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Entanglement effects at high energies (including top quark pair production at threshold) at ATLAS and CMS

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The large dataset collected by the ATLAS and CMS detectors at the LHC at the centre-of-mass energy of 13 TeV enables precision testing of theoretical predictions using an extensive sample of top quark events. One example of this is the spin correlation of top quarks, which can be probed due to the decay time being shorter than the hadronisation time. This wealth of data has also opened the door to new measurements of top quark properties, including those particularly sensitive to the top quark pair threshold region, such as quantum entanglement, which were previously beyond reach. This contribution presents the latest highlights in this area from the ATLAS and CMS experiments.

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1. Introduction

The top quark is the heaviest known elementary particle and it decays before hadronising. Consequently, measurements of the angular distributions of top quark decay products give access to the spin of the top quark, allowing the precise testing of perturbative quantum chromodynamics (QCD) in top quark–antiquark pair ($t\bar{t}$) production process. Spin correlation variables can also be exploited to test core quantum mechanical properties, such as the quantum behaviour of quarks. Furthermore, QCD predicts a quasi-bound state close to the threshold for low momentum top quarks. This report presents recent observations of quantum entanglement and bound $t\bar{t}$ states at threshold. The measurements are performed using the Run 2 proton-proton collision data at a centre-of-mass energy of 13 TeV collected with the ATLAS and CMS experiments at the CERN Large Hadron Collider [1, 2].

2. Observation of quantum entanglement

In the SM, top quark pairs are produced with correlated spins. Since the top quark decays through the weak interaction before hadronisation, the angular distributions of the top quark and antiquark decay products provide direct information about their spin states. The complete quantum state of a $t\bar{t}$ system is described by six polarisation components and nine spin–spin correlation coefficients, which can be experimentally determined from angular observables, typically in the helicity basis defined in the parent particle rest frame. Measurements of these observables allow the extraction of the polarisation and spin correlation matrix, both inclusively and differentially in variables, such as the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$) or the top-quark transverse momentum. At low and high $m_{t\bar{t}}$ values, the top quark and antiquark are entangled, which can be demonstrated using Peres-Horodecki criterion based on their spin correlation matrix. The maximally entangled states correspond to a spin-singlet produced at threshold and a spin-triplet produced at high masses.

The first measurements of quantum entanglement by ATLAS and CMS focused on dileptonic $t\bar{t}$ final states [3, 4], in which both W bosons decay to leptons. Both analyses measured the entanglement proxy $D = -\mathrm{Tr}[C]/3$ [5], derived from the spin correlation matrix C. The proxy D is extracted from the angular distribution of the two charged leptons according to

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\phi} = \frac{1}{2}\left(1 - D\cos\phi\right),$$

where ϕ is the opening angle between the leptons in the helicity basis. The entanglement criterion is $D < -1/3$. ATLAS determined D at the particle level using a calibration-curve method that maps detector-level observables to the fiducial particle level, while CMS performed a binned profile likelihood fit to $\cos\phi$ in regions of $m_{t\bar{t}} < 400$ GeV and small longitudinal velocity between the lab and $t\bar{t}$ reference frames, $\beta_{z,t\bar{t}} < 0.9$. ATLAS established that $D < -1/3$ with a significance exceeding five standard deviations, providing the first observation of quantum entanglement between top quarks at the LHC, confirmed by the CMS measurement. The results are shown in Figure 1. Additionally, the measurement by CMS considered the impact of the predicted $t\bar{t}$ bound states (discussed in the next Section), which are not included in the standard Monte Carlo simulations, and found small deviations of about 1.5 standard deviations if non-relativistic QCD effects near threshold are not considered.

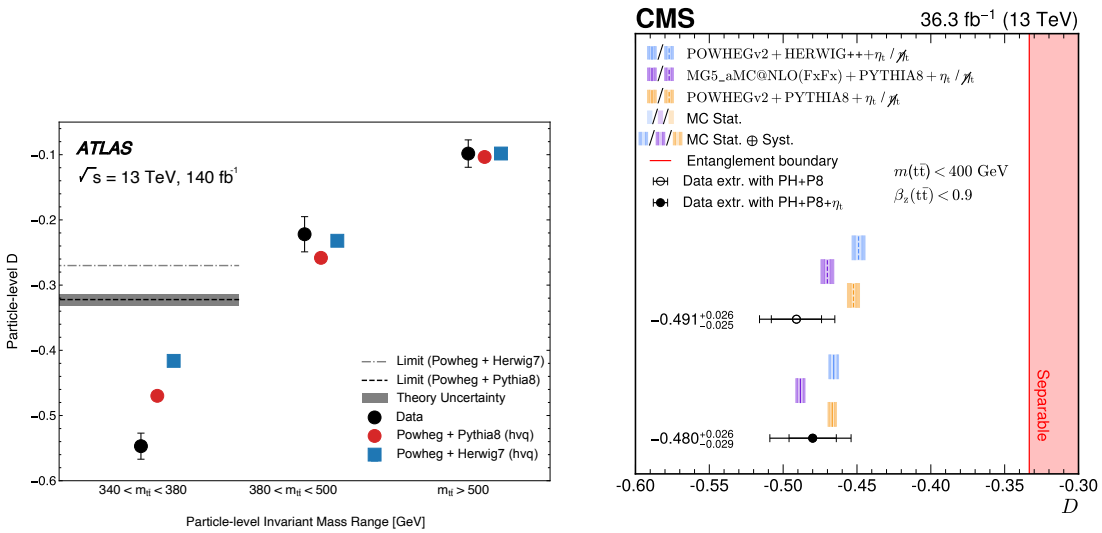

Figure 1: Left: Particle-level D results in the signal and validation regions compared with various Monte Carlo simulations. The entanglement limit shown is a conversion from its parton-level value of D = -1/3 to the corresponding value at particle level [3]. Right: Results of the entanglement proxy D at parton level in data compared with the predictions, including (solid line) or not including (dashed line) contributions from the bound state. The boundary for entanglement is indicated by the shaded region at $D = -1/3$ [4].

A more detailed exploration of spin correlations is performed by the CMS Collaboration in the single-lepton $t\bar{t}$ channel [6], where the full correlation matrix is reconstructed from the angular distributions of the down-type quark and the charged lepton. Neural networks are employed to reconstruct the kinematic properties of the $t\bar{t}$ system. All coefficients of the correlation matrix in different regions of phase space are extracted and found to be in agreement with the SM expectations. This measurement explored entanglement also in a spin-triplet state, in the regions with high $m_{t\bar{t}}$ and low scattering angle of the top quark, using a criterion based on a different entanglement proxy $\tilde{D} = 3(C_{33} - C_{11} - C_{22})$, where the coefficients C_{ii} are the diagonal elements of the spin correlation matrix. Entanglement is observed in events with high $m_{t\bar{t}}$ mass, with an observed (expected) significance of 6.7 (5.6) standard deviations.

3. Top quark pair production threshold

Theoretically, QCD predicts a quasi-bound state just below the $t\bar{t}$ threshold, arising from the attractive Coulomb potential between the top quark and antiquark, which behaves predominantly as a pseudoscalar, referred to as η_t in the following. This region is interesting by itself for threshold dynamics but also in the context of e.g., searches for Heavy Higgs bosons decaying into $t\bar{t}$ and, as mentioned above, entanglement studies to improve the modelling of $t\bar{t}$. Previous measurements by the ATLAS and CMS Collaborations had observed excesses of events near the production threshold in the dilepton and single-lepton channels. The observations were consistent with the presence of $t\bar{t}$ pairs in a pseudoscalar state [7], however, no dedicated measurements were performed.

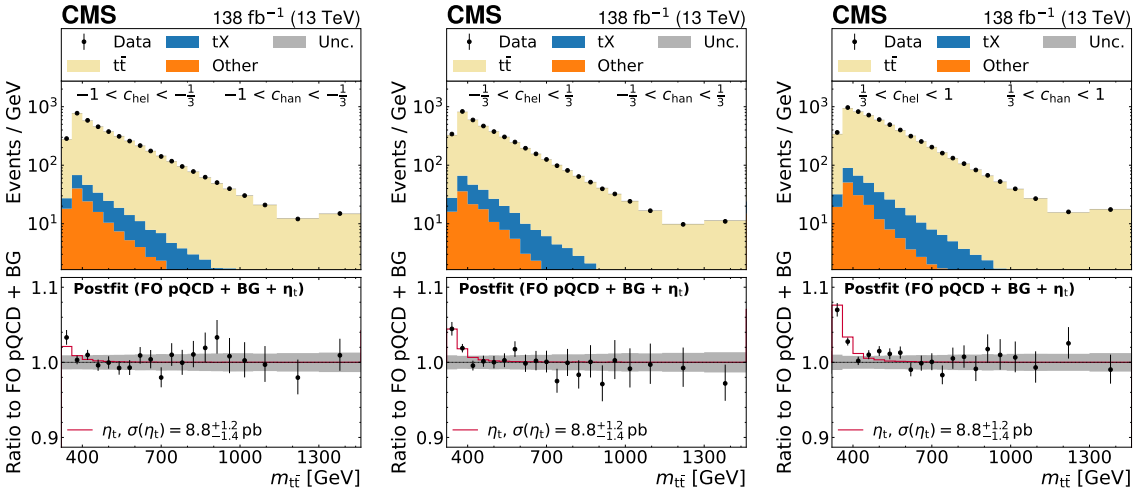

Figure 2: Observed and predicted $m_{t\bar{t}}$ distribution in three out of nine (c_{hel}, c_{han}) bins. In the upper panels, the $t\bar{t}$ histogram shows the fixed-order QCD prediction after the fit to the data that includes the η_t signal model (whose contribution is not drawn). The lower panels display the ratio of the data to the total background prediction. The η_t signal is overlaid at its best-fit cross section [9].

The expected η_t production cross section at 13 TeV is approximately $\sigma(\eta_t) = 6.4$ pb, less than 1% of the inclusive $t\bar{t}$ rate. The experimental resolution in $m_{t\bar{t}}$ is too poor to directly resolve the quasi-bound state, therefore, the recent analyses by the ATLAS and CMS Collaborations focus on spin-sensitive observables [8, 9]. The measurements are performed in the $t\bar{t}$ dilepton decay channels. A key aspect is the modelling of the quasi-bound-state effects. ATLAS modelled the state using a colour-singlet S-wave description based on the non-relativistic QCD Green's function based on Ref. [10], whereas CMS employed a simplified model simulating $gg \to \eta_t \to WbWb$ with a mass of 343 GeV and a width of 2.8 GeV, introduced in Ref. [11].

The measurements by both experiments exploit $m_{t\bar{t}}$ and the observables $c_{hel} = \vec{\ell}_+ \cdot \vec{\ell}_-$ and c_{han}, as probes of spin-singlet and spin-triplet configurations, respectively. The variable c_{hel} is defined in the helicity basis as $\vec{\ell}_+ \cdot \vec{\ell}_-$, where $\vec{\ell}_\pm$ are the directions of the leptons in the $t\bar{t}$ centre-of-mass frame, each boosted into the respective top quark and antiquark rest frames, which was also exploited in the entanglement measurements in the dilepton channel. The variable c_{han} is defined similarly with the lepton direction in the top quark rest frame flipped in sign. The $t\bar{t}$ background is modelled at next-to-leading order (NLO) in perturbative QCD, employing the narrow-width approximation and assuming a top-quark mass of $m_t = 172.5$ GeV. A kinematic reweighting is applied to account for higher-order corrections from next-to-next to leading order (NNLO) QCD calculations and NLO electroweak corrections. As an alternative, a $t\bar{t}$ sample corresponding to the full $pp \to b\ell\nu\, b\ell\nu$ process is used, which includes off-shell and non-resonant contributions as well as exact spin correlations at NLO.

CMS extracted the cross section of the pseudoscalar via a profile likelihood fit to the $m_{t\bar{t}}$ spectrum, divided into nine categories defined by c_{hel} and c_{han}. Figure 2 shows the $m_{t\bar{t}}$ distribution in three of those bins. The background contribution arising from Z+jets events is estimated with a data-driven method in a control region. The measured cross section is $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb. To explore the spin and CP structure of the resonant excess, an alternative fit was performed, including

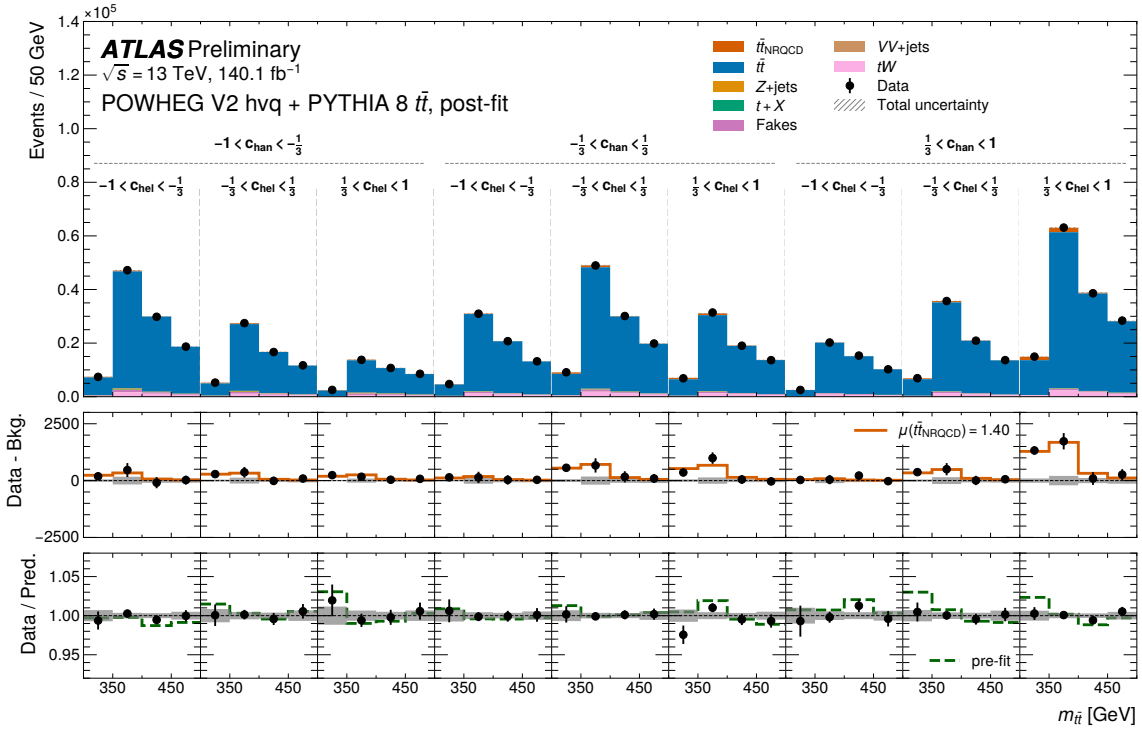

Figure 3: Pre-fit distributions of $m_{t\bar{t}}$ in the signal regions (upper panel), comparison between the $t\bar{t}$ quasibound-state prediction and the data after the background processes have been subtracted (middle panel), and the ratio of the data and the extended $t\bar{t}$ model including non-relativistic QCD contributions (lower panel) [8].

contributions from η_t and scalar χ_t production. The fit yields $\sigma(\chi_t) = 3.0^{+2.6}_{-3.3}$ pb, but the data strongly favours the pseudoscalar scenario.

ATLAS analysed the region $m_{t\bar{t}} < 500$ GeV, fitting nine signal regions and several control regions to estimate in-situ the contribution of events with fake or non-prompt leptons and from Z+jets. The pre-fit distributions of $m_{t\bar{t}}$ in the nine signal regions are shown in Figure 3. The inclusive $t\bar{t}$ normalisation was treated as a free parameter in the fit. The measured cross section is $\sigma(\eta_t) = 9.0 \pm 1.3$ pb, with an observed (expected) significance of 7.7 (5.7) standard deviations over the background only hypothesis. Considering the simplified signal model, the observed (expected) significance obtained is 7.8 (4.0) standard deviations.

4. Conclusions

The first observation of quantum entanglement by the ATLAS and CMS experiments at the LHC has been achieved through measurements of $t\bar{t}$ spin correlation observables, which serve as a test of the SM and provide new opportunities for testing quantum mechanics. In production at threshold, an excess of events is observed over the NNLO perturbative QCD prediction, with observed (expected) significances of 7.7 (5.7) standard deviations reported by ATLAS. The excess is consistent with color-singlet, S-wave, quasi-bound states predicted by non-relativistic QCD, with a measured cross section of 9.0 ± 1.3 pb, confirming the observation by CMS with $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb.

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