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Top physics: An overview

A. Signer
IPPP, Department of Physics, University of Durham - Durham DH1 3LE, UK

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Summary. — This is a very brief overview of the current status of top-quark physics at hadron colliders, a selection of some mainly theoretical aspects without any claim of completeness.

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1. – Introduction

The special role of the top quark in testing the Standard Model and looking for physics beyond it has been well documented. In this brief note I will try to give a personal overview over the field without any claims whatsoever regarding completeness. Given the special motivation for top-quark physics, let me split the note into four parts: the *bread and butter* section that deals with standard topics such as cross section calculations, mass determinations and spin correlations; the *bread only* section that—from a top-physics point of view—deals with controlling the background; the *pure honey* section that deals with looking for BSM physics through the top sector and finally the *bread and butter and a hint of honey* section, dealing with the forward-backward asymmetry. In many ways this observable is a prototype for a large number of other investigations, where a particular observable is studied in great detail in the hope of finding a deviation from the Standard Model. This procedure is of course not restricted to top-quark physics. However, a combination of two factors make the top sector particularly promising for such an attempt. First, the top can be described by perturbative methods in a very reliable way and the danger of non-perturbative effects diluting deviations from the Standard Model are much smaller than in other areas. Second, in many extensions of the Standard Model the top sector plays a special role and, thus, it is natural to expect a deviation to show up first in the top sector. It is a lucky combination of these two facts that gives us this unique opportunity and we should fully exploit it.

2. – Bread and butter

The main processes to be considered are top-pair production as well as t-channel, s-channel and associated single-top production. These processes can be studied at various levels of detail regarding the final state. The simplest approach is to treat the top quark as a stable particle. Following this approach only observables that are completely inclusive in the decay products of the tops can be studied. Going beyond this approximation, the decay of the tops has to be included. This allows for the application of more realistic cuts on the decay products as well as the study of spin correlations. Finally one can go even further by including so-called non-factorizable corrections that link the production with the decay of the tops. The theory status can roughly (!) be summarised as follows: fully differential observables including the decay of the tops are known to NLO in the strong and electroweak coupling for top pair production [1] and all single-top processes [2], including non-factorizable corrections in α_s, whereas $t\bar{t}$ pair production for stable tops basically is known at NNLO. All processes have been combined with parton showers [3]. Furthermore, resummation of large logarithms as well as bound-state effects in $t\bar{t}$ production have been studied.

So what can we do with these tools in hand? The most important observable of "bread and butter" physics is certainly the top quark mass. It is needed for Standard Model consistency checks and as input for other measurements and calculations. It is by now well known that the standard measurement of the top mass through the invariant mass of the decay products has certain limitations. First, it is not clear how precisely to relate the measured value to a theoretically well-defined quantity such as the pole mass m_t. Second, small effects that are either not included or not fully understood such as non-factorizable corrections and the non-perturbative link between the decay products and the beam remnants might have an effect that is of the same order as the currently claimed error. Finally, there is a theoretical limitation of the order of $\Lambda_{\rm QCD}$ to the error on the determination of the pole mass within a perturbative treatment, due to renormalon ambiguities.

In order to avoid some of these issues, alternative top mass measurements can be considered. The dependence of the total cross section or any other suitable observable on the top mass can be used to determine the pole mass m_t or directly the $\overline{\rm MS}$-mass $\overline{m}_t$. The latter does not suffer from renormalon ambiguities. This should lead to a better perturbative behaviour of the total cross section expressed in terms of $\overline{m}_t$ compared to m_t and, therefore, to a more precise determination. In principle, such a determination could (and actually should) also be done for other short-distance masses that are closer to the pole mass (but still free of renormalon ambiguities).

With increasing statistics it should also be possible to measure the top-quark mass through single-top production. These measurement might not lead to the same precision as measurements through top-pair production but could provide important cross checks. In this context it should be mentioned that the best possible measurement of the top-quark mass can be obtained through a threshold scan at a linear collider. Such a measurement would be free of many of the problems mentioned above and would allow to determine a short-distance top mass with an error $\delta \leq 200\,\mathrm{MeV}$.

Finally let me mention a few other interesting topics related to bread-and-butter physics. Due to the fast decay of the top its spin information is transferred to the decay products. This leads to interesting spin correlations [4] that can be studied in both, top-pair production and single-top processes. Processes involving top quarks might also be useful in constraining parton distribution functions. In fact the cross section for top-pair production has been computed to an accuracy that is better than the spread caused by the full spectrum of commonly used parton distributions. Distinguishing between single-top and single–anti-top production might also yield useful information.

Apart from the mass, the width of the top and its Yukawa coupling y_t are very important quantities. A reasonably precise determination of y_t in particular would allow for a direct test of the Higgs mechanism. Unfortunately, measuring y_t through $t\,\bar{t}\,H$ production seems to be extremely difficult.

Let me finish this section by stressing the impressive progress that has been made in computing next-to-leading–order corrections to ever more complicated processes. For the processes $p\,p \to t\,\bar{t}\,X$ with $X \in \{H, Z, \gamma, \mathrm{jet}\}$ NLO corrections have been known for a while. Very recently, they also have been computed for $p\,p \to t\,\bar{t}\,j\,j$ and $p\,p \to W^+\,b\,W^-\,\bar{b}$. For an overview with references to the various calculations see, *e.g.*, ref. [5].

3. – Bread only

In order to be able to make detailed studies of top quarks it is important to disentangle top events from background processes. A recent development is to identify boosted hadronically decaying top quarks through so-called top tagging [6]. Apart from this direct identification of top events there has also been very impressive progress in the calculation of next-to-leading–order processes for background processes, in particular the production of a vector boson with up to four jets [7].

4. – Pure honey

As mentioned in the introduction, one of the main motivations for detailed studies of the top sector is the hope to find physics beyond the Standard Model. In order to make such tests quantitative we need a way to describe BSM physics.

One way to do this is to parameterise our ignorance of what is beyond the Standard Model. This can be done through an effective-theory approach and/or using generalised vertices with anomalous couplings. This approach is very similar to what is done for triple gauge-boson couplings. The idea is to devise an observable that is very sensitive to a particular anomalous coupling and/or BSM operator and try to constrain (or even better: measure) its coefficient. The advantage of this approach is that we can write down all operators up to a certain dimension (usually all dimension 6 operators are considered) and thereby systematically cover all possibilities. One disadvantage is that these operators or anomalous couplings usually lead to violation of unitarity for large energies. At a hadron collider, the partonic energy covers a fairly large range. In order to suppress an artificially large effect from the high-energy tail of the partonic centre-of-mass energy it is often necessary to introduce *ad hoc* form factors. In other words, this approach is actually only valid as long as the deviation from the Standard Model is not too large and the BSM effect can be treated as a perturbation.

Another option is to consider explicit BSM models. A concrete model contains more information that an effective-theory approach can give and can be extended to the high-energy range. If such a model consist of introducing new heavy particles there is of course a direct connection to the effective-theory approach in that the BSM operators and their coefficients can be computed by integrating out the heavy fields. However, we can also think of possibilities for new physics that do not necessarily involve such new heavy fields and which, therefore, can not be covered by the effective-theory approach. An obvious disadvantage of considering explicit models is that there is simply too much freedom and a systematic approach is virtually impossible in the absence of clear guidance from experimental data.

5. – Bread and butter and a hint of honey

It is certainly fair to say that the new measurements of A_{FB}, the forward-backward asymmetry, by CDF [8] and D0 [9] have caused the biggest excitement in top-quark physics since its discovery. While it is clear that both measurements lie above the predicted Standard Model value, it is far less clear, whether the effect depends on the invariant mass of the top pair. There are also some issues regarding the reliability of the theoretical prediction. Since the effect vanishes at tree-level in QCD, the currently available one-loop calculation is actually a leading-order calculation for A_{FB} [10]. A full NLO calculation for A_{FB} is not yet available but there are several indications that the corrections are not expected to be unusually large and, therefore, can not explain the tension between the data and the theoretical prediction. One of the main arguments along these lines is due to partial results from resummation of logarithms. On the other hand, electroweak corrections turn out to be surprisingly large and increase the theoretical value of A_{FB}, albeit by far not enough to be in agreement with the measurement.

This tension has led to a flurry of activity in studying extensions of the Standard Model that result in an increased A_{FB} [11]. The difficulty in constructing such models is to ensure that other quantities, such as the cross section for top-pair production and notably same-sign top production is not affected too much. Typically, these models are ruled out before the ink on the paper is dry. In particular same sign top production has not been observed at the LHC and this alone has killed a large number of proposed models. There is some debate on whether or not there is room for BSM contributions in the total cross section for $t\,\bar{t}$ production, but in any case this presents another strong constraint on BSM scenarios. Rather than getting completely carried away with BSM scenarios it is essential that "more boring" explanations are also investigated.

Unfortunately, a cross-check of the Tevatron measurements at the LHC is not straightforward. There is a quantity very similar to A_{FB}, the charge asymmetry, which is caused by precisely the same effect and can be measured at a $p\,p$ collider. However, because the effect is limited to the $q\,\bar{q}$ initial state this is difficult at the LHC, where the $g\,g$ initial state dominates. Currently, the measurements of the charge asymmetry are consistent with zero (and with the Standard Model value). With additional cuts to enhance the $q\,\bar{q}$ contribution it should be possible to make more refined tests of the charge asymmetry in the future. Even so, it is perfectly possible that in top physics we will end up with a situation that is remarkably similar to LEP electroweak global fits: a very consistent picture with one $\sim 3\sigma$ outlier which, as coincidence would have it, is the forward-backward asymmetry in both cases.

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