

TOP 2014: Experimental Summary

Christian Schwanenberger

The University of Manchester, Oxford Road, Manchester, M13 9PL, UK;
now: Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, D-22607 Hamburg, Germany

E-mail: christian.schwanenberger@cern.ch

Abstract. A summary of the experimental results of the TOP2014 International Workshop in Cannes, France, is presented. This inspiring conference clearly showed the richness and diversity of top-quark physics research. Results cover a very broad spectrum of analyses involving studies of the strong and electroweak interactions of the top quark, high-precision measurements of intrinsic top-quark properties, developments of new tools in top-quark analyses, observations of new Standard Model processes, the interaction between the top quark and the Higgs boson and sensitive searches for new physics beyond the Standard Model.

1. Introduction

The top quark, discovered in 1995 at the Fermilab $p\bar{p}$ collider Tevatron, is the most recent member of the known families of quarks. The Large Hadron pp collider (LHC) is a top-quark factory providing high-precision access to top-quark physics. Although this particle appears to have no substructure and to be pointlike, its mass is of the order of a gold nucleus. Therefore it is believed to be closely related to the mechanism of mass generation together with the Higgs boson. Thus, to test our current theory of elementary particles in detail, it is of particular importance to measure the properties of the top quark precisely, to analyze its strong and electroweak interactions and to investigate its interaction with the Higgs boson. Because of its potentially special role, the top quark might be exotic in some way, and could offer a first glimpse of physics beyond the Standard Model (SM). Therefore, it is important to perform both direct searches in the top-quark sector and indirect searches for new physics through high-precision measurements of top-quark cross sections and properties. In this proceeding recent results from the Tevatron collider at a center-of-mass energy (CME) of 1.96 TeV and from the LHC at a CME of 7 and 8 TeV are highlighted.

2. Top-quark-pair production and QCD studies

At the Tevatron and the LHC, top quarks are produced in pairs via the strong interaction and singly via the electroweak interaction. It is interesting to measure the total production cross sections in all possible final states, since the impact of potential new physics could be different in different channels. In top-quark-pair production all possible final states involving leptons, jets and missing transverse momentum have been measured by the two colliders except for final states with two hadronically decaying tau leptons [1]. The results are in agreement with the predictions in next-to-next-to-leading order (NNLO) quantum chromodynamics (QCD) including next-to-next-to leading log (NNLL) corrections [2]. The different measurements are shown as a function of the CME in Fig. 1a.

More elaborate tests of QCD than these extrapolated inclusive cross-section measurements are performed by measuring differential distributions [3]. To make these measurements more usable for comparisons with calculations both today and in the future, it is advisable to unfold the differential distributions and to give the results also explicitly for the selected phase space where the measurement has actually been performed. The distributions in data provide important information when comparing them to QCD calculations and Monte Carlo (MC) simulations. As an example, Figs. 1b and 1c show the distribution of the top-quark transverse momentum in $t\bar{t}$ production and single top quark t -channel production, respectively. While the data is in agreement with the predictions of MC simulations for single-top-quark production, for $t\bar{t}$ production in measurements of both LHC collaborations the data distribution is softer than predicted for higher values of the top-quark transverse momentum [3].

It is particularly interesting to study differential cross sections in terms of kinematic variables of a top-quark proxy referred to as the “pseudo-top quark” whose dependence on theoretical models is minimal. Observables of pseudo-top quarks are constructed from objects that are directly related to detector-level observables. Figure 1d shows the differential cross section as a function of the hadronically decaying pseudo-top-quark transverse momentum. Differences between data and simulations similar to those in Fig. 1b are observed and still have to be understood.

3. Single-top-quark production and electroweak couplings

Single top quarks are produced in $p\bar{p}$ and pp scattering at tree level via the electroweak interaction in the t -channel via the exchange of a space-like virtual W boson between a light quark and a bottom quark, in the s -channel via the decay of a time-like virtual W boson produced by quark-antiquark annihilation, which produces a top quark and a bottom quark, or in association with a W boson (Wt). Recently the Tevatron collaborations have observed s -channel production [4], ATLAS has found evidence for Wt associated production, followed by an observation of Wt production at the CMS experiment [5]. Now all different single-top-quark production subchannels are observed. Figure 1e and 1f show the cross-section measurements of the Tevatron and the LHC, respectively, for different subchannels which are all in agreement with the SM predictions [6].

Other SM processes which have not yet been observed but which are important since they are sensitive to the electroweak tZ and tW couplings are $t\bar{t}Z$ and $t\bar{t}W$ production. The most sensitive search channels involve three leptons ($t\bar{t}Z$) and two same-sign leptons ($t\bar{t}W$) in the final state. Evidence for both processes has recently been claimed at the LHC using the full 8 TeV datasets [7]. The extracted cross sections are in agreement with the SM predictions.

4. Systematic uncertainties and new tools in top-quark physics

There are many new developments to understand systematic uncertainties in top-quark measurements presented at this conference [8]. For example, new investigations for a better understanding of the energy scale of jets induced by b quarks, of the uncertainties of parton density functions and of modeling uncertainties in MC simulations have been discussed in detail. The large efforts to combine many different measurements between the LHC experiments [9] and between the LHC experiments and the Tevatron experiments [10], has led to a very fruitful collaboration among all experiments which is indispensable for a detailed understanding of systematic uncertainties in top-quark analyses in general.

There is also huge progress in the developments of new tools in top-quark physics [11]. As an example, top-quark taggers in boosted top-quark regimes have made fast progress moving quickly from the R&D phase to highly sophisticated performance studies to optimize top-quark-tagging efficiency and purity. They are utilized, for example, in searches for $t\bar{t}$ resonances (see Fig. 3c) and differential cross-section measurements for highly-boosted top quarks [12].

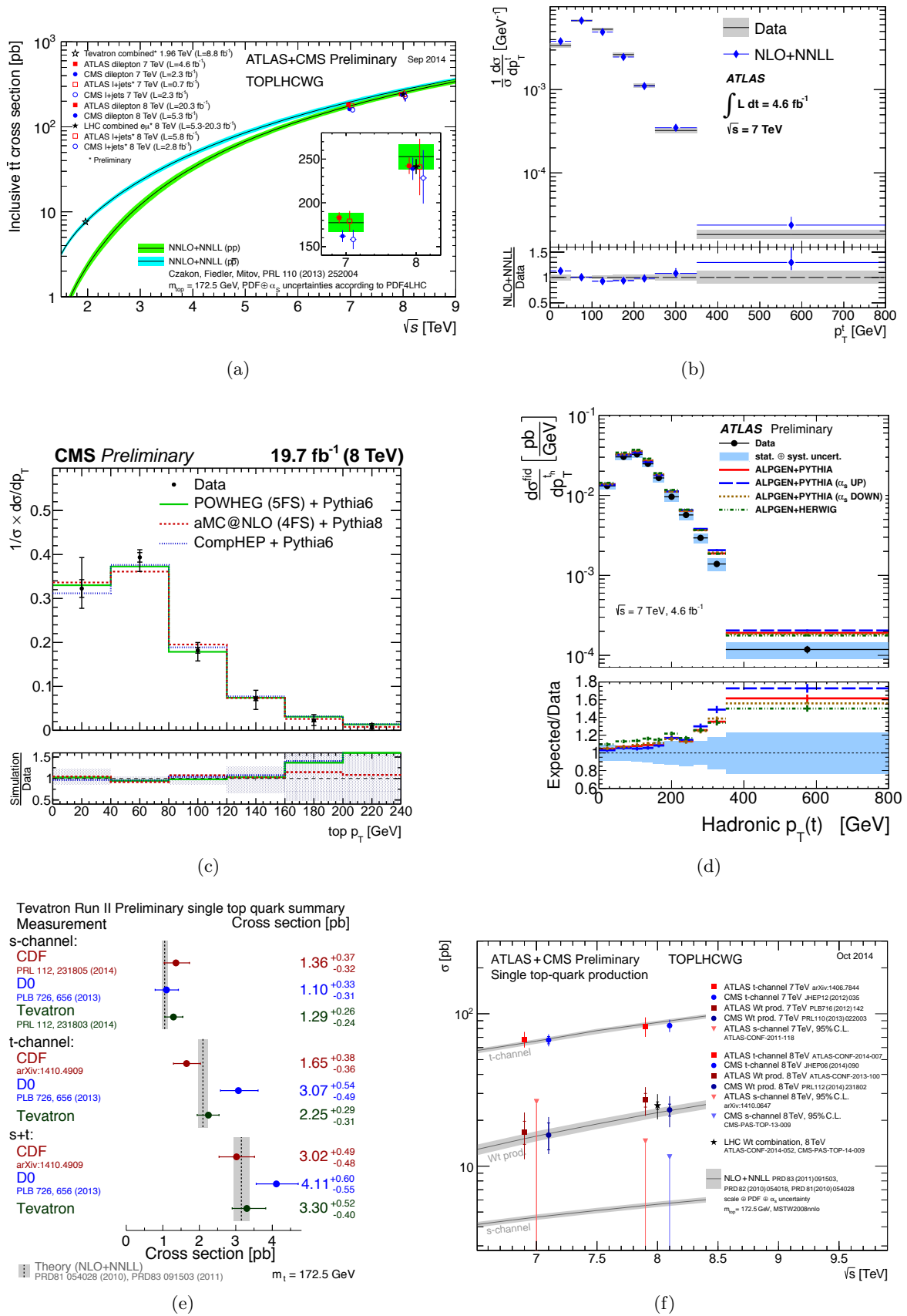


Figure 1. Top-quark production: (a) Summary of LHC and Tevatron measurements of the total $t\bar{t}$ cross section as a function of the CME compared to the NNLO+NNLL QCD calculation; (b) normalized differential cross sections for the transverse momentum of the hadronically decaying top-quark p_T^t at 7 TeV ($t\bar{t}$) and (c) at 8 TeV (single top quark) and (d) for hadronic pseudo-top quarks at 7 TeV ($t\bar{t}$); (e) single-top-quark production cross sections in various channels at the Tevatron at 1.96 TeV and (f) as a function of the CME at the LHC compared to NLO+NNLL QCD calculations.

5. Top-quark properties

High precision measurements of top-quark properties are essential since they could be the key to find new physics in the top-quark sector by comparing the results to the SM predictions.

The top-quark mass is a free parameter in the SM. High accuracy in the measurement of the top-quark mass is very important since in combination with the measurements of the mass of the W boson and the mass of the Higgs boson the self-consistency of the SM can be tested. The current world average combining measurements from the Tevatron and the LHC gives $m_t = 173.34 \pm 0.76$ GeV ($\pm 0.44\%$) [10]. Since then, new measurements have been performed that are not yet included in the world average. The most precise new measurements are from the D0 Collaboration, $m_t = 174.94 \pm 0.76$ GeV ($\pm 0.44\%$) [13], and the CMS Collaboration, $m_t = 172.04 \pm 0.77$ GeV ($\pm 0.45\%$) [14]. Investigations to understand the tension between these two results are ongoing. Detailed theoretical investigations of how the measured masses calibrated by different MC simulations translate into quantum-field-theoretically well-defined mass parameters are ongoing, as well as studies of how $WbWb$ off-shell effects can affect the measurements.

In a new measurement of the $t\bar{t}$ cross section in $e\mu$ final states the top-quark mass is determined via the dependence of the predicted cross section on the top-quark pole mass [15]. This result extracts, for the first time, unambiguously the top-quark pole mass since the experimental acceptance and therefore the extracted cross section is basically constant as a function of the assumed mass, and therefore the question of the difference between extracted mass and pole mass becomes insignificant. The result is presented in Fig. 2a. The extracted top-quark pole mass is $m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV. At a future linear collider such as the ILC, however, it is expected to measure a well-defined top-quark mass at the $t\bar{t}$ -production threshold with an uncertainty of the order of 100 MeV [16] which will be very significant progress.

Many important and interesting measurements of other top-quark properties in both $t\bar{t}$ and single-top-quark production have been presented at this conference [17]. The results involve, for example, measurements of $t\bar{t}$ spin correlation (see Fig. 2b), top-quark polarization in $t\bar{t}$ production (see Fig. 2c) and in single-top-quark production (see Fig. 2d), W -boson helicity fractions extracted in top-quark decays in $t\bar{t}$ and single-top-quark production (for the latter see Fig. 2e), searches for CP-violation, searches for anomalous top-quark couplings and many more. All results agree with the SM predictions.

Deviations between measurement and prediction of the top-antitop-quark forward-backward asymmetry and the $t\bar{t}$ charge asymmetry at the Tevatron have caused lots of interest in our field in recent years. Similar analyses of the charge asymmetry in $t\bar{t}$ events at the LHC show agreement between data and prediction. Furthermore, measurements of such asymmetries are performed in $b\bar{b}$ production at the Tevatron and at the LHCb experiment and are in agreement with the SM prediction, too. At the Tevatron the measurements were repeated with the full dataset and the analyses were improved in accuracy with the aim of increasing the potential to discover new physics. As a result the new measurements in the lepton+jets and dilepton channels exploring the full Tevatron dataset agree with recent SM predictions [18]. This is summarized in Fig. 2f.

6. Top quark interaction with the Higgs boson

Because of the large mass of the top quark and since the largest quantum corrections to the Higgs-boson mass involves a top-quark loop, the top quark is believed to be closely related to the mechanism of mass generation together with the Higgs boson. Thus, to test our current theory of elementary particles in detail, it is of particular importance to investigate top-quark interactions with the Higgs boson. At the LHC this can be studied in associated $t\bar{t}H$ production [19]. Here, $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW, ZZ$ (leading to multilepton final states) and $H \rightarrow \tau\tau$ final states are investigated with currently the most sensitive channel being the first one. The information

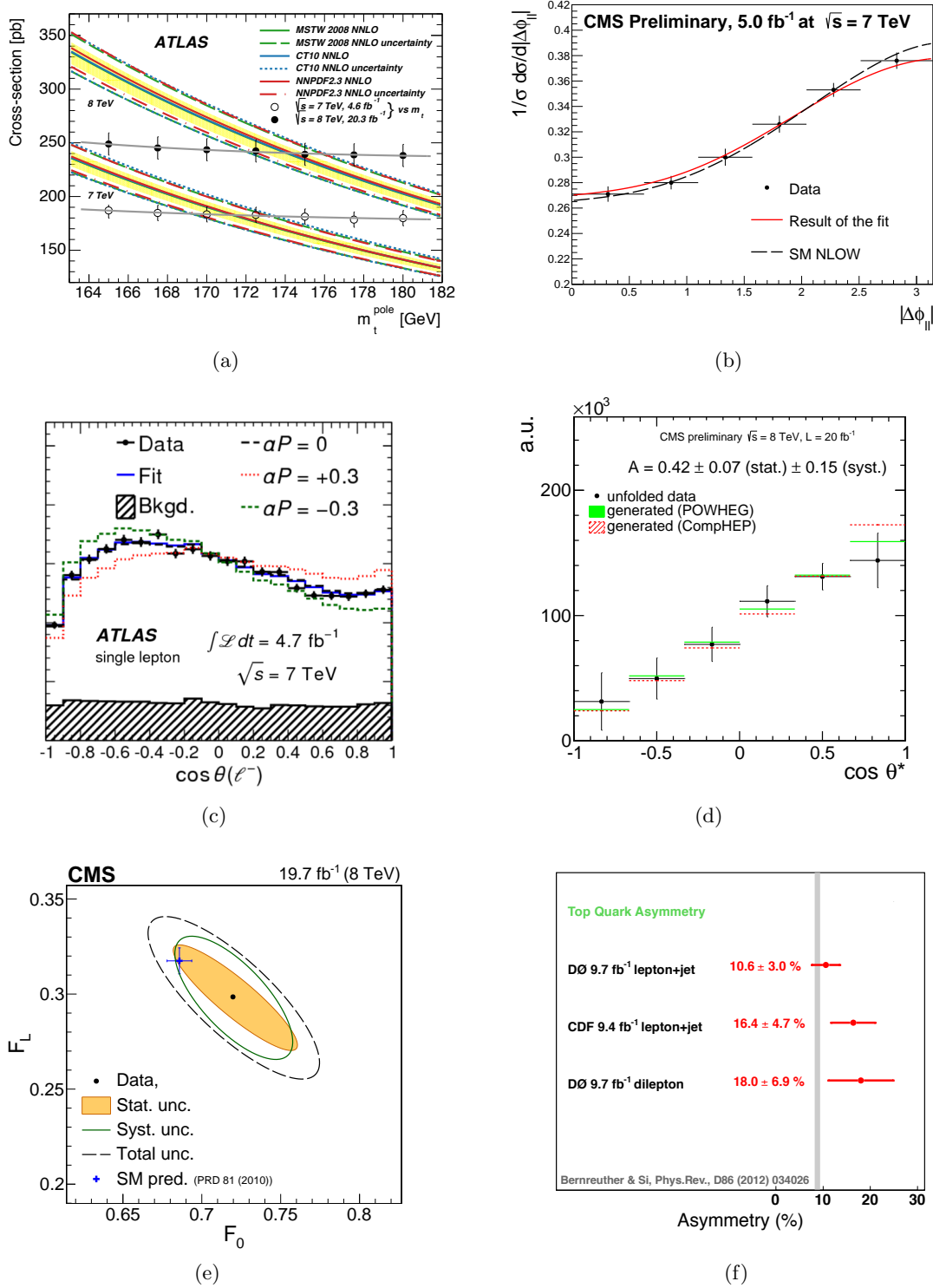


Figure 2. Top-quark property measurements: (a) $\sigma_{t\bar{t}}$ at 7 and 8 TeV as a function of the assumed value of m_t compared to NNLO+NNLL predictions as a function of m_t^{pole} ; (b) the differential cross section as a function of the difference in azimuthal angle of the two leptons in $t\bar{t}$ dilepton production as observed in data and predicted by the SM (dashed curve) at 7 TeV; (c) top-quark polarization distribution compared to the SM prediction of zero polarization and to non-vanishing polarization hypotheses in $t\bar{t} e^-, \mu^- + \text{jets}$ final states at 7 TeV; (d) unfolded distribution of the top-quark polarization in single t -channel top-quark production at 8 TeV in data and SM predictions; (e) extracted left-handed and longitudinal W boson helicity fractions from single-top-quark events at 8 TeV, shown as 68% contours for statistical, systematic, and total uncertainties, compared to the SM prediction; (f) summary of $t\bar{t}$ forward-backward asymmetry measurements using the full Tevatron dataset.

of many observables sensitive to separate between signal and background is combined using multivariate analysis techniques, such as the construction of neural networks (NN). An example NN output distribution in the single-lepton $H \rightarrow b\bar{b}$ search from the ATLAS experiment is presented in Fig. 3a. This shows that good separation between signal (concentrated at large values) and background (concentrated at low values) is achieved.

A summary of all searches for $t\bar{t}H$ production from the CMS experiment is shown in Fig. 3b. Similar results exist from the ATLAS Collaboration. All results are in agreement with the SM prediction. The CMS Collaboration has found an excess above the background-only expectation of 3.4 standard deviations. Furthermore, searches for tHq production where the cross section can be enhanced due to anomalous contributions to the top-Yukawa coupling are performed [20]. No hint for new physics is found.

7. Searches for new physics in the top quark sector

Due to the potentially special role of the top quark in electroweak symmetry breaking, the top quark might be connected to physics beyond the SM. New physics might show up in the data directly as bumps in mass distributions but it could also be found through deviations from the SM in high-precision top-quark-property measurements, for example, as a consequence of anomalous couplings or due to the existence of new Supersymmetric (SUSY) particles. At this conference, examples of both direct searches for new physics studying kinematic properties and indirect searches through high precision measurements of top-quark properties were presented.

For example, direct searches for $t\bar{t}$ resonances and heavy Z' bosons (see Fig. 3c), heavy W' bosons, vector-like heavy T' and B' quarks, excited top quarks, tb resonances and dark matter (see Fig. 3d) were performed. No hint for new physics was found [21].

The LHC collaborations also perform a wide program of searching for the SUSY scalar partner of the top quark, the top squark [22]. Large regions in the parameter space given by the top-squark mass and the mass of the lightest SUSY particle (LSP) are excluded in direct searches exploiting kinematic differences. If, however, the LSP (for example a neutralino $\tilde{\chi}_1^0$) is light and the top-squark mass is only slightly larger than the top-quark mass, two-body decays $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ in which the momentum of $\tilde{\chi}_1^0$ is very small can predominate. In this area the kinematics of top-squark-pair production event candidates look very similar to those from $t\bar{t}$ production, and direct searches are therefore not sensitive. Events with top-squark pairs, however, can be distinguished from $t\bar{t}$ events through an increase of the measured $t\bar{t}$ cross section, and since top squarks have zero spin, through measuring angular correlations sensitive to spin correlation. As a result, top-squark-pair production has not been detected, but a region for low LSP masses and top-squark masses close to the top-quark mass are excluded which is complementary to regions excluded by direct searches [22]. This is shown by the red triangle in Fig. 3e. This is an example of using a "SM candle" to probe for new physics beyond.

Finally, searches for anomalous couplings and flavor-changing neutral-current (FCNC) couplings are of particular interest. No hint for the existence of such couplings has been found so far [23]. The respective LHC limits on FCNC branching ratios in $t \rightarrow qZ$ and $t \rightarrow q\gamma$ decays are complementary to results from the LEP e^+e^- collider, the HERA ep collider and the Tevatron $p\bar{p}$ collider as can be seen in Fig. 3f. Typical models beyond the SM may give rise to FCNC branching ratios at the level of $\text{BR} < 10^{-4}$. To be sensitive enough to probe such models a High Luminosity LHC [24] or a future circular e^+e^- collider [25], for example, would be needed.

8. Conclusions

Many exciting results covering a very broad spectrum of particle physics research were presented at the TOP 2014 Conference. Particular highlights were high precision measurements of top-quark production cross sections, the top-quark mass, top-quark couplings and many more top-quark properties. Furthermore, the developments of high precision theory tools, such as

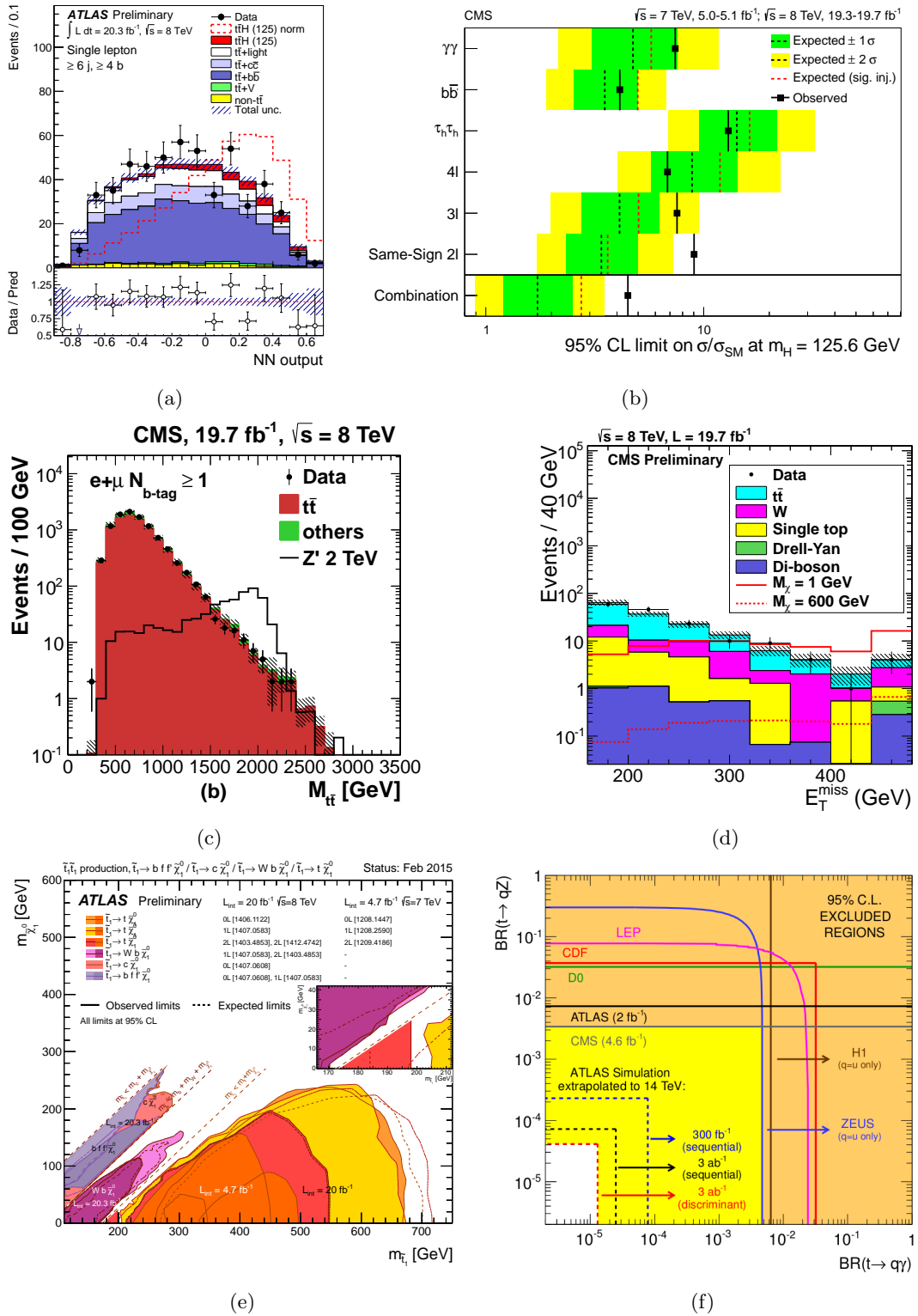


Figure 3. Searches in the top-quark sector: (a) Example NN output distribution to search $t\bar{t}H$ production in single-lepton final states with at least six jets and at least four b -tagged jets at 8 TeV. Data is compared to different backgrounds (colored histograms) and the $t\bar{t}H$ signal (dashed line); (b) limit at the 95% confidence level (CL) on the extracted $t\bar{t}H$ cross section normalized by the SM prediction for different Higgs-boson decay channels combining data taken at 7 and 8 TeV; (c) distribution of invariant $t\bar{t}$ mass using reconstructed using a scheme optimized for boosted top quarks to search for $t\bar{t}$ resonances in lepton+jets final states. Data at 8 TeV are compared to backgrounds (colored histograms) and to a $Z' \rightarrow t\bar{t}$ production signal example (solid line); (d) missing transverse energy distribution in a search for dark matter produced in association with a pair of top quarks. Data is compared to background (colored histograms) and two examples of simulated dark-matter signals with a mass of 1 GeV (solid line) and 600 GeV (dotted line) and an interaction scale of 100 GeV; (e) summary of exclusion limits for various modes of top-squark decay. The red triangle illustrates the limit derived from the spin-correlation measurement; (f) observed limits at 95% CL on the branching ratios in searches for FCNC $t \rightarrow qZ$ and $t \rightarrow q\gamma$ decays at different collider experiments (solid lines). Limits expected by ATLAS with 300 fb^{-1} or 3 ab^{-1} of integrated luminosity are added (dashed lines).

NLO+multileg MC simulations and even first calculations at NNLO QCD are just breathtaking, and clearly the experimental analyses profit from this significantly [26]. There are vast improvements in understanding theoretical uncertainties, combining results and developing tools such as top-tagging algorithms. This allows us, for example, to perform high-precision tests of QCD using unfolded differential distributions measured in fiducial regions of the detector that can directly be compared to theoretical calculations. Many new top-quark property measurements exist now utilizing both single-top-quark and $t\bar{t}$ production events. To understand the current differences in top-quark-mass measurements of different experiments is an important challenge to perform in the near future. Moreover, new SM processes were observed for the first time such as s -channel single-top-quark production and Wt production. Evidence was found for SM $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}H$ production. Furthermore, sensitive searches for new physics in the top-quark sector are performed in complementary ways, by traditional direct searches exploring kinematic properties and also by performing high-precision measurements of top-quark properties. However, so far all results agree with the SM predictions.

At the LHC Run-II, top-quark physics will become even more exciting, with more SM processes to be observed, many high-precision property and cross-section measurements to be performed, electroweak and Yukawa couplings to be extracted, and hopefully new physics to be discovered and explored.

Acknowledgments

I thank the organizers of Top 2014 for this exciting, very well-organized conference at this beautiful place at the Côte d’Azur, the speakers for their excellent presentations and the conveners for their ability to create an inspiring discussion atmosphere. I am grateful that I was honored to give the experimental summary presentation of the conference representing so many brilliant results. I am thankful to The Royal Society (UK) for the support of my research.

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