mu\nu}$ [39]. Current constraints on this quantity are not very strong, $-3.0 < a_t < 0.45$, whereas the Standard Model predictions is $a_{t,\rm SM} \approx 0.02$. To observe an effect of such an operator one can study the modification of the photon spectrum in the reaction $pp \to tX + \gamma$ at the LHC. Thanks to the non-renormalizable nature of $\mathscr{L}_{t\bar{t}\gamma}$, the spectrum of photons becomes significantly harder, see Fig. 6. However, at large $p_{\perp,\gamma}$, the applicability of the whole Effective Field Theory approach becomes questionable whereas at small $p_{\perp,\gamma}$ the effects are small and it is not clear if (observed) modifications of the spectrum are caused by a higher-dimensional operator or by radiative corrections.

A way out of this dilemma, that is currently gaining in popularity, is to combine calculations of radiative corrections and higher dimensional operators, to improve the reliability of constraints on their Wilson coefficients. The point is that if precision of the SM prediction improves, one is not forced to search for contributions of higher-dimensional operators in kinematic regions where applicability of EFTs becomes questionable. Just to illustrate potential gains that one gets by extending the EFT analysis to NLO QCD, consider the case of $t\bar{t}Z$ anomalous couplings studied in Refs. [33, 40]. Bounds on the weak anomalous magnetic moment defined as $\mathscr{L}_{ttZ} = eC^Z_{2,V}\bar{u}(p_t)\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}v(p_{\bar{t}})Z_\mu$ are shown in Fig. 7. One sees that, thanks to the NLO QCD computation, the coupling can be determined with a somewhat higher precision.

6. Conclusions

The current situation in top quark physics is reminiscent of the overall situation in particle physics. A significant progress in theory and experiment has resulted in a much better understanding of the Standard Model aspect of top quark physics. Such improved understanding should, in a longer run, give us more opportunities to search for physics beyond the Standard Model through both direct and indirect measurements at the LHC.

I will now give a few examples of an impressive progress along several directions in the top quark theory. Indeed, a very high accuracy of perturbative QCD predictions for simple top quark processes is, finally, achieved. These NNLO QCD computations offer a variety of interesting

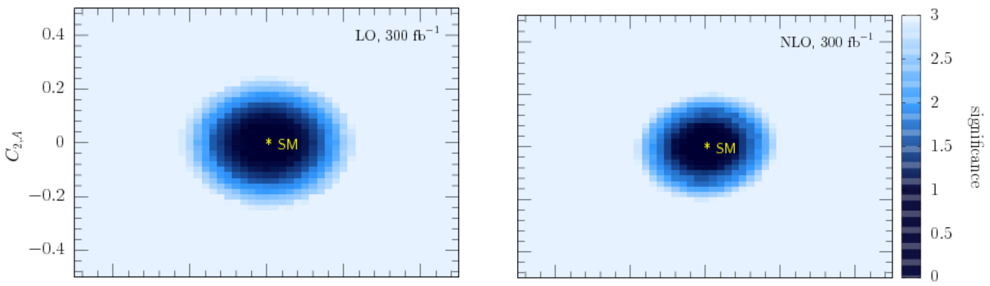

Figure 7: Limits on the coefficient of the $\mathscr{L}_{ttZ}$ operator from Refs. [33, 40] for 300 fb^{-1} at 13 TeV LHC at leading and next-to-leading order in QCD.

physics insights, from precise determination of parameters in top quark physics, to constraints on parton distribution functions, to exclusion of exotic (stop) contributions to top production cross sections. Further progress in exploring simple top quark processes will require making their theoretical description more realistic and relevant for experiments by including top quark decays and spin correlations, by computing kinematic distributions and, perhaps, by combining fixed order computations with parton showers.

The important issue in top quark physics is the measurement of the top quark mass. I have argued that the significance of short-distance masses in the context of the top quark physics is probably over-emphasized but, at the same time, the role of regular power corrections is probably not fully appreciated. Understanding non-perturbative corrections to observables used for the high-precision determination of the top quark mass is very important for reaching the ultimate precision of the top quark mass measurements at the LHC.

Complex processes with top quarks can be handled by the automated programs such as MadLoop, OpenLoops etc. Nevertheless, more realism is desirable especially in the context of a proper description of top quark decays as well as gluon and photon emissions from top quark decay products. These features are often ignored by the automated one-loop providers. This remark also applies to studies of BSM contributions to top quark physics. Such contributions can be described in the Effective Field Theory framework that is obtained by integrating out physics beyond the Standard Model. The higher-dimensional operators may affect both production and decay of top quarks, similar to radiative corrections. Existing data on top quark decays points to the BSM mass scale to be around 1 TeV, with significant error bars. When NLO QCD computations are combined with theoretical predictions that employ EFT framework, one improves the sensitivity of experimental measurements to higher-dimensional operators.

In summary, we have reviewed the recent theoretical developments in top quark physics. The impressive progress with NNLO QCD computations for simple processes with top quarks, with NLO QCD computations for complex processes where tops are produced in association with vector bosons or jets and the ensuing understanding of how effective field theories can be used to parametrize BSM contributions to top quark production and decay, clearly show that the theoretical community involved in top quark research is ready for the Run II. We should only hope that it will give us exciting and unexpected physics to think about.

References

[1] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, et al., JHEP 1208, 098 (2012).

[2] See the contribution by A. Denner, S. Dittmaier, S. Kallweit, S. Pozzorini, M. Schulze “Finite width effects in top quark pair production and decay at the LHC’ in J. Alcaraz Maestre *et al.* [SM and NLO MULTILEG Working Group and SM MC Working Group Collaborations], arXiv:1203.6803 [hep-ph]. .

[3] I. Bigi, M. Shifman, N. Uraltsev, and A. Vainshtein, Phys. Rev. D 50, 2234 (1994).

[4] M. Beneke and V. Braun, Nucl. Phys. B426, 301 (1994).

[5] P. Marquard, A. V. Smirnov, V. A. Smirnov and M. Steinhauser, Phys. Rev. Lett. **114**, no. 14, 142002 (2015) [arXiv:1502.01030 [hep-ph]].

[6] A. Czarnecki and K. Melnikov, Nucl. Phys. B544, 520 (1999).

[7] K. G. Chetyrkin, R. Harlander, T. Seidenstcker and M. Steinhauser, Phys. Rev. D60, 114015 (1999)

[8] The CMS collaboration, CMS-PAS-TOP-12-029.

[9] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B **303**, 607 (1988).

[10] M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. **110**, 252004 (2013) [arXiv:1303.6254 [hep-ph]].

[11] J. A. Aguilar-Saavedra, D. Amidei, A. Juste and M. Perez-Victoria, Rev. Mod. Phys. 87, 421 (2015).

[12] P. Skands, B. Webber and J. Winter, JHEP **1207**, 151 (2012) [arXiv:1205.1466 [hep-ph]].

[13] V.M. Abazov et al. (D0 Collaboration), Phys.Rev. **D84**, 112005 (2011).

[14] S. Dittmaier, P. Uwer and S. Weinzierl, Eur. Phys. J. C **59**, 625 (2009) [arXiv:0810.0452 [hep-ph]].

[15] K. Melnikov and M. Schulze, Nucl. Phys. B **840**, 129 (2010) [arXiv:1004.3284 [hep-ph]].

[16] M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. **115**, no. 5, 052001 (2015) [arXiv:1411.3007 [hep-ph]].

[17] M. Czakon, A. Mitov, M. Papucci, J. T. Ruderman and A. Weiler, Phys. Rev. Lett. **113**, no. 20, 201803 (2014) [arXiv:1407.1043 [hep-ph]].

[18] M. Brucherseifer, F. Caola and K. Melnikov, Phys. Lett. B **736**, 58 (2014) [arXiv:1404.7116 [hep-ph]].

[19] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1406**, 090 (2014).

[20] S. Alekhin, J. Bluemlein, S. Moch and R. Placakyte, arXiv:1508.07923 [hep-ph].

[21] A. Czarnecki, J. G. Korner and J. H. Piclum, Phys. Rev. D **81**, 111503 (2010) [arXiv:1005.2625 [hep-ph]].

[22] The CMS collaboration, S. Chatrchyan *et. al*, JHEP 10, 167 (2013).

[23] J. Gao, C. S. Li and H. X. Zhu, Phys. Rev. Lett. **110**, no. 4, 042001 (2013) [arXiv:1210.2808 [hep-ph]].

[24] M. Brucherseifer, F. Caola and K. Melnikov, JHEP **1304**, 059 (2013) [arXiv:1301.7133 [hep-ph]].

[25] A. Denner and R. Feger, arXiv:1506.07448 [hep-ph].

[26] G. Bevilacqua, M. Czakon, C. G. Papadopoulos and M. Worek, Phys. Rev. D **84**, 114017 (2011) [arXiv:1108.2851 [hep-ph]].

[27] M. V. Garzelli, A. Kardos and Z. Trocsanyi, JHEP **1408**, 069 (2014) [arXiv:1405.5859 [hep-ph]].

[28] A. Kardos, C. Papadopoulos and Z. Trocsanyi, Phys. Lett. B **705**, 76 (2011) [arXiv:1101.2672 [hep-ph]].

[29] A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, JHEP **1210**, 110 (2012) [arXiv:1207.5018 [hep-ph]].

[30] K. Melnikov, M. Schulze and A. Scharf, Phys. Rev. D **83**, 074013 (2011) [arXiv:1102.1967 [hep-ph]].

[31] A. Kardos and Z. Trocsanyi, JHEP **1505**, 090 (2015) [arXiv:1406.2324 [hep-ph]].

[32] M. V. Garzelli, A. Kardos, C. G. Papadopoulos and Z. Trocsanyi, JHEP **1211**, 056 (2012) [arXiv:1208.2665 [hep-ph]].

[33] R. Röntsch and M. Schulze, JHEP **1407**, 091 (2014) [arXiv:1404.1005 [hep-ph]].

[34] F. Cascioli, S. Kallweit, P. Maierhöfer and S. Pozzorini, Eur. Phys. J. C **74**, no. 3, 2783 (2014) [arXiv:1312.0546 [hep-ph]].

[35] S. Frixione, E. Laenen, P. Motylinski, B. R. Webber and C. D. White, JHEP **0807**, 029 (2008) [arXiv:0805.3067 [hep-ph]].

[36] K. Melnikov, M. Schulze and A. Scharf, Phys. Rev. D **83**, 074013 (2011) [arXiv:1102.1967 [hep-ph]].

[37] C. Zhang and S. Willenbrock, Phys. Rev. D **83**, 034006 (2011) [arXiv:1008.3869 [hep-ph]].

[38] C. Degrande, "Top quarks as a probe for heavy new physics", Talk at the International Workshop on Deep Inelastic Scattering and Related Subjects (DIS 2014), arXiv:1407.3183.

[39] M. Fael and T. Gehrmann, Phys. Rev. D **88**, 033003 (2013) [arXiv:1307.1349 [hep-ph]].

[40] R. Röntsch and M. Schulze, JHEP **1508**, 044 (2015) [arXiv:1501.05939 [hep-ph]].