From entanglement to toponium: new perspectives on top-quark physics at the LHC

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Summary. — The top quark offers a unique laboratory to probe both the Standard Model and possible new physics phenomena due to its large mass and short lifetime. Recent measurements by ATLAS and CMS at the LHC have exploited these features to investigate quantum correlations in $t\bar{t}$ production, including the first experimental observation of entanglement in hadron collider data. Furthermore, new theoretical and experimental developments in the study of near-threshold $t\bar{t}$ systems hint at the possible formation of a quasi-bound toponium state. This contribution presents ATLAS and CMS results on quantum effects in $t\bar{t}$ production, including entanglement, and results on BSM searches influenced by $t\bar{t}$ threshold effects.

1. – Introduction

The top quark, with a mass $m_t \approx 172.5$ GeV, is the heaviest known elementary particle, and it plays a crucial role in the Standard Model (SM). Due to its extremely short lifetime, it decays before hadronising, also preserving spin information which can be accessed via its decay products. At the LHC, $t\bar{t}$ pairs are predominantly produced via strong interactions, and their decay kinematics allow for precision studies of QCD and electroweak effects. Some of the most recent measurements and searches relative to the top quarks by the ATLAS [1] and CMS [2] collaborations are here discussed.

2. – Spin Correlation and Entanglement in $t\bar{t}$ Production

Quantum entanglement between top and antitop quarks in $t\bar{t}$ pairs manifests through angular correlations of their decay products. ATLAS performed a measurement using dileptonic events (requiring 1 e and 1 μ with opposite charge in the final state) and reconstructed the top-quark system using the ellipsis method [3].

The key observable used in the measurement is $D = -3\langle\cos\varphi\rangle$, where φ is the angle between the two charged leptons in the top-quark rest frame, shown at particle level in Figure 1. The phase space in invariant mass $m_{t\bar{t}}$ is divided into a Signal Region (SR), defined as $340 < m_{t\bar{t}} < 380$ GeV, where the entanglement is investigated, and Validation Regions (VR) at higher invariant masses, used to assess the robustness of the fit

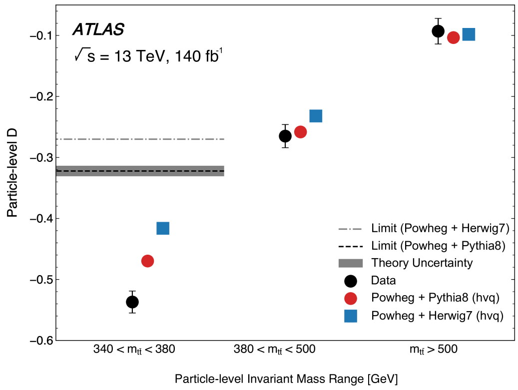

Fig. 1. – Observation of entanglement in $t\bar{t}$ at low invariant mass in ATLAS. Particle-level D results in the signal and validation regions compared with various MC models [3].

procedure. The entanglement limit corresponding to $D = -1/3$, expected for entangled top-quark pairs, is shown in Figure 1 translated to particle level for different Monte Carlo generators. In the SR, both the data and SM predictions lie significantly below the classical entanglement threshold, leading to the first observation of entanglement in top-quark pair production [3].

CMS presented complementary results [4] using dilepton channels (with 2 e , 2 μ or 1 e and 1 μ) and kinematic reconstruction of the $t\bar{t}$ quark pair imposing the W boson and t quark mass constraints and a smearing technique. Entanglement signatures are observed in regions with high $\beta_z(t\bar{t}) > 0.9$ (longitudinal boost of the $t\bar{t}$ system) and low $m_{t\bar{t}} < 400$ GeV, again supporting non-classical correlations. Figure 2 shows the measured value of the entanglement marker D, and the predicted values from different MC event generators compared with the boundary for entanglement of top quarks.

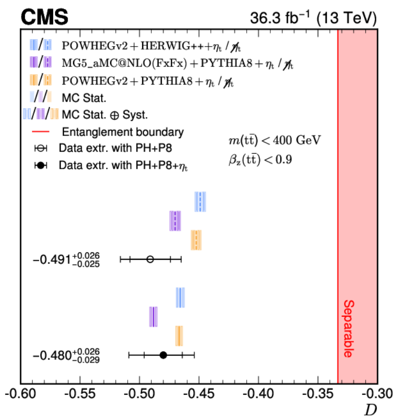

Fig. 2. – Measurements of the entanglement marker D in data (black filled or open point) compared with MC predictions including (solid line) or not including (dashed line) contributions from the η_t toponium state [4].

3. – Toponium and Threshold Effects

In the SM, the production of top-quark pairs near the kinematic threshold is influenced by QCD dynamics that go beyond fixed-order perturbation theory. When a $t\bar{t}$ pair is produced close to threshold, the relatively low relative velocity of the quarks enhances the impact of the QCD potential, leading to non-relativistic bound-state-like effects. These can be described using effective theories such as NRQCD.

The resulting system, often referred to as *toponium*, is a quasi-bound state of a top and an antitop quark mediated by gluon exchange [5]. Unlike conventional heavy quarkonia (e.g. $b\bar{b}$, $c\bar{c}$), the top quark decays before it can hadronize. The QCD potential allows for different colour configurations. The colour-singlet state, which is related to an attractive potential, dominates near threshold and contributes to potential enhancements in the differential cross section. Conversely, the colour-octet state, related to a repulsive potential, was not included in the first available MC models, such as [8]. These models simulate toponium-like effects using potential models matched to parton-level generators.

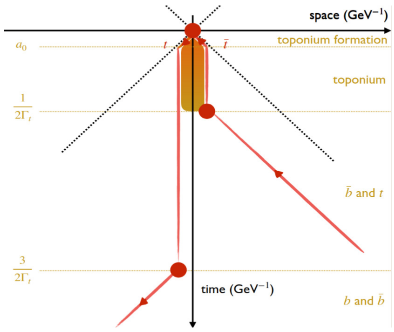

Fig. 3. – Space-time sketch of toponium formation [6, 7].

These threshold effects could explain the discrepancy observed by the ATLAS collaboration in the observation of entanglement in top quark pairs [3] between data and MC predictions. Indeed, the existence of this quasi-bound-state (not included in the $t\bar{t}$ MC simulations) increases the spin correlation effect between the top and the antitop quarks, as observed in the ATLAS measurement. Similarly, in the case of CMS entanglement observation in top quark pairs [4], the introduction of a toy model of toponium improves the agreement between data and MC predictions, as it can be seen in Figure 2.

4. – Searches for Heavy Scalars Decaying to $t\bar{t}$

Searches for heavy scalar resonances decaying into top-quark pairs are motivated by the large Yukawa coupling of the top quark to the Higgs field, which makes it a natural probe of electroweak symmetry breaking and potential new physics. Two-Higgs-Doublet Models (2HDM) provide a minimal extension of the Standard Model scalar sector [9], predicting additional neutral bosons (H, A) and charged ones ($H^{\pm}$). ATLAS and CMS have explored various 2HDM scenarios to constrain or observe such decays in different kinematic regimes. In particular, both collaborations have searched for A/H heavy Higgs bosons decaying to top quark pairs.

ATLAS [10] employed both dileptonic and semi-leptonic final states, interpreting results in the 2HDM Type II model with $m_H = m_A$. In the semi-leptonic final state, the fitted observable $m_{t\bar{t}}$ is reconstructed with a Deep Neural Network (DNN). The $m_{t\bar{t}}$ observable is also divided into intervals of $cos\theta^*$ (where θ^* is the top quark's production polar angle in the $t\bar{t}$ center-of-mass frame). In the dileptonic decay channel the fitted observable is the invariant mass of the two leptons and the two $b-$tagged jets, which is divided in bins of $\Delta\phi_{\ell\ell}$ (where $\phi_{\ell\ell}$ is the azimuthal angle between the two leptons). The results, shown in Figure 4, are extracted between 400 GeV and 1.4 TeV and no significant deviations from the SM expectations are found.

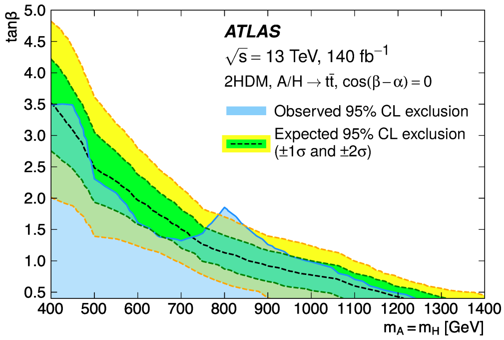

Fig. 4. – ATLAS observed and expected exclusion contours in the $m_{A/H} - \tan\beta$ plane for the 2HDM Type II model with $m_H = m_A$. The observed exclusion regions are indicated by the shaded area. The boundary of the expected exclusion region under the background-only hypothesis is marked by the dashed line [10].

CMS [11] conducted similar searches. In the semi-leptonic decay channel, the top quark pair invariant mass is reconstructed with a Likelihood function. A 2-dimensional fit is performed to the $m_{t\bar{t}}$ and the top reconstruction angle. In the dileptonic final state a 3-dimensional fit is performed to the reconstructed $m_{t\bar{t}}$ and the C_{han} and C_{hel} variables.

Two angular observables C_{hel} and C_{han} are here used to probe spin correlations: they are defined from the scalar product of the lepton momenta in the rest frames of their respective parent top quarks. Specifically, $C_{\rm hel} = \hat{\ell}_+ \cdot \hat{\ell}_-$, while $C_{\rm han}$ is obtained by flipping the component of one lepton vector along the top-quark direction before computing the scalar product. These observables are sensitive to the spin and parity structure of the production process., defined from the scalar product of the lepton momenta in the rest frames of their respective parent top quarks. Specifically, $C_{\rm hel} = \hat{\ell}_+ \cdot \hat{\ell}_-$, while $C_{\rm han}$ is obtained by flipping the component of one lepton vector along the top-quark direction before computing the scalar product. These observables are sensitive to the spin and parity structure of the production process.

The results, shown in Figure 5, are extracted between 365 GeV and 1 TeV. An excess is seen at the $t\bar{t}$ threshold region, compatible with a pseudo-scalar A. Including a toy model of the toponium, the pseudo-scalar excess is mitigated, and a toponium cross-section of η_t = 7.1 pb $\pm 11\%$ is extracted. In this paper, the toponium is observed for the first time.

5. – Observation of a Threshold Excess: Evidence for Toponium?

A recent CMS analysis [12] has reported the first evidence of an excess in the $t\bar{t}$ invariant mass spectrum near threshold, with a local significance exceeding 5σ. The

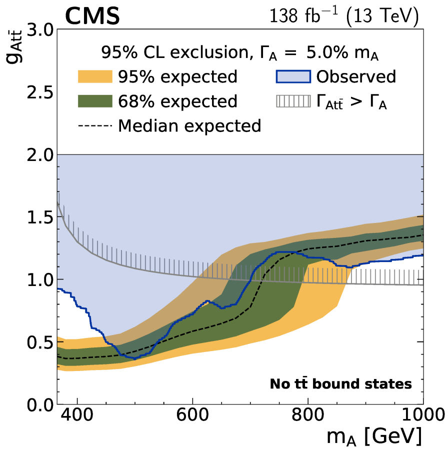

Fig. 5. – CMS analysis of $A/H \rightarrow t\bar{t}$ with and without toponium hypothesis. Observed and expected constraints as a function of the A mass for relative widths of 5%. The observed constraints are indicated by the blue shaded area [11].

analysis targets the dileptonic decay channel (ee, $\mu\mu$, $e\mu$, with opposite electric charge) and uses a kinematic reconstruction of the $t\bar{t}$ system, imposing the W boson and top quark mass constraints. The $m_{t\bar{t}}$ distribution in different C_{hel} and C_{han} bins is shown in Figure 6.

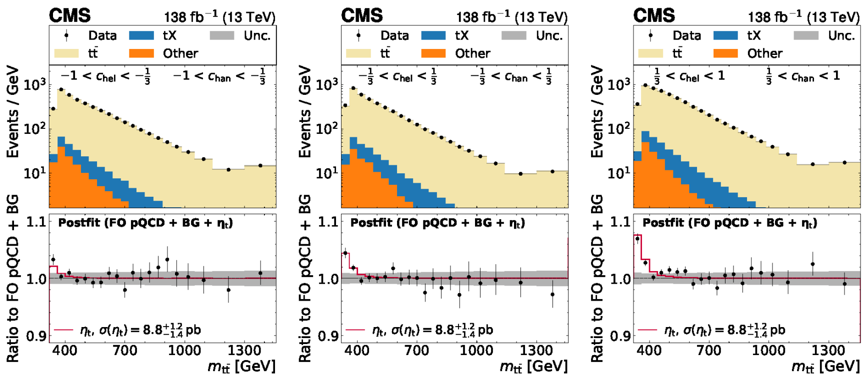

Fig. 6. – Observed and predicted $m_{t\bar{t}}$ distribution in three (C_{hel} , C_{han}) bins. The $t\bar{t}$ histogram shows the FO pQCD prediction after the fit to the data that includes the η_t signal model [12].

A 3D template fit is performed simultaneously in $m_{t\bar{t}}$, C_{hel}, and C_{han}. The data exhibit a clear excess in the region around $m_{t\bar{t}} \approx 343$ GeV, consistent with the presence of a resonance compatible with the toponium model used in the analysis. This toy model is composed of two MC simulations: the pseudo-scalar η_t corresponding to the colour singlet state of the toponium (which has the dominant effect near the $t\bar{t}$ production threshold) and the scalar χ_t corresponding to the colour octet state. The η_t sample is simulated with MadGraph5_aMC@NLO [13, 14] with an effective contact interaction between the gluon and the η_t. Here, the toponium is assumed to have a mass of 343 GeV and a width of 2.8 GeV. The χ_t sample is produced in the same way as the η_t one, changing the CP-odd couplings to CP-even.

As shown in Figure 7 an excess compatible with the toponium model is observed with a significance of more than 5σ with respect to the fixed-order perturbative QCD calculations, and the extracted η_t cross-section is of $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb.

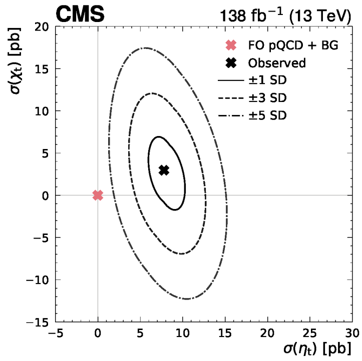

Fig. 7. – Best fit value (cross) and allowed regions at 1, 3 and 5 standard deviations for the cross section of η_t and χ_t production, as observed in data. [12].

6. – Conclusions

Top-quark pair production at the LHC continues to be an interesting process for exploring the SM dynamics. The first observation of entanglement at the LHC experiments and the measurement of spin correlations between top quarks opens the door to quantum information-based studies. Simultaneously, the first observations of a bound-state near the $t\bar{t}$ production threshold raise fundamental questions about QCD in the top sector.

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