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Top Properties and Asymmetry measurements at the LHC

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More than 100 million top quarks were produced during Run 2 of the LHC. With this data set the ATLAS and CMS collaborations are able to measure a broad spectrum of different properties of the top quark. In addition, limits on various different models for physics beyond the standard model can be set by probing the couplings of the top quark. This talk presents the latest results of these measurements by both collaborations at the LHC.

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With the end of Run 2 of the LHC, both the ATLAS [1] and CMS [2] Collaboration have accumulated around 140 fb^{-1} of proton-proton collision data at a center-of-mass energy of $\sqrt{s} =$ 13 TeV. This data set allows to select events of top quark production with a high purity, yet with a sufficient amount of events, to measure a multitude of different properties of the top quark.

The top quark mass is probably the most prominent property of the top quark, measured historically in many different channels. However, with the ever increasing data set the accuracy of measurements is not anymore limited by the limited size of the data set, but by the systematic uncertainties, of which uncertainties related to jets are the most limiting factor on the experimental side. The ATLAS Collaboration has therefore made a measurement of the top quark mass using only leptonic observables [3]. This is made possible by not measuring the b jet from the top quark decay, but rather measuring the soft lepton stemming from a b hadron decay inside the b jet. A template fit to the invariant mass distribution of the dilepton system, which is derived from the prompt lepton of the W boson decay and the nonprompt lepton of the b hadron decay, for different top quark mass hypotheses yields a result of

$$m_{\mathrm{t}} = 174.48 \pm 0.40(\mathrm{stat}) \pm 0.67(\mathrm{syst})\,\mathrm{GeV}. \quad (1)$$

The sensitivity of the measurement strongly depends on the heavy flavor decay modeling, the pileup and the b fragmentation.

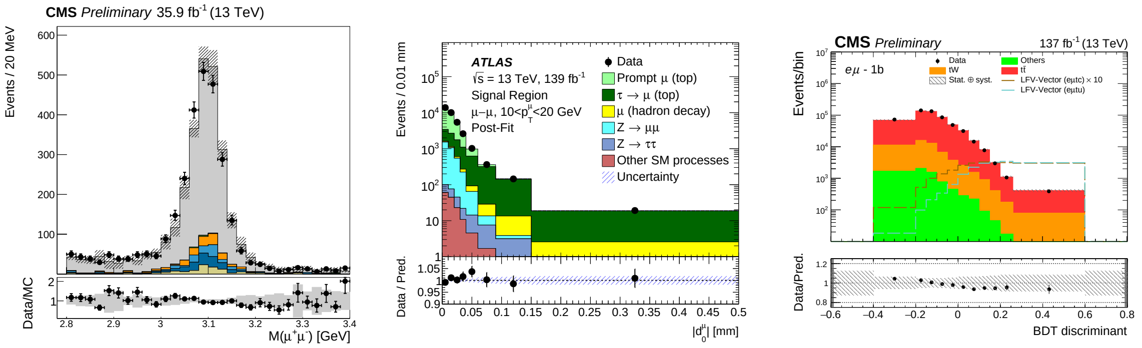
Given the dependence on accurate b fragmentation modeling of this top quark mass measurement, the ATLAS Collaboration has measured various kinematic variables that are sensitive to quark fragmentation modeling [4]. The results are unfolded to particle level and compared to different simulation settings and types of simulation. It was found that overall the nominal simulation describes the data best on average, while different programs or settings in the simulation are able to achieve better description of single variables isolated.

The CMS Collaboration instead has measured the r_b parameter in the Lund-Bowler fragmentation model directly by reconstructing J/ψ and D^0 decays inside b jets [5]. The reconstructed mass of J/ψ candidates from two muons is shown in Fig. 1a. This is the first time that the b fragmentation function has been measured in top quark pair events at the LHC. The measured value of

$$r_b = 0.858 \pm 0.037(\mathrm{stat}) \pm 0.031(\mathrm{syst}) \quad (2)$$

is in agreement with the value used in Pythia 8 (Monash tune) of $r_b = 0.855$ [6]. The sensitivity is significantly improved with respect to previous measurements that rely on data from lepton colliders at the Z boson mass. Furthermore, no environmental dependence on the initial state is found. Most dominant systematic uncertainties are the number of simulated events, the fit procedure and the shape modeling from Pythia 8.

In the standard model (SM) the coupling of leptons to the weak gauge bosons is universal, meaning the coupling does not depend on the flavor of the lepton. This principle can be tested in different ways. The ATLAS Collaboration has performed a measurement of the ratio of branching fractions from W boson to tau lepton decays and to muons decays in the production of top quark pair events [7]. This is achieved by measuring the impact parameter distribution of muons, which allows to separate events with muons from prompt W boson decays and muons from subsequent W boson to tau lepton decays. An exemplary distribution of the impact parameter is shown in Fig. 1b.



(a) **(b)** **(c)**

Figure 1: Reconstructed mass of J/ψ candidates in the b fragmentation analysis (a) [5], impact parameter distribution of muons in the lepton flavor universality analysis (b) [7] and distribution of the boosted decision tree classifier in the search for lepton flavor violation (c) [8].

The ratio is measured as

$$R(\tau/\mu) = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})\,, \tag{3}$$

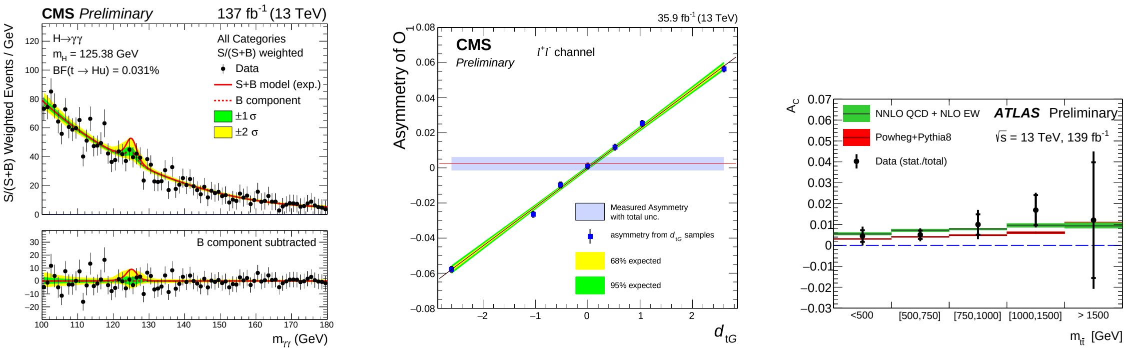
which is in agreement with lepton flavor universality predicted by the SM. The sensitivity of the measurement is limited by the modeling and reconstruction of muons and parton shower variations. The CMS Collaboration has instead performed a new search for charged lepton flavor violation in the production of single top quarks and the decay of top quark pairs [8], specifically targeting eμtu and eμtc vertices. A boosted decision tree (BDT) is trained to separate a possible signal arising from new physics against different SM background processes. The distribution of the BDT classifier is shown in Fig. 1c. No significant deviation from the predictions is found and thus limits are set on various EFT operators describing four-fermion interactions.

Flavor changing neutral currents (FCNC) are strongly suppressed in the SM since such processes require higher order box diagrams. However, enhancements of such branching fractions are predicted in many theories of physics beyond the SM. The CMS Collaboration has conducted a new search for FCNC interactions, where the top quark decays into a lighter up-type quark and a Higgs boson, with the Higgs boson decaying into a pair of photons [9]. Different BDTs are trained to separate the signal process against various resonant SM Higgs boson background processes and other non-resonant background processes. The invariant mass distribution of the photon pair is shown in Fig. 2a. No signal is observed and thus limits at a 95% confidence level are determined:

$$\mathcal{B}(\mathrm{t} \to \mathrm{Hu}) = 1.9 \times 10^{-4}\,, \qquad \mathcal{B}(\mathrm{t} \to \mathrm{Hc}) = 7.3 \times 10^{-4}\,. \tag{4}$$

These are the most stringent limits on t → Hu and t → Hc FCNC interactions up to date.

The absence of CP violation in quantum chromodynamics (QCD) is still one of the open questions of the SM. The CMS Collaboration has searched for CP violation in top quark pair production within a model where the QCD Lagrangian is extended with a term accounting for a chromoelectric dipole moment [10]. The effect of this extension can be probed by measuring different operators that depend on the kinematic properties of the top quark pair system. To enhance the sensitivity, the asymmetry of these operators is measured and compared to the asymmetry



(a) **(b)** **(c)**

Figure 2: The invariant mass of the diphoton system in the search for flavor changing neutral currents (a) [9], the construction of the limit on a chromoelectric dipole moment from the measured asymmetry (b) [10] and the differential charge asymmetry as a function of the invariant mass of the top quark pair system at parton level (c) [11].

obtained from dedicated simulations in which a specific coupling strength was induced. This procedure is illustrated in Fig. 2b. No significant deviation from the SM was observed.

The production of top quark pairs is charge symmetric in leading order at the LHC, but contributions from higher orders cause the rapidity distributions of top quarks to smear out in comparison to the distribution of top antiquarks. This top quark charge asymmetry can be measured as the rapidity difference between top quarks and top antiquarks. The ATLAS Collaboration has measured the inclusive charge asymmetry, as well as the differential charge asymmetry as a function of the invariant mass and the longitudinal boost of the top quark pair system [11]. The differential charge asymmetry measured as a function of the invariant mass of the top quark pair system, unfolded to parton level, is shown in Fig. 2c. The measurement yields an inclusive charge asymmetry of

$$A_{\mathrm{C}} = 0.0060 \pm 0.0015(\mathrm{stat{+}syst})\,, \tag{5}$$

which is compatible with the predicted value from higher order calculations. Furthermore, this result is the first evidence for the charge asymmetry at the LHC with a significance of 4σ.

A similar effect is the top quark forward-backward asymmetry in which the rapidity distribution is not smeared out but instead shifted between top quarks and top antiquarks. Measuring this effect relies on the knowledge of the direction of the initial quark and antiquark, which was possible at the proton-antiproton collider Tevatron, but not at the LHC. The CMS Collaboration has measured this effect by estimating the direction of the incoming (anti)quark with the longitudinal momentum fraction of the top quark pair system in the laboratory frame [12]. The result of

$$A_{\mathrm{FB}}^{(1)} = 0.048^{+0.095}_{-0.087}(\mathrm{stat})^{0.020}_{0.029}(\mathrm{syst}) \tag{6}$$

is both compatible within the uncertainties with the predicted value, as well as with an asymmetry of zero.

With the amount of top quarks produced at the LHC, the measurement of top quark properties has become a very active research field with a broad range of different topics. Many new results are expected in the near future.

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