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Top physics at the ILC and hadron colliders

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Summary. — I discuss a selection of recent developments in top quark physics relevant for either ILC or Tevatron/LHC, or both.

PACS `14.65.Ha` – Top quarks.
PACS `13.85.-t` – Hadron-induced high- and super-high-energy interactions (energy $> 10\,\mathrm{GeV}$).
PACS `13.66.-a` – Lepton-lepton interactions.
PACS `12.38.-t` – Quantum chromodynamics.

1. – Top is special

Of the particles seen so far in collider experiments, the top quark is clearly the most glamorous, due to its rarity and special role in many theories of physics beyond the Standard Model. Because it has many quantum numbers and thus couples to almost all other particles, through various (chiral, vector, scalar) structures, precise scrutiny of its behavior is very interesting. It is also feasible because the large top mass implies, firstly, that it couples strongly to whatever breaks the electroweak symmetry, and secondly, the resulting large width minimizes obscuring hadronization effects and allows preservation of spin information. Top is also a troublemaker for the Standard Model, contributing significantly to the quadratic divergences of the Higgs self energy, but is at the same time a life raft for beyond the Standard Model (BSM) theories such as the MSSM (raising the upper limit on the light Higgs mass in that theory). While Tevatron has made the first precious thousands top quarks, the LHC will be a genuine top quark mine, producing millions of events per year. The ILC would have about 60 K top quark pairs after $100\,\mathrm{fb}^{-1}$, which would allow finely detailed study of its behavior. Here I review some recent developments for top physics at these colliders, but will of necessity be short on length and details, and well as citations. I refer to recent reviews [1-5] for much more top physics of interest.

2. – Top couplings

While the LHC will enable us to determine some Standard Model top couplings, for a precise determination the ILC will be particularly powerful. Thus [6], the $\bar{t}t(\gamma/Z)$ couplings will not be easily measured from the LHC, but at the ILC their value can be inferred from $\bar{t}t$ production to lepton plus jets final states, where angular distributions, possibly enhanced by polarizing the beam or raising the energy, can help disentangle the various structures. Accuracies at the percent level seem achieveable [7, 8]. The left-handed charged current couplings can be found from the LHC and Tevatron data through single-top production, with an eventual uncertainty on V_{tb} of about 5%. At the ILC this coupling can be studied when running below the $\bar{t}t$ threshold, selecting the $WWbb$ final state, as virtual top quarks are the predominant mediator. Accuracies are thought to better the LHC results by a factor two. Particularly interesting is of course measuring the top quark Yukawa coupling, predicted to be very close to 1 in the Standard Model. At the LHC the best channel is associated $\bar{t}tH$ production, but the backgrounds pose a challenge. At the ILC sensitivity to the Yukawa coupling exists both in the $\bar{t}t$ cross-section through Higgs vertex corrections, and radiative production ($\bar{t}tH$). A 10% measurement is expected [9, 10]. Optimal may be a combination of LHC and ILC measurements [11, 10].

3. – Top mass

The top quark property that is most readily employed in top physics is its mass. By measuring it to less than 1% accuracy (173.1±1.3 GeV) the Tevatron experiments have set the standard to a level that will be hard to pass by the LHC. Together with an accurately measured W boson mass it severely constrains the mass range of a possible Higgs boson both in the Standard Model and in the MSSM. Therefore its precise measurement is of considerable importance, and thus also its careful definition. A natural definition is based on the location of the pole of the full top quark propagator: the pole mass. However, because the top quark, being colored, can never propagate out to infinite times—a requirement for the definition of a particle mass in scattering—such a pole only exists in perturbation theory, and its location is intrinsically ambiguous by $\mathcal{O}(\Lambda_{\rm QCD})$ [12-14]. A theoretically more precise definition is the $\overline{\rm MS}$ mass $\bar{m}(\mu)$ whose relation to the pole mass is known to sufficiently high order. For μ one often takes the implicit value found when intersecting the $\bar{m}(\mu)$ curve with the $\bar{m}(\mu) = \mu$ axis, yielding $\bar{m}(\bar{m})$. For the top quark, this value is about 10 GeV smaller than the pole mass, and thus the question often arises what mass the Tevatron and LHC experiments measure.

It is useful to remark that for constraining the Standard Model through the $m_{\rm top}$, m_H, m_W relation an accuracy of about 1%, already reached, is sufficient. In case extensions of the Standard Model reveal themselves, a precision of about 100 MeV would however be very useful in testing the extension. For such accuracy short-distance mass definitions are required, which can be tailored to various observables at the ILC.

Particularly relevant to the $\bar{t}t$ inclusive cross-section is the potential-subtracted mass [15]. Near threshold one can use a Schrödinger equation to describe the top quark pair, with a potential term. This mass definition exploits the fact that the IR sensitive parts of the pole mass and of the potential cancel each other in this equation, leading to a much more stable description when increasing the accuracy from LL to NNLL [16]. Recently, the computation of necessary NNNLO effects was completed [17, 18]. Beyond this, experimental effects such as beamstrahlung would have to be well understood for a precise measurement.

Other recent progress is the definition of the top jet mass [19] for production well-above threshold at a linear collider. This definition relies on gathering all top decay products into a hemisphere, and provides a precise description using factorization in the context of effective field theories.

At the LHC the top quark mass is reconstructed by collecting jets and leptons. Soft particles arising from both within and outside these jets or the underlying event may enter them, and thus affect the reconstructed mass. Moreover, various experimental methods used (*e.g.*, track quality cuts), and Monte-Carlo–based corrections, do not have a clean perturbation theory description. Therefore a precise measurement in such an environment seems challenging, though interesting ideas exist [20, 21].

4. – Top cross-section

The top quark inclusive cross-section at hadron colliders has received continued theoretical attention over many years, with steady progress toward its more accurate determination.

A full NNLO result is not yet here, although many ingredients now exist, in particular for the quark annihilation channel [22]. Approximate results in the threshold limit do exist to NNLO [23, 24] based on methods from threshold resummation. The large threshold logarithms L that result from gluons emitted softly and/or collinearly may be resummed to all orders and brought into the form

$$\mathrm{d}\sigma = \exp[Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots] \times C(\alpha_s). \tag{1}$$

Recent progress has concerned the determination of g_3 and C. For the former, an important ingredient is the two-loop soft-anomalous dimension with mass effects [25, 24], for the latter the one-loop matching coefficients per color structure [26, 27], as well as Coulomb effects.

NLO plus NLL resummed results have been given in [28]. Taking threshold resummation into account lessens uncertainties due to scale variations. PDF uncertainties have also been included. At the LHC the scale uncertainties are significantly larger than the PDF uncertainties, and it is important to vary the renormalization μ_R and factorization scale μ_F independently. Another important estimate [29] at two-loop accuracy is based on the double differential cross-section, and includes uncertainties due to PDF, scale, and kinematics choice. The NLO cross-section has also been presented in [30] with CTEQ6.6 uncertainties, with an eye for employment as a standard candle for gluon density extractions.

5. – Top distributions

While the inclusive cross-section has received much theoretical and experimental attention, the interest in distributions in certain variables is increasing, given the increased Tevatron data set, and the LHC start. An important distribution for both the Tevatron and the LHC is in the invariant mass $M_{t\bar{t}}$. The Standard Model shape has relatively small uncertainty but is sensitive to the top mass, and may thus assist in determining it. Shape deviations from the QCD predictions in this distribution (peaks, peak-dip structures) are telltales of new physics, such as resonances with various spin, parity and color quantum numbers. A study employing the flexibility of MadGraph in a bottom-up approach was performed in ref. [31], in which only the most generic aspects of new models are used.

An interesting suggestion has been made [27,32] that the invariant mass spectrum very near threshold may reveal an enhancement from bound state effects in the color-singlet channel, in analogy to e^+e^- production, leading possibly to a better mass determination.

6. – Associated top production

Many interesting top producing reactions involve particles in association. These reactions allow new tests of the top SM interactions, such as its coupling to the photon, Z or Higgs boson.

Among the most interesting is $pp \to t\bar{t}H + X$, which, if a good sample can be isolated, would allow a direct determination of the top Yukawa coupling (the SM value is very close to 1). It may take some time to gather sufficient data to allow the Higgs to be cleanly identified and reconstructed (via the $H \to \gamma\gamma$ decay mode), and backgrounds may be large. A NLO calculation has been carried out [33, 34] using a variety of methods, the $2 \to 3$ kinematics with different masses of the final state particles making the calculations challenging.

Study of associated production with an electroweak boson could reveal anomalous couplings with the top. Robust theoretical tools exist [35-37] which will allow fairly accurate determinations of these couplings using LHC data.

Production of $t\bar{t}$ with a jet is another interesting reaction to test the top couplings, and assess the usefulness of the charge asymmetry at the LHC (which is low). A NLO calculation was completed recently [38]. Even more impressive is the recent work on $t\bar{t}$ with two b quarks at NLO [39, 40].

7. – Top and Monte Carlo

Perhaps the most widely useful progress in describing top quark processes at hadron colliders is in the realm of Monte Carlo. Efforts in recent years have led to descriptions beyond $2 \to 2$ processes in LO QCD (with subsequent decay and parton showering) in general purpose Monte Carlo programs. These fall short when extra hard jets are present besides the top quarks, nor are they intrinsically normalized as their only scale dependence in the coupling, with no compensating terms in the matrix element. Much ingenuity and labor has been brought to bear to remedy these deficiences.

Higher-multiplicity matrix element Monte Carlo's now reach $t\bar{t}$ plus up to six jets, and use a variety of methods. ALPGEN ($t\bar{t}+ \leq 6$ jets) does not use Feynman diagrams but recursion relations to compute the matrix element. COMPHEP ($t\bar{t}+ \leq 1$ jets) uses squared amplitudes. MADGRAPH/MADEVENT ($t\bar{t}+ \leq 3$ jets) uses complex helicity amplitudes. However, while matrix element Monte Carlo's improve the description of radiative hard emission events, they should if possible not sacrifice the power of the parton showers to account for collinear and soft radiation. Matching procedures have been defined to this end [41, 42].

Other important progress has been in made in matching NLO to parton shower-based Monte Carlo (MC@NLO [43] and POWHEG [44]). Matching is essentially an issue of avoiding double counting in the one-emission contribution, which can either come from NLO or from the PS, as well as in the virtual parts. A small percentage of the events that MC@NLO generates have a negative weight, reflecting virtual contributions and subtractions present in NLO and matching. POWHEG insists on having positive weights, and exponentiates the complete first-order real matrix element to that end. Both these frameworks are growing in the list of processes, and realism (*e.g.*, spin correlations [45]).

Agreement is generally very good, also with PS-matched matrix-element generators [46], although interesting differences exist. Such differences reflect genuine ambiguities.

8. – Single top

Single tops are produced by the weak interaction, in processes that are customarily categorized from Born kinematics as s-, t- and Wt channel.

A particularly interesting aspect of single-top production is the prospect of directly measuring V_{tb} and testing the chiral structure of the associated vertex: top produced singly in this way is highly polarized, and offers a chance to study its spin. Furthermore, the dominant t channel at the LHC will, when confronting measurements with a 5-flavor NLO calculation, allow extraction of the b-quark density. This will be useful in predicting other production processes at the LHC. The single top production characteristics are sensitive to new physics, depending on the channel. Thus, the s-channel will be sensitive to, *e.g.*, W' resonances, the t-channel to FCNC's. Experimentally, this process turns out to be very difficult to extract from backgrounds, but a 5σ discovery has been made by the D0 [47] and CDF [48] Collaborations, with a 95% CL lower limit on V_{tb} of 0.77. The measured cross-sections agree within errors with the NLO calculations [49-53]. The inclusive cross-sections at the Tevatron are rather small, 0.9 (s) and 2 (t) pb, with the Wt channel negligible. At the LHC the numbers are, approximately, 10, 246 and 60 pb, respectively. At the LHC the dominant process is therefore t-channel, which, besides being interesting in its own right, is a background to putative new physics processes, such as Higgs production in association with a W boson.

Part of the attractiveness of the top quark as a study object is its power to self-analyze its spin, through its purely left-handed SM weak decay. This is both a useful aid in signal-background separations, and itself a property worthy of detailed scrutiny, as certain new physics models could introduce right-handed parts in top production and decay (even though certain observables are insensitive to new physics in the decay [54]). In single-top quark production, which occurs via the charged weak interaction, the top is produced left-handed, so a correlation should be a clear feature of the production process and a discriminant from the background. A robust correlation of the lepton flight direction with the recoiling light quark jet can be shown even in the framework of event generation with NLO corrections [45].

In top quark pair production a correlation of an individual quark with a fixed direction is almost absent, however there is a clear correlation between the top and anti-top spins. The size of the correlation depends on the choice of reference axes [55-57].

8˙1. *Wt production.* – An interesting issue arises in the Wt mode of single top production. Some diagrams occurring at NLO contain an intermediate anti-top that can become resonant. These diagrams can be interpreted as LO $t\bar{t}$ "doubly resonant" production, with subsequent $\bar{t}$ decay.

It thus becomes an issue to what extent the Wt and $t\bar{t}$ can be properly defined as individual processes. In ref. [58] the issue of interference was addressed extensively in the context of event generation, in particular the MC@NLO framework. Two different procedures for subtracting the doubly-resonant contributions and recovering a perturbatively well-behaved Wt cross-section were defined. In "Diagram Removal (DR)" the graphs were eliminated from the calculation, while in "Diagram Subtraction (DS)" the doubly resonant contribution was removed via a counterterm. The difference between these procedures is in essence a measure of the interference term. It was shown that, with suitable cuts, the interference terms are small. A particularly suitable cut is putting a maximum on the p_T of the second hardest b-flavored hadron, a generalization of a proposal made in ref. [53]. Thus defined, the Wt and $t\bar{t}$ cross-sections can indeed be separatedly considered to NLO. Their separation at LHC does remain difficult however, but is possible and worthwhile [59].

9. – Conclusions

Top's attractiveness as a study object remains very high, with new observables still being enlisted. The characteristics of production and decay, in association with other particles, are very revealing. Top does not hide its spin, and awareness of the importance of studying angular distributions of its decays has grown. Also at a linear collider it will one of the most important objects of study, particularly near threshold. Even with the LHC top-quark factory starting up, we are confident that the top quark will remain special for years to come.

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