

Keynote: Some remarks on top

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Summary. — A few key issues of present and future explorations of the physics of top quarks at the Tevatron and LHC are discussed.

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1. – Where do we stand?

It is no exaggeration to state that significant progress has been made in the exploration of top quarks since the *Top2008* Workshop at La Biodola/Elba. During the last two years, an impressive number of new results have been obtained by the CDF and DØ experiments at the Tevatron. Let me mention a few highlights. The measurements of $\sigma_{t\bar{t}}$ in the main channels have been improved. The experimental uncertainty now reaches $\sim 6.5\%$ [1]. The measurements of the top mass have become more precise than anticipated several years ago. The uncertainty of the CDF and DØ average as of 2009 is 0.75% [2, 3]—it is the most precisely known quark mass (and the value of m_t^{exp} “converges”). Single top-quark production at the Tevatron made it from evidence to being observed [4–7]. The experimental information about top-quark decays—or to put it differently, the information about those modes into which the top quarks produced so far have not decayed—has been refined: $t \rightarrow bW$ is still the only decay mode observed. From the measurements of the single top cross section and of the branching ratios $B(t \rightarrow bW (h_W = 0, \mp))$ one can conclude that the strength and structure of the tWb vertex is known now to a precision of about 10–20% [8, 9]. Quite recently, the experimental knowledge about the total width Γ_t of the top quark has been improved [8, 9]. As far as the analysis of the $t\bar{t}$ events at the Tevatron is concerned, a number of distributions have been measured, including the top-quark charge asymmetry [10–12, 8] and $t\bar{t}$ spin correlations [13–16]. The $t\bar{t}$ invariant-mass spectrum has been explored up to about $M_{t\bar{t}} \sim 1$ TeV in the (so far negative) search for heavy, electrically neutral resonances that (strongly) couple to top quarks [17]. Last but not least, it should be appreciated that quite a number of methods that were developed to analyze $t\bar{t}$ and single top events [18] (will) serve as templates in the search for other heavy (colored) particles.

Also theorists have not been idle in the past two years. There has been an ever increasing number of papers on top-quark phenomenology, both within the standard model (SM) and beyond. Already at the *Top2008* Workshop, theory updates (NLO QCD plus NLL threshold resummations) of the $t\bar{t}$ cross sections for the Tevatron and the LHC were presented [19-21]. More recently, threshold resummations were extended to NNLL order for the partonic cross sections [22, 23] and for the $t\bar{t}$ invariant-mass distribution [24]. The $t\bar{t}$ cross section was computed in terms of the running $\overline{\text{MS}}$ top mass and its value was extracted from the measured Tevatron cross section [25]. These and related issues, including building blocks obtained so far for the computation of $\sigma_{t\bar{t}}$ to order α_s^4 , will be discussed at this workshop by [26]. The formation of a smeared $t\bar{t}$ resonance peak in $gg \rightarrow t\bar{t}$ at threshold and the resulting distortion of the $M_{t\bar{t}}$ distribution at $M_{t\bar{t}} \approx 2m_t$ was analyzed for top-quark pair production at the LHC [27, 28]. It is an interesting effect; yet it seems not possible with present state-of-the-art methods to experimentally resolve it. A number of refined SM predictions were made for distributions that can be measured in $t\bar{t}$ events, including the top-quark charge asymmetry in threshold resummed (NLL [29] and NNLL [24]) QCD perturbation theory, charge asymmetries in dileptonic final states [30], and final-state angular correlations induced by $t\bar{t}$ spin correlations at next-to-leading order in the strong and weak gauge couplings [30]. Recently, an interesting suggestion was made how spin correlations for low-mass dileptonic $t\bar{t}$ events can be measured at the LHC, once enough events will have been collected [31, 32]. Concerning the general-purpose NLO QCD Monte-Carlo generators MC@NLO, MCFM, and POWHEG, a number of new features were added to these programs in recent years concerning reactions that involve top quarks. This will be discussed by [33, 34]. Results based on computer programs specific to hadronic top-quark pair production *and* decay at NLO QCD including spin correlations were reported [35, 30]. (The investigation in [30] includes also weak-interaction corrections.) The W -boson helicity fractions in $t \rightarrow bW$ decay were computed to NNLO QCD [36]. Concerning hadronic single top production the dominant t -channel production cross section and distributions were determined to NLO QCD in the 4-flavor scheme and compared with corresponding results in the 5-flavor scheme [37, 38]. This is important for assessing the uncertainties of the SM predictions. Phenomenological studies include the development of algorithms to analyze high- p_T top-quark events (“boosted tops”) [39-41] and studies for determining possible anomalous couplings in the tWb vertex from data on single top and $t\bar{t}$ production [42].

There have been many phenomenological investigations on effects beyond the standard model (BSM) in top-quark production and decay. For instance, the measurements of the top-quark charge asymmetry at the Tevatron by $D\bar{0}$ and especially by CDF, which do not quite match the QCD predictions, have induced a plethora of papers on possible new physics contributions to this observable. This will be discussed by [43]. An issue that has recently been revived is the possible existence of a fourth sequential heavy quark generation [44], or of more exotic, *e.g.*, vectorlike quarks. The existence of such quarks would have an impact on top-quark physics, too, see below. A central theme is and will be the use of top quarks as a probe of the hitherto unknown mechanism of electroweak gauge symmetry breaking. In a more general context many studies were made on heavy BSM resonances that strongly couple to top quarks. A few comments on this topic will be made below. Furthermore, the issue of how dileptonic and semileptonic $t\bar{t}$ events can be used to search for non-standard CP violation has been taken up again [45], in view of the forthcoming LHC data samples.

At this workshop we are mainly interested in the physics of “top as a signal”. But top-quark production and decay constitutes also an important background to a number of new

physics searches, including searches for (non-SM) Higgs boson(s) and SUSY particles. In order to understand and control this background, precise SM predictions for the respective top quark reactions are required. For the most important background reactions that involve $t\bar{t}$, predictions of the cross sections and of distributions are now available at NLO QCD, namely for $t\bar{t}$ +jet [46,47], $t\bar{t}+b\bar{b}$ [48-50], and $t\bar{t}$ +2 jets [51], see the talk by [52].

To sum up the present state of the art of top physics: The results of the CDF and DØ experiments imply that the top quark behaves pretty much standard. (The measurements of the charge/forward-backward asymmetry may point to an exception.) On the theory side, the main $t\bar{t}X$ and single top processes were computed to NLO in the SM gauge couplings, and many options for BSM effects have been studied.

As to present and future top-physics issues at the Tevatron and the LHC: Needless to say, the analysis of increased data samples will further sharpen the profile of this quark. Besides further determinations of its already very precisely known mass, direct measurements, respectively extractions, of its charge and spin will be possible. We expect to eventually obtain very detailed knowledge about the top-quark decay modes and perhaps also of its width—although no method is known to *directly* measure the top width Γ_t at a hadron collider with a precision of, say, $\lesssim 40\%$. (From what is presently known about the top quark, one can conclude that its width Γ_t cannot differ, if at all, more than about 40% from $\Gamma_t^{\text{SM}} \simeq 1.4 \text{ GeV}$.) There will be more detailed measurements and theoretical investigations of the cross sections and distributions for the main reaction channels. From a more general point of view we expect that top-quark physics will significantly contribute to gaining insights into two grand questions of particle physics, namely the flavor problem and the issue of electroweak gauge symmetry breaking. Flavor-physics aspects, already pursued at the Tevatron, include the search for new decay modes, *e.g.*, $t \rightarrow \tilde{t}\tilde{\chi}^0$, $t \rightarrow H^+b$, for FCNC decays $t \rightarrow c, u$ and for detectable FCNC in top production, $p\bar{p}, pp \rightarrow t\bar{c}X, t\bar{u}X$, and further searches for an additional sequential quark generation or exotic heavy quarks which may mix with the top quark. We expect that the LHC experiments will eventually be able to explore also top's capability to probe the mechanism of electroweak gauge-symmetry breaking (EWSB) by its coupling to the SM Higgs boson (if it exists) or possibly by its couplings to other spin-zero resonances from the EWSB sector.

These themes will be discussed in detail in the forthcoming talks at this workshop. Here I shall restrict myself to some comments on a few selected topics.

2. – Remarks on selected topics

2.1. Top mass. – CDF and DØ have precisely determined the top mass by exploiting the $t\bar{t}$ event kinematics, using Born matrix element, template, and ideogram methods. The CDF and DØ average as of 2009 is $m_t^{\text{exp}} = 173.1 \pm 1.3 \text{ GeV}$ [2,3]. This average has an error of 0.75%—but which mass is measured, *i.e.* how does m_t^{exp} relate to a (well-defined) quark mass parameter used in quantum field theory? We had this discussion already at the *Top2008* Workshop [53]. Obviously, m_t^{exp} is the mass parameter in the Monte Carlo programs with which the experiments form their templates, etc. that are fitted to their data. It is reasonable to identify m_t^{exp} with the pole or on-shell mass m_t^{on} —but this cannot be completely correct, because the top quark is a colored resonance, while the data involve color-singlet final states. The determination of m_t^{exp} is hard to map onto a higher-order QCD calculation.

A well-known uncertainty which is involved in the top-mass determinations from the peak of the top invariant mass distribution and from fits to perturbative (Born)

matrix elements of the partonic reactions $q\bar{q}, gg \rightarrow t\bar{t} \rightarrow f$ are color reconnection effects, *i.e.* the color exchange between the t, \bar{t} decay products (specifically b and \bar{b}) and the proton remnants. This is a non-perturbative QCD effect, which at present can be (and is) taken into account by heuristic Monte Carlo estimates, which yield an uncertainty $\delta m_t \sim 0.5 \text{ GeV}$. The *ab initio* calculation of color reconnection effects in hadronic $t\bar{t}$ production and decay remains a challenge.

A promising method, which does not suffer from this problem, is the exploitation of the fact that the QCD cross section $\sigma_{t\bar{t}}$ varies with m_t as $\Delta\sigma/\sigma \simeq -5\Delta m_t/m_t$, both for the Tevatron and the LHC. Thus, the strategy is to compute $\sigma_{t\bar{t}}$ in terms of a short-distance mass, *e.g.*, $m_t^{\overline{\text{MS}}}$. (Unlike m_t^{on} these mass parameters are well defined.) The comparison of $\sigma_{t\bar{t}}^{\text{exp}}$ and $\sigma_{t\bar{t}}^{\text{th}}$ then yields $m_t^{\overline{\text{MS}}}$ [25]. Comparing with the Tevatron cross section the authors of [25] extracted the running top-mass $\overline{m}_t(\mu = \overline{m}_t) = 160.0 \pm 3.3 \text{ GeV}$. Converting this mass parameter to the on-shell mass yields $m_t^{\text{on}} = 168.9 \pm 3.5 \text{ GeV}$, which compares well with the CDF and DØ average m_t^{exp} . It should be kept in mind, however, that SM production dynamics is assumed in the computation of $\sigma_{t\bar{t}}$. In addition, the extraction of $\sigma_{t\bar{t}}^{\text{exp}}$ requires to correct for acceptance cuts, which depend on the value of the top mass. If one aims at a more precise determination of \overline{m}_t in the future, one should eventually compute in higher-order QCD the $t\bar{t}$ cross sections for dileptonic and lepton + jets final states with acceptance cuts.

In the literature several other kinematical methods for determining m_t were proposed and may be applied, especially in the high luminosity era of the LHC. A well-known suggestion is the exploitation of $t\bar{t} \rightarrow b(\rightarrow J/\Psi \rightarrow \mu\mu) + l\nu_l + \text{jets}$, where m_t is correlated with the invariant mass $M_{J/\Psi\ell}$ [54]. A similar variable is the invariant mass distribution $M_{\ell^+j_b}$. (To leading order, $\max M_{\ell^+j_b}^2 = m_t^2 - m_W^2$.) The sensitivity of this distribution to m_t was recently studied in NLO QCD by [55]. The decay length of a b -hadron from top decay is also correlated with m_t [56]. Moreover, as pointed out in [57], the average of the $t\bar{t}$ invariant mass, $\langle M_{t\bar{t}} \rangle$, and higher moments are sensitive to the mass of the top quark. These methods have different experimental and theoretical uncertainties (*e.g.*, color reconnection, hadronization), which remain to be studied in detail [58].

2.2. Strength and structure of tWb vertex, new decay modes. – Here the issue is to test the CKM universality of the charged weak quark current, *i.e.* the $V-A$ law, in the decay $t \rightarrow bW$. In the 3-generation SM, the respective branching fraction is $B(t \rightarrow bW) \simeq 99.9\%$. The DØ experiment has measured $B(t \rightarrow bW) = 0.97_{-0.08}^{+0.09}$ [9]. The Lorentz structure of the tWb vertex can be determined from the W -boson helicity fractions $f_{0,\mp}$. In the SM they are precisely known [59, 36]: $f_0(h_W = 0) \simeq 70\%$, $f_-(h_W = -1) \simeq 30\%$, $f_+(h_W = +1) \simeq 0.1\%$ ($f_0 + f_- + f_+ = 1$); the numbers depend somewhat on the value of m_t . (As an aside, it is worth pointing out that top-quark decay is the most copious source of longitudinally polarized W bosons at the Tevatron and at the LHC.) These fractions are experimentally determined by measuring the $\cos\theta_\ell^*$, $M_{\ell b}^2$, p_T^ℓ distributions in semileptonic top-quark decay. The CDF and DØ Collaborations have performed 1- and 2-parameter fits to these distributions and obtained values for $f_{0,\mp}$ with errors of order $\delta f_{0,\mp} \sim 10\%$. For details, see [8, 9].

Lorentz covariance dictates that the on-shell $t \rightarrow Wb$ amplitude depends on four form factors, two chirality-conserving (f_L, f_R) and two chirality-flipping (g_L, g_R) ones, which may in general be complex. In the SM with 3 quark generations we have, to Born approximation, $f_L = V_{tb}$ (modulo $g_W/\sqrt{2}$), *i.e.* $|f_L| = 1$, $f_R, g_L, g_R = 0$. The Tevatron experiments have obtained bounds on these form factors from the measured

W -boson helicity fractions [8, 9]. There are strong indirect constraints on f_R and g_L from decays $B \rightarrow X_s \gamma$: $|f_R|, |g_L| \lesssim \text{few} \times 10^{-3}$, but these bounds are not water-proof. Simulation studies [60, 61] for the LHC (14 TeV) with 10 fb^{-1} anticipate sensitivities $|\delta f_R| \gtrsim 0.06$, $|\delta g_L| \gtrsim 0.05$, $|\delta g_R| \gtrsim 0.03$. The strength of the dominant left-chiral form factor f_L can be inferred from the measured single top cross section at the Tevatron. This yields $f_L = 1.07 \pm 0.12$ (DØ [4]) and $f_L = 0.91 \pm 0.11 \pm 0.07$ (CDF [5]). At the LHC (14 TeV) it is expected to reach a sensitivity of $|\delta f_L| \sim 0.05$. At this point it should be emphasized that for a joint analysis of $t\bar{t}$ and single top production and decay data, a form factor decomposition of the tWb vertex is no longer appropriate; for a (relatively model-independent) gauge-invariant parameterization of possible new physics effects one should use an effective Lagrangian which contains, in particular, the anomalous couplings $\delta f_L = f_L - 1$, f_R , g_L , and g_R (see [62]).

Computations of these form factors in a number of SM extensions with 3 quark generations (multi-Higgs and SUSY extensions, top-color assisted technicolor (TC2)) [63] yield that 1-loop radiative corrections induce non-zero, but very small anomalous form factors $f_L - 1, f_R, g_L, g_R \neq 0$, typically $\lesssim 0.01$. In particular the phases of these form factors due to final-state interactions or non-standard CP violation turn out to be small. As to f_L , a deviation $\delta f_L \sim 0.1$ is possible if new, heavy quarks with charge $Q = 2/3$ exist that mix with the top quark [64]. If a 4th sequential quark generation t', b' exists, then one expects $|f_L| = |V_{tb}| < 1$. A scan using input from B, D, K decays and electroweak precision measurements yields $|f_L| = |V_{tb}| > 0.93$ [65]. A more exotic possibility is the existence of a new heavy vector-like T quark as predicted, for instance, by Little Higgs models or by extra-dimension models. Mixing of t and T would reduce f_L ; one expects $|f_L| \gtrsim 0.9$. If a significant reduction of f_L with respect to its SM value were measured, it would point to the existence of a heavy $Q = 2/3$ quark.

What about top decay modes other than $t \rightarrow bW$? In the SM all such modes are rare; for instance the CKM-suppressed modes $t \rightarrow s, d$ have branching fractions $B(t \rightarrow W^+ s) = 1.9 \times 10^{-3}$, $B(t \rightarrow W^+ d) = 10^{-4}$. In SM extensions new decay modes are possible, notably the decay into a light charged Higgs boson, $t \rightarrow bH^+$, and the decay into a light stop and a neutralino, $t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0$. Searches for these modes at the Tevatron have been negative so far. At the LHC these modes will either be seen or excluded. Another issue are flavor-changing neutral currents involving the top quark, *i.e.* the existence of $t \rightarrow c, u$ transitions. CDF has obtained the upper bound $B(t \rightarrow Zq) < 0.037$, while DØ has recently extracted the upper bounds $B(t \rightarrow gu) < 2.0 \times 10^{-4}$ and $B(t \rightarrow gc) < 3.9 \times 10^{-3}$ from their single-top event sample [66]. In the SM the branching fractions of the FCNC modes $t \rightarrow c, u$ are unmeasurably tiny due to almost perfect GIM cancellations; but even in many of the popular SM extensions the branching fractions of these modes are, in view of the phenomenological constraints on these models, typically $\lesssim 10^{-5}$. (For a review, see *e.g.* [67].) If branching ratios $B(t \rightarrow Zc) \gtrsim \times 10^{-4}$ were found, it would point to mixing of t with exotic (*e.g.*, vector-like) quark(s). If a neutral Higgs boson h lighter than the top quark with FCNC couplings exists, then $B(t \rightarrow hc) \sim 10^{-3}$ and $B(t \rightarrow gc) \sim 10^{-4}$ are possible.

2.3. Charge asymmetry at the Tevatron. – The inclusive top (*versus* antitop) quark charge asymmetry A_t in $t\bar{t}$ production at the Tevatron has recently stirred much interest, because the measurements do not quite match the SM expectations. In the SM this asymmetry is induced at NLO QCD (predominantly through $q\bar{q} \rightarrow t\bar{t}$). Assuming CP invariance, A_t amounts to a top-quark forward-backward asymmetry A_{FB}^t . At NLO QCD $A_t = 0.051(6)$ [68, 69], while a related pair-asymmetry was computed to be

$A^{t\bar{t}} = 0.078(9)$ [69]. (Some weak-interaction contributions are included in these predictions.) For kinematical reasons $A^{t\bar{t}}$ is larger than A_t . Resummation of QCD threshold logarithms [29, 24] does not change these predictions significantly, but leads to a more realistic estimate of the theory uncertainty, namely ~ 15 – 20% . It should be emphasized that all these predictions are made at the level of $t\bar{t}$ states without acceptance cuts.

At the Tevatron the top quark charge asymmetry was measured for $\ell + j$ final states. DØ obtained $A^{t\bar{t}} = 0.12 \pm 0.08 \pm 0.01$ [10]. This result has not been unfolded, while CDF has unfolded their data and obtained $A_{FB}^t = 0.193 \pm 0.065 \pm 0.024$ in their analysis of 2009 [12, 8]. Although there is no statistical significant discrepancy between experiments and the SM predictions, the present situation leaves ample room for speculations about possible new physics contributions to $t\bar{t}$ production which (so far) show up only in this distribution. During the last two years many papers have appeared that address this issue, see [43].

Here, I want to add two remarks. A top quark charge asymmetry induces an asymmetry A^ℓ for the charged leptons ℓ^\pm from t and \bar{t} decay in dileptonic and in $\ell + j$ final states. Likewise, the $t\bar{t}$ pair asymmetry leads to a leptonic pair asymmetry $A^{\ell\ell}$ in the dileptonic sample. (See [30] for the precise definitions of A^ℓ and $A^{\ell\ell}$.) These leptonic asymmetries were computed to NLO QCD with respect to $t\bar{t}$ production and t, \bar{t} decay, with weak-interaction corrections and full NLO $t\bar{t}$ spin correlations included [30]. When standard Tevatron acceptance cuts are applied, these asymmetries are $A^\ell = 0.034(4)$ and $A^{\ell\ell} = 0.044(4)$. (Only the uncertainties due to scale variations are given.) These asymmetries are smaller than the corresponding asymmetries at the level of the intermediate $t\bar{t}$, because i) the charged lepton does not follow the direction of its mother particle, ii) the acceptance cuts diminish the asymmetries, and iii) the $t\bar{t}$ spin correlations do have some effect on $A^{\ell\ell}$. So far there are no experimental results on A^ℓ and $A^{\ell\ell}$ available. These asymmetries should be measurable more easily and with a higher precision than the above top-charge asymmetries. This may provide a more conclusive comparison with the SM results.

Second, suppose there is a new physics contribution to the top-quark charge asymmetry. This new interaction need not be C - or P -violating in order to generate a non-zero contribution to A_t , but if it is P -violating, it would, in addition to contributing to A_t , also polarize the t and \bar{t} quarks of the $t\bar{t}$ sample in the production plane to some degree. (The t, \bar{t} polarizations due to the standard weak-interaction contributions to $t\bar{t}$ production are less than 1%.) This can be checked by measuring the distributions $\sigma^{-1}d\sigma/d\cos\theta_{\ell^\pm}$ in $\ell + j$ final states, where θ_{ℓ^\pm} are the ℓ^\pm helicity angles with respect to the top rest frame. The NLO SM predictions of these distributions are given in [30]. Without acceptance cuts they would be essentially flat, but the acceptance cuts distort these distributions in the backward region $\cos\theta_\ell < 0$. A sizeable longitudinal polarization of the (anti)top-quark sample would result in a non-flat distribution in the forward region $\cos\theta_\ell > 0$. As the Tevatron experiments have already accumulated $\sim 10^3$ lepton + jets events, these ℓ^\pm distributions should be measurable with reasonable precision.

2.4. $t\bar{t}$ spin correlations. – Top spin effects, in particular $t\bar{t}$ spin correlations are a rather unique feature of top quark physics, as compared to the physics of lighter quarks. Final-state angular distributions and correlations induced by top-spin effects are “good” observables because this quark does not hadronize. Final state angular correlations induced by $t\bar{t}$ spin correlations contain information about the $t\bar{t}$ production and decay dynamics. Assuming that $t \rightarrow bW$ is the only decay mode of the top quark (possibly with small anomalous couplings), then a closer look reveals that these correlations, especially

the dilepton angular correlations, essentially probe the $t\bar{t}$ production dynamics only. In the SM, the correlation of the t and \bar{t} spins is predominantly a QCD effect which is induced already at Born level. The degree of correlation depends, for a specific production reaction/dynamics, on the reference axes with respect to which the t and \bar{t} spin states are defined. At the Tevatron the SM-induced $t\bar{t}$ spin correlations are largest in the so-called off-diagonal and beam bases, while at the LHC the helicity basis and an opening angle distribution defined in a specific way are good choices. These correlations were predicted to NLO QCD for dileptonic, $\ell + \text{jets}$, and all jets final states [70]. These predictions were recently updated, taking weak-interaction contributions and acceptance cuts into account [30]. The measurements of $D\emptyset$ and CDF [13-16] agree with these predictions within the still large experimental errors.

At the LHC $t\bar{t}$ spin correlations should eventually be measurable with significantly higher precision due to much larger data samples. If this is the case, then these observables will serve their purpose, namely to provide a further tool for exploring the $t\bar{t}$ production dynamics in detail. As mentioned, the angular correlations in the helicity basis and the opening angle distribution $\sigma^{-1}d\sigma/d\cos\varphi$ are good choices for detecting the SM-induced $t\bar{t}$ spin correlations at the LHC, both for the $\ell\ell'$ and $\ell + \text{jets}$ final states. As was shown recently for the case of the LHC, also the $\ell\ell'$ azimuthal angle correlation $\sigma^{-1}d\sigma/d\Delta\phi$ (where $\Delta\phi = \phi^+ - \phi^-$) measured in the laboratory frame discriminates between correlated and uncorrelated $t\bar{t}$ events if only events with low pair-invariant mass $M_{t\bar{t}}$ are taken into account [31,32]. For the LHC at 14 TeV a useful cut is $M_{t\bar{t}} \leq 400$ GeV. It was shown that the NLO QCD corrections to this distribution in $\Delta\phi$ are sizeable, but its power to discriminate between correlated and uncorrelated $t\bar{t}$ events remains [30]. At the LHC (14 TeV) the ratio $\sigma_{\ell\ell'}(M_{t\bar{t}} < 400 \text{ GeV})/\sigma_{\ell\ell'} \simeq 18.6\%$. Thus with an integrated luminosity of 1 fb^{-1} one expects ~ 3200 dilepton events with low $M_{t\bar{t}}$ before event selection. It remains to be investigated how much luminosity has to be accumulated in order to measure this distribution at the level of several percent.

Clearly, the $\Delta\phi$ distribution is easier to measure than the opening angle distribution or the helicity correlation which require the reconstruction of the t and \bar{t} rest frames. However, the shapes of the $\Delta\phi$ distributions for correlated and uncorrelated events depend sensitively on how precisely $M_{t\bar{t}}^{\text{cut}}$ can be experimentally determined, and this distribution loses its discriminating power rapidly for $M_{t\bar{t}}^{\text{cut}} > 400$ GeV. On the other hand, the opening angle and helicity observables discriminate by design between correlated and uncorrelated $t\bar{t}$ events, irrespective of whether or not they are evaluated for all events or whether a maximum ($< M_{t\bar{t}}^{\text{cut}}$) or minimum ($> M_{t\bar{t}}^{\text{cut}}$) selection cut is applied. While $\sigma^{-1}d\sigma/d\Delta\phi$ probes the $t\bar{t}$ spin dynamics in the low-energy tail of the $M_{t\bar{t}}$ spectrum, the helicity and the opening angle correlation can be used also for the high energy tail, where (non)resonant new physics effects may show up. The latter observables should also be measured for $\ell + j$ events at the LHC. Although the sensitivity decreases by a factor of about 2 for these channels, the data samples will be about 6 times larger.

2.5. Single top production. – The hadronic production of single (anti)top quarks is interesting for a number of reasons. These include: i) The weak interactions are involved, and this provides a unique opportunity to directly explore the top quark's charged current interactions. In the SM, the production cross section $\sigma_t \propto |V_{tb}|^2$. In fact, a closer look shows that all squared matrix elements $|V_{tq}|^2$ of the 3rd row of the CKM matrix are involved. ii) Due to the production mechanism, the single (anti)top samples are highly polarized. This remains to be exploited for the investigation of both the production and the decay dynamics. iii) Single top production is sensitive to BSM interactions that differ

from those that can be traced in $t\bar{t}$ production. The single top production modes may be affected by t - and s -channel exchanges of new, heavy charged resonances or by FCNC interactions. iv) By the time the production cross sections will have been measured with sufficient precision and the partonic production mechanisms will have been pinned down, the data can be used for a direct determination of the b -quark content of the proton.

In the SM the three main production reactions are t -channel W -boson exchange (which is the dominant mode both at the Tevatron and the LHC), s -channel W -boson exchange, and the tW production mode. At the time of this workshop the $t + \bar{t}$ production cross sections were measured by DØ and CDF with a respective uncertainty of $\delta\sigma^{t+\bar{t}} \sim 25\%$. The goal for the LHC (14 TeV), where the signal-to-background ratios become more favorable, is to measure the t -channel cross section with a precision of $\lesssim 10\%$, which would amount to determining the strength f_L of the tWb vertex to $\sim 5\%$ accuracy, provided the theoretical description is sufficiently precise. In view of the large backgrounds the present and future analyses of single top events at the Tevatron and the LHC depend heavily on theory, *i.e.* on the calculated cross sections and distributions and their implementation in Monte Carlo codes. At present, in the 5-flavor scheme, the three $2 \rightarrow 2$ single top production modes are known to NLO CQD [71-76] (plus threshold resummations [77], plus weak-interaction corrections [78, 79]); the dominant t -channel production mode was computed to NLO QCD also in the 4-flavor scheme [37] (where one considers $qg \rightarrow q't\bar{b}$ to be the leading-order process). The status of the perturbative calculations and of the NLO Monte Carlo codes will be discussed by [38] and by [33], respectively. In spite of these impressive results there is still quite some work to do on the theory side in order to reach the goal of exploring single top physics at the LHC at the level of $\sim 5\%$. For the time being we are eager to learn about the expectations of rediscovering single top events at the LHC [80].

2'6. New heavy resonances $X_J \rightarrow t\bar{t}$ in “early” LHC phase? – SM extensions and/or alternatives to the SM Higgs mechanism, *e.g.*, supersymmetric extensions, top-condensation and technicolor models, or models that involve extra dimensions predict new heavy resonances, some of which couple (strongly) to top quarks. Examples are neutral or charged non-SM Higgs bosons, technicolor or top-color bound states, Kaluza-Klein (KK) excitations, heavy t' and b' quarks, or a heavy stop \tilde{t} . At the Tevatron CDF and DØ have searched for such resonances and have set mass/coupling limits for instance on a heavy W' , H^+ , t' , b' , and \tilde{t} .

The $t\bar{t}$ invariant mass distribution is the key observable in the search for electrically neutral bosonic resonances X_J that couple to $t\bar{t}$. CDF and DØ have not found a significant excess in the measured $M_{t\bar{t}}$ spectrum up to ~ 1 TeV compared to the SM expectation. The searches for $p\bar{p} \rightarrow X_J \rightarrow t\bar{t}$ led to the exclusion of a leptophobic Z' boson (which appears in TC2 models) with mass $M_{Z'} < 820$ GeV and of massive KK gluons with mass $M_G \lesssim 1$ TeV, see [17]. It will take a while before these limits/sensitivity ranges will be superseded by the LHC experiments.

Most of the above-mentioned SM extensions contain heavy, neutral Higgs bosons or Higgs-like spin-zero resonances ϕ in their physical particle spectrum. For instance 2-Higgs doublet extensions or the MSSM predict 3 neutral Higgs bosons, and both models allow for the possibility that two of the three states have a mass of about $2m_t$ or larger. In the case of a pseudoscalar state $\phi = A$ ($J^{PC} = 0^{-+}$) there is the specific feature that A does not couple to W^+W^- , ZZ in lowest order because of CP mismatch. In addition, the loop-induced decays into the golden channels $A \rightarrow W^+W^-$, ZZ are suppressed in many models in large portions of their parameter spaces [81]. But A can strongly couple to top

quarks, like the other states ϕ . The most likely production mode of a ϕ resonance is gluon fusion. The amplitude of $gg \rightarrow \phi \rightarrow t\bar{t}$ interferes with the amplitude of the non-resonant $gg \rightarrow t\bar{t}$ background, which leads to a typical peak-dip resonance structure in the $M_{t\bar{t}}$ spectrum [82, 83]. If such a state ϕ exists, with a mass in the range $300 \text{ GeV} \lesssim m_\phi \lesssim \mathcal{O}(600 \text{ GeV})$ and with a strong Yukawa coupling to the top quark, then it is conceivable that it would be seen as a resonance bump at the LHC, but not at the Tevatron! It remains to be investigated how precisely the $M_{t\bar{t}}$ spectrum can be measured after the first LHC (7 TeV) running period.

3. – Outlook

The top quark, the heaviest known fundamental particle, offers the unique possibility to explore the interactions of a bare quark at distances below the attometer scale. The future of top quark physics is certainly bright. As far as top quark physics at the LHC in its present operating mode is concerned we have to face reality. We are all happy that the LHC is running at 7 TeV, and we have to see how much integrated luminosity will have been delivered to the experiments by the end of 2011; perhaps $\sim 200 \text{ pb}^{-1}$ or up to $\sim 1 \text{ fb}^{-1}$? Needless to say: the ATLAS and CMS experiments first have to calibrate their detectors and software tools with the recorded data. What kind of top physics can we expect? We will learn about it in the talks [84-86]. If one stays on the pessimistic side assuming only $L \sim 200 \text{ pb}^{-1}$ by the end of 2011, then from the $t\bar{t}$ cross section $\sigma_{t\bar{t}} \simeq 150 \text{ pb}$ at 7 TeV one would have 30 k $t\bar{t}$ events before selection, *i.e.* roughly $\sim 200 \ell\ell'$ and $\sim 2 \text{ k } \ell + j$ events after selection. When will the first single Euro tops be observed? Is this possible within the present LHC running period? The single-top cross section $\sigma_t \simeq 65 \text{ pb}$ implies $\geq 13 \text{ k}$ tops before selection if $L \geq 200 \text{ pb}^{-1}$. What will come more from CDF and D0? These questions will hopefully be addressed, too, in the next days. We all look forward to a week of stimulating talks and discussions.

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