A theory perspective on Top2014

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Abstract: This is the write-up of the theory keynote talk on the Top2014 conference in Cannes, France.

1 Introduction

It is widely appreciated that the top quark indeed is a very special particle, for a number of reasons. First of all, it is the only strongly interacting fundamental particle, which does not experience the effect of asymptotic freedom: due to its short lifetime it will always decay before the strong interactions can force it into a bound state. This in itself makes it a highly interesting laboratory for precision studies of QCD in the perturbative regime. Furthermore, and maybe even more importantly, its large mass guarantees the top quark to play a dominant role in the running of the Higgs boson mass. This tight link to the electroweak symmetry breaking sector renders a deeper and detailed understanding of all of its properties from quantum numbers to interaction properties a cornerstone for our understanding of the particle universe, the fundamental laws of physics at the smallest distances and largest energies. In this context it is somewhat amusing to note that its couplings to the Higgs boson are perturbative although the ratio of the top mass to the vacuum expectation value, $m_t/v$ is very close to unity. This makes a closer study of its coupling to the Higgs boson a high priority in top physics, and in particular the confirmation of the predicted identity of physical top mass and its Yukawa coupling $Y_t$ will provide an important test of the Standard Model. This, ultimately provided by precision measurements of the $ttH$ production rate and distributions, is a very challenging centrepiece of the physics programme at the Run II of the LHC. At the same time, it will also be important to confirm that the element $V_{tb}$ of the Cabibbo–Kobayashi–Maskawa (CKM) matrix indeed is close to one, as predicted from the unitarity constraint of the very same matrix. This can be achieved by precision studies of single top production at the LHC. In both cases, deviations from these relations, $m_t = Y_t$ and $V_{tb} \approx 1$, would directly signal new physics. Lastly, due to its large mass, production of top quarks in various processes probably is the most notorious background in nearly all searches for new physics and thereby a precise understanding of processes leading to top quarks in the final state will be hugely important to find or constrain new physics in direct searches.

In this contribution I will report on the fairly amazing progress in theory before the conference, discuss some of the available tools, and will finally reflect on the progress on the experimental side.

2 Theory Progress: High-Precision

Probably the most notable progress on the theory side is the first complete calculation of the inclusive top–pair cross section to next-to–next-to leading order (NNLO) accuracy in the strong coupling, reported last year in [1]. Their result also forms the basis for a number of further calculations, which may further
supplement it with the resummation of soft logarithms up to next-to–next-to leading logarithms or Coulomb effects, for example [2]. The results obtained from such calculations and some others based on various approximations [3–5] are compared with each other and data in Fig. 1. As a consequence of this success it is now possible to extract the top mass to 3% precision from the production cross section. This provides a more than welcome, simulation independent cross check of the standard determination of $m_t$ through top decays or other methods based on kinematics.

In a similar way, the single-top cross section by now also is known at NNLO accuracy. Focusing on $t$-channel production, which is the dominant channel at the LHC, contributing more than 80% of the overall single-top cross section, it is worth noting that the NLO $K$-factor is relatively small, roughly of the order of the effect of scale variations on the LO result. For a 8 TeV LHC, this correction ranges from 3% to 18% in dependence on a cut on the top transverse momentum between 0 GeV and 60 GeV. One may therefore wonder whether this numerical smallness is an accident. This has been investigated in [7], where only factorisable contributions have been taken into account, essentially ignoring cross-talk between the two coloured lines mediated by real or virtual gluon exchanges. In this approximation the NNLO contribute of the order of about 1-2% with respect to the NLO result, ranging from a destructive effect at $p_T > p_{T,\text{cut}} = 0$ GeV to a constructive effect at $p_{T,\text{cut}} = 60$ GeV, see also Fig. 2. This result may have been anticipated, as similar processes driven by the exchange of colourless particles in the $t$–channel typically usually exhibit only relatively small higher-order QCD corrections – however, to precisely quantify such effects is of great value for any precision measurement in this channel. One of the consequences of this result is that by now the CKM element $V_{tb}$ can be deduced with an accuracy in the order of about 10%.

In the near future most of these calculations will probably become publicly available as parton-level event generators, allowing the production of differential distributions, a further great step forward. Matching with a subsequent parton shower and therefore enabling event simulation at NNLO precision is the logical next step, which will most likely happen during Run-II.

### 3 Progress with Tools

Turning from the highest precision calculations in top-physics to actual state-of-the-art tools ready to be used, it is clear that by now the precision that can be expected in practically all channels is NLO in the strong coupling matched or merged with the parton shower. And while the first such NLO–matched simulation
for $t\bar{t}$ production became available about a decade ago in MC@NLO \cite{9,10}, by now similar simulations are available for practically all processes with up to four particles in the final state, embedding fully automated matrix elements at NLO accuracy into parton shower simulations. At the forefront of this development are the MADGRAPH5@MC@NLO \cite{11} or POWHEG@BOX \cite{12,14} programs, interfaced to the PYTHIA \cite{15,16} or HERWIG \cite{17,18} event generators, or more integrated solutions such as OPENLOOPS \cite{19}+SHERPA \cite{20} or GO SAM \cite{21}+SHERPA.

With these tools it is possible, for instance, to simulate at NLO accuracy processes such as top–associated Higgs boson production in $t\bar{t}H$ final states, one of the big challenges for Run-II of the LHC. This measurement is necessary to precisely pin down the top–Yukawa coupling. However, after applying the usual cuts the backgrounds look very similar to the signal, and therefore precision simulations will become an indispensable ingredient to every such measurement. And while backgrounds such as $t\bar{t}X_S$ production, where $X_S$ denotes any singlet such as $Z$, $ZZ$, $W$, etc. in principle is not problematic with the current NLO–matching tools, the production of additional coloured particles in association with the tops is not so straightforward to handle. This is true for the added intricacies of QCD radiation, for example the possible fragmentation of a gluon into a $b\bar{b}$ pair, which of course would impact on the number of $b$-tagged jets. One way out is the systematic merging of multijet matrix elements with increasing jet multiplicity into one inclusive sample, a procedure that has been pioneered in \cite{22,25} about a decade ago for such towers of LO processes. Recently, the same logic has also been extended to multijet merging of NLO matrix elements in various schemes \cite{26–30}. Examples for results obtained with this procedure, for the case of $t\bar{t}$+jets production, taken from \cite{31}, are displayed in Figs. 3 and 4. While inclusive observables such as the ones displayed in the former do not show any improvement of the NLO–merged sample over a regular NLO–matched one, the more exclusive observables exhibited in the latter do. In the next months such simulation tools will need to be further scrutinised and compared. Systematic uncertainties such as the one related to the choice of the merging scale or the renormalisation and factorisation scale must be further quantified. In addition, it is time to define meaningful ways to systematically evaluate the uncertainties stemming from the parton shower and the non–perturbative parts of the simulation.

Finally, concerning tools it is interesting to note that with Run-II the boosted regime of top production will become increasingly important: ultimately the LHC will become a factory of highly boosted objects, see for example Tab. 1 and transverse momenta at the TeV scale will be copiously produced and frequently studied. There is a large and apparently ever increasing number of tools and procedures to extract information out of these topologies, but it is probably important now to understand their similarities and differences in more.

Figure 2: Cross section for $t$-channel single-top production at the 8 TeV LHC, obtained with the MSTW2008 PDF \cite{6}, and for different values of the minimal transverse momentum of the top quark, $p_{T,\text{cut}}$. Figure taken from a talk by F. Caola at “top-quark physics day” at MPI Munich 2014.
Figure 3: Differential distributions in $H_T$ (left) and the transverse momentum of the top quark (right), obtained with an OPENLOOPS +SHERPA simulation [31], comparing LO (blue) and NLO–merged (orange) samples and their errors with the S-MC©NLO simulation in SHERPA.

Figure 4: Differential distributions in jet multiplicities with various jet transverse momentum thresholds (left) and the transverse momentum of the three leading jets, obtained with an OPENLOOPS +SHERPA simulation [31], comparing LO (blue) and NLO–merged (orange) samples and their errors with the S-MC©NLO simulation in SHERPA.
detail, to fully appreciate their relative virtues, and to work out their respective systematic uncertainties.

| $N_{tt}$ in three regimes | Tevatron Run-II | LHC 2012 | LHC design |
|---------------------------|----------------|----------|------------|
| inclusive                 | 57k            | 2.6M     | 155M       |
| $M_{tt} > 1$ TeV          | 25             | 30k      | 3M         |
| $M_{tt} > 2$ TeV          | 0              | 300      | 47k        |

Table 1: Number of expected $tt$ events in three different regimes at three different collider setups.

4 Experimental Progress

Naturally, it is very hard and possibly not fully adequate to also comment on the progress on the experimental side – I will try to formulate a few thoughts and concerns nevertheless.

After its discovery there has been a large number of ground-breaking measurements of top quark properties, some of which have large impact on our understanding of the inner dynamics and consistency of the Standard Model. The most important example obviously is the precise determination of the top mass, which by now has errors at the GeV scale only. The only standing concern in most of the measurements to date is that they are quite often heavily based on MC event generators and, for example, templates obtained from them. This of course immediately poses the question in how far the measured value is a very MC specific mass, dependent on details of how parton showering etc. is being implemented. Fortunately, both the theory and the experimental community have picked up on this issue, and consequently there is a lot of progress on both sides, by fixing the MC scheme the mass is defined in – very close to the on-shell scheme – and by moving to more and better observables, such as the total cross section or similar, which allow a more MC-independent determination of the top mass. As there have been a number of talks on this subject during the conference, for example the ones by Hoang [32] and Adomeit [33], I will not further elaborate here.

Turning to inclusive pair-production cross sections, the sheer amount of results collected by the Tevatron and LHC experiments in the past years is nothing but staggering. It is fairly satisfying to see the by far and large very good consistency of the measured cross sections among each other and also their typically excellent agreement with theory, see for example the talks presented by Shabalina and Brochero Cifuentes. It is fair to say that this certainly is a job well done and continuing to be well done!

Turning to more differential distributions, the picture is not quite as convincing. Up to this conference, and with a few notable exceptions such as for instance the measurement of rapidity gaps [34], or of jet multiplicities [35] in top-pair production, quite a lot of the results are to be taken with a grain of salt: Quite often they are either over-corrected, for instance by extrapolating to full acceptance detectors or by correcting to top-quark partons, or under-corrected by not accounting for detector effects.

Take as an example the inclusive production of top-pairs. It appears as if there is a simple pattern in how the currently used tools perform with respect to data: While by far and large they appear to agree very well with the invariant mass spectrum of the pair, $m_{tt}$, the transverse momentum distribution of the individual tops, $p_{t}^{(t)}$, seems to be a bit tricky. It would be great if the theory community could check these effects and try to find possible issues related to the simulation. This, however, is not quite possible, as quite often the data are extrapolated to a full acceptance (“4$\pi$”) detector and to top partons. By correcting in this way, the data already are modified by a simulation tool and it is very hard or probably even impossible to exactly figure out how this modified the results. It is therefore crucial that the experiments report their data, corrected for detector effects, on the particle level, i.e. on the basis of physical objects, within the actual acceptance of the detector. Of course, a further interpretation of the results, by comparing on the parton level with higher-order calculations is more than welcome then.

This is even more important for channels which are not very clearly defined. As an example for this consider single-top production. Common lore has it that this process proceeds along three channels: $t$-channel, $s$-channel, and $Wt$ production, see Fig. [5]. While this works nicely at leading order, this discrimination breaks down at higher orders; adding the decay of the top quark, at NLO accuracy $Wt$–associated production will have contributions e.g. from top pair production, as shown in Fig. [6]. This shows that such a differentiation
makes sense at LO level only, where $Wt$ production contributes about 20% of the total single-top cross section. To me, trying to “measure” $Wt$ production cross sections sounds a bit like a waste of time there; instead it seems more reasonable to define physical objects in the full $bbW^+W^-$ final states, for instance one could identify regions of double-, single- or non-resonant $bW$ production, and (rightly) interpret the resonances as top quarks. Reporting measurements based on fiducial cross sections would then ensure that different interpretations, like for instance top production in different channels, become feasible.

A simple lesson from this example is that in presenting the data – and especially those for differential cross sections – it must be guaranteed that they can be interpreted to all order of perturbation theory; this is the only way to ensure that the gruelling efforts in and the amazing successes of the higher-order calculations discussed in the first part of the talk are not in vain. Of course, this does not forbid that such data, based on physical object definitions and the fiducial volume of the detector are extrapolated to the parton level at full coverage to be directly compared to such calculations! This comparison certainly is an integral part of the interpretation of the data.

I am more than happy that during the conference a number of talks presented results where exactly the procedure outlined above – data based on physical objects in the fiducial volume – has been followed. One example for this is the pseudo-top method reported for instance in the talk by Katzy.

5 Concluding remarks

Instead of a summary I would like to take the opportunity to briefly discuss certain aspects of data preservation. This is based on the very real possibility that the LHC is the experiment of our lifetimes. This implies that, in a lab-based and controlled environment, we explore physics at the largest energies ever accessible to
Clearly, if this is the case we should do our utmost to make this experiment count. This means that we owe it to us and to future generations to make our results as reproducible as possible. But how can this be achieved? First of all, it is obvious that nobody but the current experimenters is better placed to understand the detector, which implies that any data not unfolded during the lifetime of an experiment will never be unfolded. In many cases this will result in the data effectively being unusable, essentially lost. Therefore: please, unfold your measurements to the particle level. Furthermore, my feeling is that it is probably simpler to present, understand and possibly migrate the detailed knowledge of the experimental environment of an analysis, the cuts employed etc., when it is based on code rather than text. Text nearly always tends to have a slightly approximate character, which is not the case with computer code. A tool like Rivet \[36\] comes to my mind here, but any other publicly available and documented software is as good. It just must be linked to the data, stored on a database such as HEPData. Similar reasoning also holds true for the Monte Carlo tools – in order to allow reproducibility it would be great if the exact version of the used code(s), the run card(s) or similar would be tagged and linked to the data. This, together with only using publicly available code would allow future generations to reproduce our results. In addition it would offer them a great way to learn from our errors and mistakes.

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\[2\] The slightly sad corollary is that going to Run II is the last energy upgrade we may experience.
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