Theoretical summary

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This is a summary of theoretical progress presented at TOP2013. I review new results and methods in producing top quarks singly, in pairs or in association with other particles and/or jets, in addition to special aspects of its production like the forward-backward asymmetry. The role of top in certain New Physics models was discussed, as well as the careful definition of its mass. The emergent picture is one of impressive progress on the theoretical front of top quark physics.

1 Introduction

In this meeting many interesting new results in top physics were presented, in both experimental and theoretical talks. Very interestingly, and quite typically for this conference series there was much experimental detail in theoretical presentations, and vice versa.

The top quark long reigned supreme as the most interesting particle to study at high-energy colliders, but in July 2012 it was surpassed by the appearance of the Higgs boson in the ATLAS and CMS detectors. But even here top plays a key role, enabling Higgs boson production through gluon fusion and a top quark loop.

Let us briefly review why the top quark, its production and decay characteristics and its behavior in loops is such an important particle. First, it has many quantum numbers and thus couples to almost all other particles, through various (chiral, vector, scalar) structures, all of which bear scrutiny for deviations. Precise scrutiny is feasible because the large top mass implies, first, that it couples weakly to QCD, but strongly to whatever breaks the electroweak symmetry, and second, that its resulting large width minimizes hadronization effects and allows preservation of spin information.

But the possibility of its accurate study is not sufficient reason for devoting so much energy to this scrutiny. It is especially promising because top is a troublemaker for the Standard Model, contributing significantly to the quadratic divergences of the Higgs self energy. But, in yet another twist, the troublesome top quark is also a life raft for beyond the Standard Model (BSM) theories such as the MSSM, by raising, through its role in loop corrections, the allowed upper limit on the light Higgs mass in that theory.

With the Tevatron having made the first thousands top quarks, leading to its discovery and tests of some of its properties, the LHC, especially in the upcoming 13 TeV run, is a genuine top quark factory and will allow us to study the top quark in great detail, which this conference bears witness to.

2 Top production

To study tops, we must make them first and moreover understand very well the production mechanism. Very interesting results were reported in both pair and single top production. Let us briefly recall some basic aspects of fixed order (LO, NLO, NNLO, etc) calculations. LO is defined by the simplest way, with the lowest number of QCD interactions, in which the desired final state can be made. Usually, but not always (cf. Higgs production through gluon fusion) this implies a tree-level amplitude. The LO approximation to the cross section is the amplitude times its complex conjugate, summed (averaged) over final (initial) quantum numbers. NLO then includes both virtual corrections to either the amplitude or its complex conjugate, or the amplitude with one parton more, squared. The NNLO consists of a purely virtual 2-loop or 1-loop squared component, a 1-real plus 1-virtual component, and finally a 2-real component squared. Handling the intermediate infrared and collinear divergences is not easy, especially for NNLO. The benefit of these higher-order corrections is a more accurate estimate (due to the mere fact of including the corrections, as well as the very typical smaller resulting uncertainty due to scale variations), and a better description of the physics by allowing for extra partons. We were reminded by Frederix in this conference that NLO calculations are now fully automatized in the aMC@NLO framework [1], and that the act of calculating now is just a series of steps involving downloading the code, generate a process through python, and after writing the process to disk, start event generation with NLO plus parton shower accuracy.

2.1 Pair production

Let us review the status of, and main ideas behind theoretical calculations for top quark pair production. The inclusive top pair production cross section has always played a role that is both useful and instructive in perturbative QCD, because it only involves QCD couplings, and involves a truly large mass that must be accounted for in the matrix elements and the phase space measure. The NLO corrections were computed in the late 80's [2, 3, 4, 5]. In these first calculations phase space was (partially) integrated over analytically; a fully differential calculation was completed shortly thereafter [6]. The combination of such a fully differential calculation with parton showers, such as `MC@NLO` [7, 8] and `POWHEG` [9, 10] is now the state of the art at this order in perturbation theory. These codes combine the virtues of the exclusiveness of an parton shower event generator with the accuracy of a NLO calculation.

A recent major development has been the completion of the full NNLO calculation for the inclusive pair production cross section[11, 12, 13, 14], which was presented at this conference by Czakon. This is veritably a milestone in top quark physics. The result is a hadronic cross section computed with a theoretical accuracy at the percent level. The calculations involving corrections to both the $q\bar{q}$ and the gg channel have been completed, as well as the NLO corrections to the qg channels. For both the $q\bar{q}$ and gg channel, the second order corrections are composed of three classes of contributions, some computed at different times by various authors. These are (i) the two-loop corrections, (ii) the one-loop plus one real emission corrections, and (iii) the double real emission contribution [16, 17, 18]. The one-loop, one real emission contributions are done, since the NLO calculation for $t\bar{t}+$ jet is available [19, 20]. The two-loop virtual corrections have been performed in Refs. [21, 22, 23, 24, 25]. The methods used so far are a combination of analytical and numerical ones. The latter involve solving differential equations in the kinematic invariants, which requires a highly accurate initial condition (chosen to be at high energy), and avoiding singularities in the equations. The double-real emission contribution was achieved through the use of a method called STRIPPER [16]. The one-loop, one-real emission diagrams could be computed with well-established techniques. The tour-de-force calculation has produced remarkable results, with good perturbative convergence and very small uncertainties. Given these properties and the excellent agreement with measurements, as shown in Fig. 1, a comparison of theory and data for the inclusive cross section can be used to infer useful knowledge about the gluon density. Recently a first study in this direction was done [26], demonstrating the feasibility and desirability of this.

On top of the exactly calculated orders one can add to arbitrarily high orders logarithms that are enhanced near threshold, i.e. threshold resummation. As the latter also underlies recent theoretical estimates of the top quark charge asymmetry, discussed in section 5, as well as various distributions, let us review this method briefly here, in general terms. When the top quark pair is produced near threshold in hadronic collisions, certain logarithms can become numerically large. It is important to note here that the definition of the threshold depends on the observable. Thus, for the inclusive cross section threshold is given by the condition $T_1 : s - 4m^2 = 0$. For the transverse momentum distribution we have $T_2 : s - 4(m^2 + p_T^2) = 0$, and for the doubly differential distribution in p_T and rapidity we can choose

$$T_3 : s - 4(m^2 + p_T^2) \cosh y = 0 \quad \text{or} \quad T_3 : s + t + u - 2m^2 = 0\,. \tag{1}$$

The perturbative series for any of these (differential) cross sections can be in general be expressed as

$$d_\alpha \sigma(T_\alpha) = \sum_n \sum_k^{2n} \alpha_s^n c_{n,k}^\alpha \ln^k(T_\alpha)\,, \tag{2}$$

plus non-logarithmic terms. Here T_α represents any of the threshold conditions, suitably normalized, for the observables enumerated by α. Note that it is allowed to use e.g. T_2 for the inclusive cross section, by first analyzing $d\sigma/dp_T$ and then integrating over p_T, and similarly for T_3. For any complete fixed order calculation this will give the same answer, but if one only selects the logarithmic terms because the exact answer is unknown, numerical differences will occur. Such kinematic differences can then be classified as a theoretical uncertainty [27].

The threshold logarithms result from integration over phase space regions where the emitted gluons are soft and/or collinear to their on-shell emitter. Resummation concerns itself with carrying out the sum in Eq. (2), and the result takes the generic form

$$d\sigma = \exp\left(L g_0(\alpha_s L) + g_1(\alpha_s L) + \alpha_s g_2(\alpha_s L) + \ldots\right) \times C(\alpha_s)\,. \tag{3}$$

Including up to the function g_i in the exponent amounts to N^{i}LL resummation, with the coefficient $C(\alpha_s)$ then evaluated to $i-1$ order. Key benefits of threshold resummation are (i) gaining all-order control of the large, positive terms plague fixed-order perturbation theory, thereby restoring predictive power, and (ii) reduction of scale uncertainty. Regarding the first point, the reason these resummable terms are positive for the top quark pair inclusive cross section is that, while the hadronic cross section is Sudakov suppressed near threshold, the PDF's provide too much suppression, which the partonic cross section must then partially compensate with positive corrections. Regarding the second point, when examining the sources of μ_F dependence, they occur both in the PDF and in the partonic cross section now both *in the exponent*, which improves the cancellation[28].

The state-of-the-art accuracy for threshold resummation for inclusive pair production cross section at present is NNLL [29, 30]. From such all-order results, approximate NNLO results

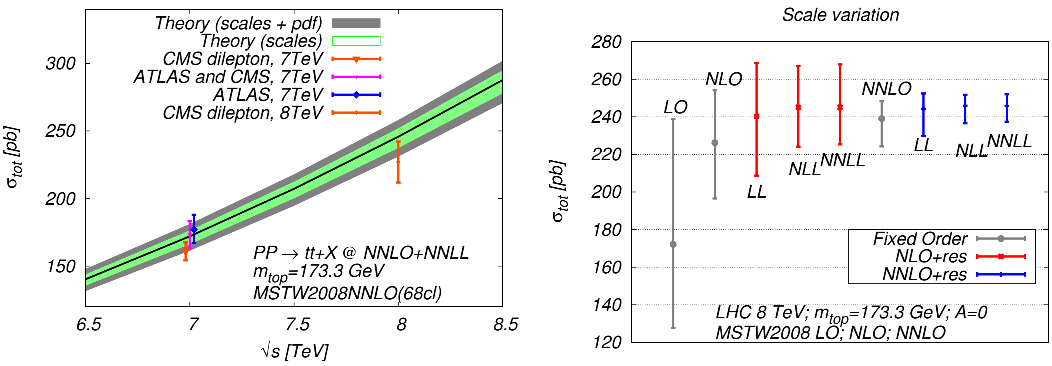

Figure 1: Left pane: NNLO-NNLL prediction for the LHC as function of the collider c.m. energy. Right pane: progress in reducing scale variation due to increasing perturbative and resummation accuracy. [14]

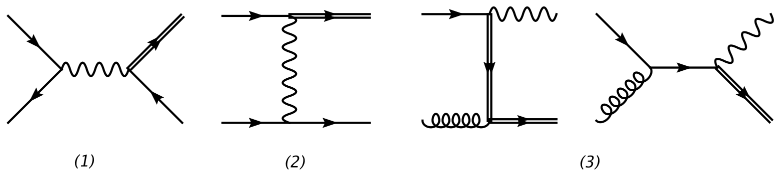

Figure 2: From left to right the s-channel (1), t-channel (2) processes, and the Wt associated (3) production channel.

were constructed before the completion of the exact calculation. This is of particular interest for thresholds T_1 and T_3. The latter, being dependent on t and u, then allows estimating threshold resummation corrections to the forward-backward asymmetry. Other approximate NNLO calculations use threshold T_3, and, as mentioned above, assign the ambiguities due to using pair-invariant mass (PIM) or one-particle inclusive (1PI) kinematics in the precise definition of the threshold to a theoretical error [27, 32, 33].

The state of the art was presented by Czakon, who showed (see Fig. 1) also the impressive progress over time in accuracy of the theoretical description. Each component of the uncertainty is now at the few percent level.

2.2 Single top

Tops are produced singly through the weak interaction, in processes that are usually referred to in relation to Born kinematics, see Fig. 2. A particularly important aspect of single-top production is that both V_{tb} can be directly measured and the chiral structure of the tWb vertex can be tested. This is because top quarks produced in this way through a charged current interaction are highly polarized. Also important, and stressed at this meeting, is the issue of how many active quark flavors to choose. For instance, through the dominant t-channel at the LHC, inclusive measurements can be confronted with a 5-flavor NLO calculation, allowing extraction of the b-quark density. For situations with a tagged jet, and 4-flavor scheme seems

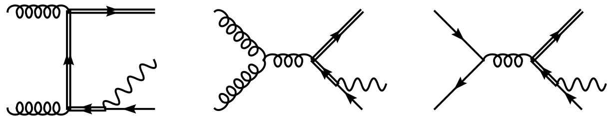

Figure 3: Doubly resonant diagrams in NLO corrections to Wt production.

more natural. Finally, we note that the different single top production channels are each sensitive to different varieties of New Physics, Thus, the s-channel will be sensitive to e.g. W' resonances, the t-channel to FCNC's.

The inclusive cross sections at the Tevatron are rather small, their contributions being about 1 pb for the s channel and 2 pb for the t channel, with the Wt channel negligible.

2.2.1 s and t channel

Experimentally, both of these single top production processeses turned out to be rather more difficult to separate from backgrounds than expected, as the latter were larger, and similar to shape to the signals. Based on samples of 3.2 fb^{-1} by CDF and 2.3 fb^{-1} by D0, the Tevatron combination[34] of a number of CDF and D0 measurements yielded an inclusive single top production cross section of

$$\sigma = 2.76^{+0.58}_{-0.47}\ \text{pb}\,, \tag{4}$$

and a measurement of $|V_{tb}| = 0.88 \pm 0.07$. Based on samples of up to 9.7 fb^{-1} per experiment, recently CDF and D0 reported the Tevatron combination[35] for s-channel single top production

$$\sigma_s = 1.29^{+0.26}_{-0.24}\ \text{pb}\,. \tag{5}$$

Furthermore, a D0 measurement [36] of only the t-channel cross section yielded $\sigma_t = 3.07^{+0.54}_{-0.49}$ pb. The measured cross sections agree within errors with the NLO calculations [37, 38, 39, 40, 41, 42, 43, 44], and with `MC@NLO` [45] and `POWHEG` [46].

At the LHC at 7 TeV, the inclusive SM production rates of the s-channel, t-channel and Wt channel are approximately 4.6, 65 and 16 pb respectively; at 8 TeV they are 5.6, 88 and 22 pb, respectively. Evidently the t-channel yields by far the dominant contribution. Within errors, the t-channel cross section measurements above agree with the NLO calculations, and the values of V_{tb} which are extracted are compatible with 1.

2.2.2 Wt channel

An interesting and subtle issue arises in the Wt mode of single top production. In the radiative corrections some diagrams contain an intermediate anti-top splitting into a W and anti-down type quark, a process which can become resonant. From another viewpoint, these diagrams can be seen as LO $t\bar{t}$ on-shell' pair production (having an order-of-magnitude larger cross section), with subsequent $\bar{t}$ decay, see Fig. 3. One is therefore faced with the issue to what extent the Wt and $t\bar{t}$ can be defined and/or separated as individual processes, with the main difficult caused by interference between the resonant and non-resonant diagrams. To this end several definitions of the Wt channel have been given in the literature, each with the aim of recovering a well-behaved expansion in α_s for a meaningfully defined observable.

In Ref. [48] the interference issue was addressed extensively in the context of event generation, in particular the MC@NLO framework (POWHEG has implemented essentially the same method [49]). Two different procedures for subtracting the doubly-resonant contributions and thereby recovering a perturbatively well-behaved Wt cross section were defined. In “Diagram Removal (DR)” the graphs in Fig. 3 were eliminated from the calculation, while in “Diagram Subtraction (DS)” the doubly resonant contribution was removed via a subtraction term. The DS procedure leads to the following expression for the cross section

$$d\sigma^{(2)} + \sum_{\alpha\beta} \int \frac{dx_1 dx_2}{x_1 x_2 S} \mathcal{L}_{\alpha\beta} \left(\hat{S}_{\alpha\beta} + I_{\alpha\beta} + D_{\alpha\beta} - \tilde{D}_{\alpha\beta} \right) d\phi_3, \tag{6}$$

where $\alpha\beta$ labels the initial state channel in which the doubly-resonant contribution occurs: gg or $\mathrm{q\bar{q}}$. $\hat{S}$ is the square of the non-resonant diagrams, I their interference with D, the square of graphs of Fig. 3. The subtraction term $\tilde{D}$ requires careful construction [48]. It was shown that, with suitable cuts, the interference terms are small. From Eq. (6) one sees that the difference of DR and DS is essentially the interference term. A particularly suitable cut is a puttting a maximum on the p_T of the second hardest b-flavored hadron, a generalization of a proposal made in Ref. [41]. Thus defined, the Wt and $t\bar{t}$ cross sections can be separatedly considered to NLO.

The experimental status of this production mode at the time of writing is as follows. In the 7 TeV run, ATLAS [50] and CMS [51] have measured the Wt-channel cross section, with the results

$$\begin{aligned} \text{ATLAS}[2.05\,\text{fb}^{-1}]: &\quad \sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat}) \pm 4.9(\text{sys})\,\text{pb}\,, \\ \text{CMS}\,[4.9\,\text{fb}^{-1}]: &\quad \sigma_{Wt} 16^{+5}_{-4}\,\text{pb}\,. \end{aligned} \tag{7}$$

Based on a data set of 12.2 fb^{-1}, recently CMS has in fact identified the Wt-channel cross section for the 8 TeV run[52] at the 6.1σ level

$$\sigma_{Wt} = 23.4 \pm 5.4\,\text{pb}\,. \tag{8}$$

Within errors, the Wt-channel cross section measurements above agree with the NLO calculations[53, 41, 54], and the NLO plus parton showers discussed above [48, 55, 49].

One way to avoid the above difficulties in separating Wt from $\bar{t}t$ is to consider the common final state $WWbb$ (in the 4-flavor scheme) and not ask if there were one or two intermediate top quarks involved in producing this final state – zero intermediate top quarks is also a possibility here. For zero b-quark mass, two groups have computed the NLO corrections to this production process [56, 57]. A preliminary result, using aMC@NLO was shown for the case where the b quark is taken massive. For the rates and distributions examined there seemed to be only small changes with respect to the massive case.

A completed study was shown investigating off-shell effects in t-channel production, in part as a test of the narrow-width approximation. Also confronted with the exact calculation was an effective theory approach [59]. It was shown that the NWA approximation does not always work well, whereas the ET approach does.

3 Top spin

Part of the attractiveness of the top quark is its capacity to self-analyze its spin, through its purely left-handed SM weak decay. This is both a useful aid in signal-background separations,

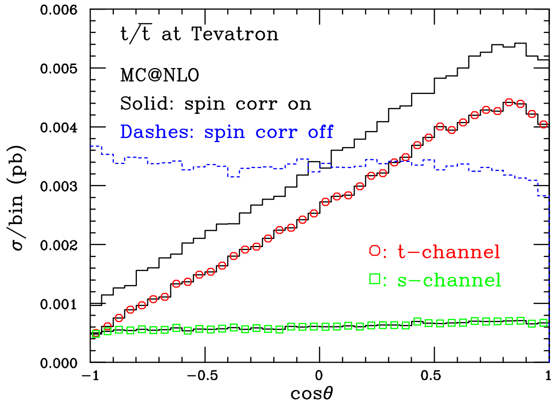

Figure 4: In t-channel single-top production at the Tevatron, a clear correlation of the lepton flight direction with the recoiling light quark jet. The correlation disappears when spin-correlations are turned off in MC@NLO [60].

and itself a property worthy of detailed scrutiny, as certain New Physics models could introduce right-handed couplings. The correlation between top spin and directional emission probability for its decay products is expressed through

$$\frac{d \ln \Gamma_f}{d \cos \chi_f} = \frac{1}{2} \left(1 + \alpha_f \cos \chi_f\right) \tag{9}$$

where $|\alpha_f| \leq 1$, with 1 indicating 100% correlation. For the dominant decay mode

$$t \to b + W^+(\to l^+ + \nu) \tag{10}$$

at lowest order, we have $\alpha_b = -0.4, \alpha_\nu = -0.3, \alpha_W = 0.4, \alpha_l = 1$. QCD corrections to these values are small. The charged lepton direction (or the down-type quark in a hadronic decay of the intermediate W) is indeed 100% correlated with the top quark spin. This is amusingly more than for its parent W boson, a consequence of interference of two amplitudes with different intermediate W polarizations.

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. In Fig. 4 this correlation as computed with MC@NLO [60] is shown. A preliminary study from CMS [61] was shown in which the pattern of Fig. 4 was looked for, and was indeed found. From such a constant slope one might infer [62] the inclusive t-channel cross section, using only a straight-section piece to extrapolate to all angles.

4 Top, friends and imitators

Among the classic imitators of a top quark signal at hadron colliders is the V+jet final state. The QCD corrections for V+jets are now known up to 5 jets at least, and matched to parton showers. We were reminded of the very impressive progress made in this direction in recent years. In particular also the merging of matrix elements to parton showers is now a well-mastered craft.

A very clear overview was given of the tremendous advances made in describing $\bar{t}t$ plus various particles or jets, plotting calculations in 3D using the axes of increasing powers of α_s (NLO, NNLO), of the number of external lines, and of finite width and other effects. Especially noteworthy is that the processes $\bar{t}t$ plus QCD objects such as one or two jets, two extra b quarks or even two extra t quarks (four tops) have been computed to NLO in recent years. Depending on the final state, parton shower effects or narrow/finite width effects are included. But also processes such as $\bar{t}t$ plus a photon, vector boson or a Higgs are available to NLO, sometimes with an additional jet, and in cases with either stable tops, or including its decays. Also for New Physics showing up indirectly through $\bar{t}t$ plus missing E_T for certain modes available at least through NLO [63]. For top pair plus Higgs production, available as an NLO calculation, matched to parton showers, and interfaced to MadSpin [65], an interesting and fairly well-working approximation involving top fragmentation into top plus Higgs was explained. With the major backgrounds also available to NLO, it seems the main tools for a good extraction of the top Yukawa are available. Backgrounds will be very challenging for $\bar{t}th$, so testing for deviations from the Standard Model will be hard. We were reminded that it might be better to look at single top plus Higgs production [66], where the Standard Model amplitude is strongly suppressed due to interference effects so BSM might come more easily to the fore.

5 Charge asymmetry

Another, complementary test of the top quark production mechanism is the charge asymmetry: the difference in production rates of tops and anti-tops at fixed rapidity

$$A_t(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}\,. \tag{11}$$

While electroweak production via a Z-boson could produce a (very small) asymmetry at LO, QCD itself produces it at $\mathcal{O}(\alpha_s^3)$ through a term proportional to the SU(3) d_{abc} symbol [3, 5, 67, 19]. In the $q\bar{q}$ channel this arises from an interference between the Born and the one-loop box diagram. In the matrix elements, the asymmetry reveals itself in terms of the Mandelstam variables t and u as terms that are odd under $t \leftrightarrow u$ interchange. In $t\bar{t}$ plus 1 jet production an asymmetry can already occur at tree level (essentially, this amounts to a different cut of the same amplitude). Measurements [68, 69, 70, 71] by the Tevatron experiments show substantial deviations from the Standard Model prediction for pair production, especially a deviation of more than 3 standard deviations by CDF at large invariant $t\bar{t}$ masses [69]. There is therefore considerable interest in this observable. In recent analyses by D0 [72, 73] the asymmetry is found to be not so large, though a discrepancy persists.

The effect of this interference amounts to the intuitive picture that the incoming quarks (as opposed to anti-quarks) tend to repel the produced top quarks towards larger rapidity, and/or attract the produced anti-top quarks toward slightly smaller rapidities. The net effect, therefore, at the Tevatron, where the top- anti-top pairs are produced in $q\bar{q}$ annihilation, is a shift of the top quark rapidity distribution towards larger rapidity, and of the anti-top distribution towards smaller values. This clearly creates a y-dependent asymmetry of the type (11). Because of the asymmetry in the amount of quarks and anti-quarks in the two Tevatron beams, this translates also to a forward-backward asymmetry A_{FB}.

Since the leading contribution to this effect for pair production involves a loop diagram, the asymmetry itself is of leading order accuracy. Clearly, the impact of even higher orders becomes interesting which at this stage can only be assessed from approximate, resummation based calculations to NLL [74, 27] or NNLL [75]. For this only resummations based on threshold T_3 (1) can be used. The higher order corrections so computed are small, so that the computed QCD asymmetry is stable with respect to their inclusion. The higher order asymmetry is then also reasonably insensitive to scale variations. With the methods discussed by Czakon we can look forward to the exact NLO asymmetry

Besides defining the asymmetry in terms of the top quark itself (11), one may define it also in terms of the leptons produced in top and/or anti-top decay , either in the lepton-plus-jets or the di-lepton channel. The A_{FB}^{ll} asymmetry will be in general a little washed out, but leptons are relatively easy to measure. (There is however still a need for unfolding due to limited acceptance.)

At the Tevatron, CDF and D0 have performed a set of measurements for various types of asymmetries. At the constructed top quark level the measured asymmetries exceed the theory prediction by a few standard deviations. Recent A_{FB} measurements in the lepton-plus-jets channels corrected to the parton level are $16.4 \pm 4.7\%$ (CDF) [76] and $19.6 \pm 6.5\%$ (D0) [71], vs. $8.8 \pm 0.6\%$ according to the SM.

In this conference the theoretical status of the charge asymmetry was reviewed quite comprehensively by Westhoff [77], who also discussed a number of New Physics options that would fit the observed enhanced asymmetry, such as axigluons, or a Z' boson.

As noted above, the charge asymmetry is present at leading order in $t\bar{t}+$ jet production. However, here NLO corrections [19, 20] wash out the asymmetry for this reaction. An explanation for this effect was given in [20], based on the following structure of the NLO forward-backward asymmetry for this reaction

$$A_{\rm FB}(t\bar{t}j) = \alpha_s^3 \frac{C}{\ln(m/p_{T,j})} + \alpha_s^4 D_{\rm hard}\,. \tag{12}$$

The second term, appearing at NLO, cancels the first as they have opposite signs. The inverse logarithm is due to the fact that the denominator in the asymmetry has a higher power of leading soft logarithms. Also for $t\bar{t}jj$ the NLO term seems to reduce the LO contribution to the asymmetry [78].

At the LHC, the net effect of the QCD induced asymmetry is an overall broadening of the top quark rapidity distributions and a slight narrowing of the anti-top rapidity distribution. Because of the symmetry of two proton beams there is no forward-backward asymmetry, but a charge asymmetry that is most pronounced at larger rapidities. Recently proposed new observables [79, 80]. with promising sensitivity for the LHC were also discussed in this meeting by Westhoff.

6 Top and New Physics

Nierste reviewed the status of limits on SUSY signals. For $g-2$ of the muon, the 3.6σ discrepancy with the Standard Model prediction would be alleviated by SUSY. He pointed out that certain off-diagonal elements of the squark mass matrix, in particular those involving the third generation, can lead to an enhanced single top production rate.

According to the MSSM, stops are among the most promising new particles to look for, being colored and thus having a large cross section, and being in most reasonable scenarios the lightest among the squarks. Spannowsky reviewed the reasoning behind this, and outlined various search strategies, which are generally in good shape. He pointed out that there are however gaps in parameter space, which given how central this search is for the ATLAS and CMS experiments, should be closed, and he discussed a number of strategies to do so.

Weiler reminded us of the attractiveness of the possibility of the Higgs boson being composite, and a pseudo-Goldstone boson of an enhanced symmetry. Drawing further inspiration from pion physics, this idea, if correct, would suggest fermionic symmetry partners of the top quark to be relatively light, below a TeV, and worth looking for.

The top-Higgs Yukawa coupling, discussed earlier in the context of $\bar{t}tH$ production, plays of course a direct role in the direct gluon fusion channel of Higgs production, through a top quark loop. Delaunay addressed the issue of how to extract information about possible New Physics contributions to this loop effect. Clearly, given the measured production rate being in fairly good agreement with the Standard Model, the net deviation is not very large, but this could be due to a cancellation of New Physics vertex and propagators effects. To pry apart this cancellation, one might look at Higgs plus one jet production, the contributions to which include diagrams where the extra gluon is emitted from within the New Physics loops, thereby disturbing the putative balance of NP propagator and vertex effects, and giving a handle on such New Physics.

Godbole pointed out the importance of angular distributions and kinematic distributions to probe for modifications of the top quarks couplings [81, 82]. With the scale of New Physics apparently high, an effective operator approach

$$\mathcal{L}^{\text{eff,BSM}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

seems the appropriate approach, which in turn causes such coupling modifications. Top produced in the decay of stops and sbottoms are polarized, and this may be used both in search strategies, and beyond that in determining the squark interactions [83]. For instance, if a Z' would polarize tops at production, the azimuthal asymmetry

$$A_\phi = \frac{\sigma(\cos\phi_l > 0) - \sigma(\cos\phi_l > 0)}{\sigma(\cos\phi_l > 0) + \sigma(\cos\phi_l > 0)}\,, \tag{13}$$

where ϕ_l is the azimuthal angle of the lepton with respect to the beam-top plane, would be sensitive to the amount of left-handed and right-handed coupling, even more so when judicious cuts on the p_T of the top are chosen. Also when a charged Higgs is present, such an asymmetry, would also discriminate [83] among Wt and H^-t production.

7 Top mass

Central to top quark physics is the meaning and value of its mass. The Tevatron experiments [84, 85] have measured the mass with an error of 0.87 GeV/c^2, *i.e.* to an accuracy of less than 0.5%; the LHC experiments [86] with an error of 0.95 GeV/c^2,

$$\begin{aligned} \text{CDF/D0}\,[8.7\,\text{fb}^{-1}]: &\quad 173.20 \pm 0.51(stat) \pm 0.71(sys)\,\text{GeV}/c^2\,, \\ \text{ATLAS/CMS}\,[4.9\,\text{fb}^{-1}]: &\quad 173.29 \pm 0.23(stat) \pm 0.92(sys)\,\text{GeV}/c^2\,. \end{aligned} \tag{14}$$

Together with an accurately measured W boson mass, a precisely known top mass severely constrains the mass range of the Higgs boson [87]. Indeed the measured Higgs boson mass seems quite consistent given present accuracies. Therefore its precise measurement is of considerable importance, and so also its careful definition. Given the measured mass of the Higgs boson, a precise determination of the top quark mass becomes especially interesting in the issue of the (meta)stability of the EW vacuum, as discussed by Shaposhnikov at this meeting.

A natural definition of an elementary particle mass is based on the location of the pole of the full quark propagator, i.e. the pole mass. After summing self-energy corrections the full propagator reads

$$\frac{1}{\not{p} - m_0 - \Sigma(p, m_0)}, \tag{15}$$

where Σ contains $1/\epsilon$ UV divergences from loop integrals. Renormalization now amounts to replacing the bare mass m_0 by an expression involving the renormalized mass m

$$m_0 = m\Big(1 + \frac{\alpha_s}{\pi}\Big[\frac{1}{\epsilon} + z_{finite}\Big]\Big), \tag{16}$$

after which the UV divergences cancel in (15). The choice of z_{finite} determines the scheme. Choosing it such that

$$\frac{1}{\not{p} - m_0 - \Sigma(p, m_0)} = \frac{c}{\not{p} - m} \tag{17}$$

defines the pole-mass scheme, which amounts to pretending that the particle can be free and long-lived. 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 $\mathcal{O}(\Lambda_{QCD})$ [88, 89, 90].

Experimentally, the top quark mass is reconstructed by collecting jets and leptons. The decay channels used are the dilepton channel - two isolated leptons with opposite charge and at least two jets[91, 92]; the lepton + jets channel - an isolated lepton and at least four jets[93, 94]; the all-hadronic channel[95, 96]. However, soft particles originating from both within and outside these jets may affect the reconstructed mass.

Although the experiments reconstruct the pole mass (or something close to it), theoretically it would be more desirable to have a short-distance mass, free of $\mathcal{O}(\Lambda_{QCD})$ ambiguities. Such is the $\overline{\mathrm{MS}}$ mass $\bar{m}(\mu)$ evaluated at some scale μ, whose relation to the pole mass is known to three loops in QCD[98]. For μ one often takes the implicit value found when intersecting the $\bar{m}(\mu)$ curve with the $\bar{m}(\mu) = \mu$ axis, yielding $\bar{m}(\bar{m})$.

Theoretical and MC aspects of the top mass were discussed in this meeting by Mangano, the theoretical aspects especially addressing ambiguities.

Numerically, the relation between the pole mass and the the $\overline{\mathrm{MS}}$ mass reads

$$m = \bar{m}(\bar{m}) \times (1 + 0.047 + 0.010 + 0.003)$$

each term corresponding to a loop order. The series shows excellent convergence. The remaining uncertainty is about 500 MeV, when assuming the asymptotic series starts diverging again. (The 4-loop result would be very interesting in order to test this issue.) Note that this still exceeds the non-perturbative ambiguity on the pole pole due to renormalon effects from infrared sensitive regions.

The $\overline{\mathrm{MS}}$ mass $\bar{m}(\mu)$ may be extracted more indirectly, through a proxy observable such as the inclusive cross section expressed in the $\overline{\mathrm{MS}}$ mass [99]. Mangano pointed out that this seems a very safe procedure, in contrast to e^+e^- collisions, as the IR sensitive region only contributes about a permille to the inclusive cross section, and that, to good accuracy, it seems safe to interpret the MC mass parameter as the pole mass.

He also proposed a different and interesting mass proxy: (twice) the end-point energy of the electron in a semi-leptonic decay in the top quark restframe. Uncertainties from b-jet reconstruction are greatly suppressed to well below the permille level. The difficulty will be however the reconstruction of the top quark rest frame, or more generally the top quark momentum.

8 Conclusions

Although discovery of the top quark is now nearly 20 years old, in a sense top quark physics as a field is just beginning. A flood of new, higher energy data are in the offing that will also challenge their theoretical description and interpretation. The severe constraints of precise measurement, the entry of the Higgs boson and its strong interaction with the top quark sector, are inspiring not only remarkable increases in theoretical accuracy and the developments of methods thereto, but also novel ideas from New Physics modelling to enhancing data analysis methods. Therefore, in spite of the occasional rain at this conference, the outlook for top quark physics seems very bright indeed.

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References

[1] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. -S. Shao and T. Stelzer *et al.*, JHEP **1407** (2014) 079, arXiv:1405.0301 [hep-ph].

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

[3] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B **327** (1989) 49 [Erratum-ibid. B **335** (1990) 260].

[4] W. Beenakker, H. Kuijf, W. L. van Neerven and J. Smith, Phys. Rev. D **40** (1989) 54.

[5] W. Beenakker, W. L. van Neerven, R. Meng, G. A. Schuler and J. Smith, Nucl. Phys. B **351** (1991) 507.

[6] M. L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B **373** (1992) 295.

[7] S. Frixione and B. R. Webber, JHEP **0206** (2002) 029, hep-ph/0204244.

[8] S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003) 007, hep-ph/0305252.

[9] P. Nason, JHEP **0411** (2004) 040, hep-ph/0409146.

[10] S. Frixione, P. Nason and C. Oleari, JHEP **0711** (2007) 070, arXiv:0709.2092 [hep-ph].

[11] P. Brnreuther, M. Czakon and A. Mitov, Phys. Rev. Lett. **109** (2012) 132001, arXiv:1204.5201 [hep-ph].

[12] M. Czakon and A. Mitov, JHEP **1212** (2012) 054, arXiv:1207.0236 [hep-ph].

[13] M. Czakon and A. Mitov, JHEP **1301** (2013) 080, arXiv:1210.6832 [hep-ph].

[14] M. Czakon, P. Fiedler and A. Mitov, Phys. Rev. Lett. **110** (2013) 25, 252004, arXiv:1303.6254 [hep-ph].

[15] M. Czakon, Nucl. Phys. B **849** (2011) 250, arXiv:1101.0642 [hep-ph].

[16] M. Czakon, Nucl. Phys. B **849** (2011) 250, arXiv:1101.0642 [hep-ph].

[17] G. Abelof and A. Gehrmann-De Ridder, JHEP **1104** (2011) 063, arXiv:1102.2443 [hep-ph].

[18] W. Bernreuther, C. Bogner and O. Dekkers, JHEP **1106** (2011) 032, arXiv:1105.0530 [hep-ph].

[19] S. Dittmaier, P. Uwer and S. Weinzierl, Phys. Rev. Lett. **98** (2007) 262002, hep-ph/0703120.

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

[21] M. Czakon, A. Mitov and S. Moch, Phys. Lett. B **651** (2007) 147, arXiv:0705.1975 [hep-ph].

[22] M. Czakon, A. Mitov and S. Moch, Nucl. Phys. B **798** (2008) 210, arXiv:0707.4139 [hep-ph].

[23] W. Bernreuther, R. Bonciani, T. Gehrmann, R. Heinesch, T. Leineweber, P. Mastrolia and E. Remiddi, Nucl. Phys. B **706** (2005) 245, hep-ph/0406046.

[24] R. Bonciani, A. Ferroglia, T. Gehrmann, A. von Manteuffel and C. Studerus, JHEP **1101** (2011) 102, arXiv:1011.6661 [hep-ph].

[25] P. Brnreuther, M. Czakon and P. Fiedler, JHEP **1402** (2014) 078, arXiv:1312.6279 [hep-ph].

[26] M. Czakon, M. L. Mangano, A. Mitov and J. Rojo, JHEP **1307** (2013) 167, arXiv:1303.7215 [hep-ph].

[27] N. Kidonakis, E. Laenen, S. Moch and R. Vogt, Phys. Rev. D **64** (2001) 114001, hep-ph/0105041.

[28] G. F. Sterman and W. Vogelsang, JHEP **0102** (2001) 016, hep-ph/0011289.

[29] M. Czakon, A. Mitov and G. F. Sterman, Phys. Rev. D **80** (2009) 074017, arXiv:0907.1790 [hep-ph].

[30] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. -L. Yang, JHEP **1109** (2011) 070, arXiv:1103.0550 [hep-ph].

[31] M. Beneke, P. Falgari, S. Klein and C. Schwinn, Nucl. Phys. B **855** (2012) 695, arXiv:1109.1536 [hep-ph].

[32] N. Kidonakis, Phys. Rev. D **82** (2010) 114030, arXiv:1009.4935 [hep-ph].

[33] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. L. Yang, Phys. Lett. B **703** (2011) 135, arXiv:1105.5824 [hep-ph].

[34] T. E. W. Group [CDF and D0 Collaborations], arXiv:0908.2171 [hep-ex].

[35] T. A. Aaltonen *et al.* [CDF and D0 Collaborations], Phys. Rev. Lett. **112** (2014) 231803, arXiv:1402.5126 [hep-ex].

[36] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **726** (2013) 656, arXiv:1307.0731 [hep-ex].

[37] B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan and S. Weinzierl, Phys. Rev. D **66** (2002) 054024, hep-ph/0207055.

[38] Q. -H. Cao, R. Schwienhorst and C. -P. Yuan, Phys. Rev. D **71** (2005) 054023, hep-ph/0409040.

[39] Q. -H. Cao, R. Schwienhorst, J. A. Benitez, R. Brock and C. -P. Yuan, Phys. Rev. D **72** (2005) 094027, hep-ph/0504230.

[40] J. M. Campbell, R. K. Ellis and F. Tramontano, Phys. Rev. D **70** (2004) 094012, hep-ph/0408158.

[41] J. M. Campbell and F. Tramontano, Nucl. Phys. B **726** (2005) 109, hep-ph/0506289.

[42] N. Kidonakis, Phys. Rev. D **74** (2006) 114012, hep-ph/0609287.

[43] J. M. Campbell, R. Frederix, F. Maltoni and F. Tramontano, JHEP **0910** (2009) 042, arXiv:0907.3933 [hep-ph].

[44] N. Kidonakis, Phys. Rev. D **83** (2011) 091503, arXiv:1103.2792 [hep-ph].

[45] S. Frixione, E. Laenen, P. Motylinski and B. R. Webber, JHEP **0603** (2006) 092, hep-ph/0512250.

[46] S. Alioli, P. Nason, C. Oleari and E. Re, JHEP **0909** (2009) 111 [Erratum-ibid. **1002** (2010) 011], arXiv:0907.4076 [hep-ph].

[47] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **85** (2012) 091104, arXiv:1201.4156 [hep-ex].

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

[49] E. Re, Eur. Phys. J. C **71** (2011) 1547, arXiv:1009.2450 [hep-ph].

[50] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 142, arXiv:1205.5764 [hep-ex].

[51] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **110** (2013) 022003, arXiv:1209.3489 [hep-ex].

[52] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **112** (2014) 231802, arXiv:1401.2942 [hep-ex].

[53] S. Zhu, Phys. Lett. B **524** (2002) 283 [Erratum-ibid. B **537** (2002) 351].

[54] Q. -H. Cao, arXiv:0801.1539 [hep-ph].

[55] C. D. White, S. Frixione, E. Laenen and F. Maltoni, JHEP **0911** (2009) 074, arXiv:0908.0631 [hep-ph].

[56] A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, Phys. Rev. Lett. **106** (2011) 052001, arXiv:1012.3975 [hep-ph].

[57] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, JHEP **1102** (2011) 083, arXiv:1012.4230 [hep-ph].

[58] A. S. Papanastasiou, R. Frederix, S. Frixione, V. Hirschi and F. Maltoni, Phys. Lett. B **726** (2013) 223, arXiv:1305.7088 [hep-ph].

[59] P. Falgari, F. Giannuzzi, P. Mellor and A. Signer, Phys. Rev. D **83** (2011) 094013, arXiv:1102.5267 [hep-ph].

[60] S. Frixione, E. Laenen, P. Motylinski and B. R. Webber, JHEP **0704** (2007) 081, hep-ph/0702198.

[61] O. Kind, these proceedings.

[62] J. van der Heide, E. Laenen, L. Phaf and S. Weinzierl, Phys. Rev. D **62** (2000) 074025, hep-ph/0003318.

[63] W. Beenakker, R. Hopker, M. Spira and P. M. Zerwas, Nucl. Phys. B **492** (1997) 51, hep-ph/9610490.

[64] W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper, M. Spira and P. M. Zerwas, Nucl. Phys. B **653** (2003) 151, hep-ph/0211352.

[65] P. Artoisenet, R. Frederix, O. Mattelaer and R. Rietkerk, JHEP **1303** (2013) 015, arXiv:1212.3460 [hep-ph].

[66] M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP **1305** (2013) 022, arXiv:1211.3736 [hep-ph].

[67] J. H. Kuhn and G. Rodrigo, Phys. Rev. D **59** (1999) 054017, hep-ph/9807420.

[68] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **101** (2008) 202001, arXiv:0806.2472 [hep-ex].

[69] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **83** (2011) 112003, arXiv:1101.0034 [hep-ex].

[70] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100** (2008) 142002, arXiv:0712.0851 [hep-ex].

[71] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84** (2011) 112005, arXiv:1107.4995 [hep-ex].

[72] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **88** (2013) 11, 112002, arXiv:1308.6690 [hep-ex].

[73] A. Chapelain [D0 Collaboration], arXiv:1311.6731 [hep-ex].

[74] L. G. Almeida, G. F. Sterman and W. Vogelsang, Phys. Rev. D **78** (2008) 014008, arXiv:0805.1885 [hep-ph].

[75] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. L. Yang, Phys. Rev. D **84** (2011) 074004, arXiv:1106.6051 [hep-ph].

[76] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **87** (2013) 092002, arXiv:1211.1003 [hep-ex].

[77] S. Westhoff, these proceedings.

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

[79] S. Berge and S. Westhoff, Phys. Rev. D **86** (2012) 094036, arXiv:1208.4104 [hep-ph].

[80] S. Berge and S. Westhoff, JHEP **1307** (2013) 179, arXiv:1305.3272 [hep-ph].

[81] R. M. Godbole, K. Rao, S. D. Rindani and R. K. Singh, JHEP **1011** (2010) 144, arXiv:1010.1458 [hep-ph].

[82] D. Choudhury, R. M. Godbole, S. D. Rindani and P. Saha, Phys. Rev. D **84** (2011) 014023, arXiv:1012.4750 [hep-ph].

[83] R. M. Godbole, L. Hartgring, I. Niessen and C. D. White, JHEP **1201** (2012) 011, arXiv:1111.0759 [hep-ph].

[84] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **109** (2012) 152003, arXiv:1207.6758 [hep-ex].

[85] M. Muether [Tevatron Electroweak Working Group and CDF and D0 Collaborations], arXiv:1305.3929 [hep-ex].

[86] ATLAS Collaboration, CMS Collaboration, ATLAS-CONF-2013-102, CMS-PAS-TOP-13-005.

[87] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, R. Kogler, K. Moenig and M. Schott *et al.*, Eur. Phys. J. C **72** (2012) 2205, arXiv:1209.2716 [hep-ph].

[88] M. Beneke and V. M. Braun, Nucl. Phys. B **426** (1994) 301, hep-ph/9402364.

[89] I. I. Y. Bigi, M. A. Shifman, N. G. Uraltsev and A. I. Vainshtein, Phys. Rev. D **50** (1994) 2234, hep-ph/9402360.

[90] M. C. Smith and S. S. Willenbrock, Phys. Rev. Lett. **79** (1997) 3825, hep-ph/9612329.

[91] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2202, arXiv:1209.2393 [hep-ex].

[92] ATLAS Collaboration, ATLAS-CONF-2013-077.

[93] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **72** (2012) 2046, arXiv:1203.5755 [hep-ex].

[94] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1212** (2012) 105, arXiv:1209.2319 [hep-ex].

[95] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **74** (2014) 2758, arXiv:1307.4617 [hep-ex].

[96] ATLAS Collaboration, ATLAS-CONF-2012-030.

[97] A. H. Hoang and I. W. Stewart, Nucl. Phys. Proc. Suppl. **185** (2008) 220, arXiv:0808.0222 [hep-ph].

[98] K. Melnikov and T. v. Ritbergen, Phys. Lett. B **482** (2000) 99, hep-ph/9912391.

[99] U. Langenfeld, S. Moch and P. Uwer, Phys. Rev. D **80** (2009) 054009, arXiv:0906.5273 [hep-ph].