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Charge asymmetry measurements at the LHC

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Summary. — Measurements of the differences in angular distributions between top and anti-top quarks, referred to as charge asymmetry, in proton-proton collisions at the LHC at a centre-of-mass energy of 7 TeV are presented. The data were collected by the ATLAS and CMS experiments and correspond to integrated luminosities of $0.7\,\text{fb}^{-1}$ and $1.1\,\text{fb}^{-1}$, respectively. To measure the charge asymmetry in the charge-symmetric initial state processes at the LHC, the difference of absolute (pseudo-)rapidities of the top and anti-top quarks is used. The asymmetry is measured inclusively and also as a function of the top-quark pair invariant mass.

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1. – The top-quark charge asymmetry at the LHC

The charge asymmetry in the top-quark pair production is sensitive to the production mechanism of top quarks in quantum chromodynamics (QCD). In the Standard Model (SM), only a small charge asymmetry in the $\mathrm{t\bar{t}}$ production via the quark anti-quark annihilation mode is predicted arising from next-to-leading order (NLO) effects. The interference of Born and box diagrams as well as the interference between initial and final state gluon emissions lead to a slight preference of the top quark to be emitted in the direction of the incoming quark, whereas anti-top quarks are preferably emitted in the direction of the initial anti-quark. The charge asymmetry might be altered by processes involving effects beyond the SM contributing to the $\mathrm{t\bar{t}}$ production.

Although the LHC provides symmetric proton-proton collisions the charge asymmetry in the top-quark pair production can be observed. Since the quarks in the initial state are mostly valence quarks whereas anti-quarks can only occur as sea quarks in the proton, the $\mathrm{t\bar{t}}$ charge asymmetry transfers the difference in the average momenta of initial quarks and anti-quarks to the top and anti-top quarks. Top quarks are on average produced with a larger rapidity than anti-top quarks. Therefore, the $\mathrm{t\bar{t}}$ charge asymmetry manifests itself in an asymmetry of the widths of the rapidity distributions of top and anti-top quarks.

The influence of the charge asymmetry can then be observed in the difference of the absolute values of the (pseudo)-rapidities of top and anti-top quarks, $\Delta(|\eta|) = |\eta_{\mathrm{t}}| - |\eta_{\bar{\mathrm{t}}}|$ or $\Delta(|y|) = |y_{\mathrm{t}}| - |y_{\bar{\mathrm{t}}}|$, or in the variable $\Delta(y^2) = (y_{\mathrm{t}} - y_{\bar{\mathrm{t}}}) \cdot (y_{\mathrm{t}} + y_{\bar{\mathrm{t}}})$. The $\mathrm{t}\bar{\mathrm{t}}$ charge asymmetry can be defined as

$$A_C = \frac{N^+ - N^-}{N^+ + N^-}\,, \tag{1}$$

where N^+ and N^- are the numbers of observed $\mathrm{t}\bar{\mathrm{t}}$ events with positive or negative values of the respective sensitive variable. For all three variables, asymmetries of about 1% are predicted in the SM [1] whereas in certain beyond SM theories asymmetries of several percent can be expected [2]. Additional exchange particles contributing to the $\mathrm{t}\bar{\mathrm{t}}$ production could enlarge the value of the charge asymmetry in certain kinematic regions, for instance, the asymmetry might be enhanced for $\mathrm{t}\bar{\mathrm{t}}$ events with large invariant mass, $M_{\mathrm{t}\bar{\mathrm{t}}}$.

Here, two analyses are presented performed with data taken by the two LHC experiments, ATLAS [3] and CMS [4]. The ATLAS analysis [5] measures the asymmetry in the $\Delta(|y|)$ variable and a data set corresponding to an integrated luminosity of $0.7\,\mathrm{fb}^{-1}$ is used. At the CMS experiment [6], the charge asymmetry measurement is performed in the variables $\Delta(|\eta|)$ and $\Delta(y^2)$ using a data sample with an integrated luminosity of $1.1\,\mathrm{fb}^{-1}$.

2. – Event selection and background estimation

Both presented analyses perform the measurement of the charge asymmetry by selecting candidate events in the electron+jets and muon+jets decay channels of the top-quark pair. Selected candidate events have to fulfil certain criteria matching the expected event topology of $\mathrm{t}\bar{\mathrm{t}}$ events in these decay channels. Both analyses demand the presence of exactly one well isolated electron or muon. In the ATLAS analysis, electrons (muons) are required to have a transverse momentum $p_{\mathrm{T}} > 25$ (20) GeV/c and a pseudorapidity $|\eta| < 2.5$. Electrons (muons) in the CMS analysis have to fulfil $E_{\mathrm{T}} > 30\,\mathrm{GeV}$ ($p_{\mathrm{T}} > 25\,\mathrm{GeV/c}$) and $|\eta| < 2.5$ ($|\eta| < 2.1$). Both analyses select events with at least four jets fulfilling $p_{\mathrm{T}} > 25\,\mathrm{GeV/c}$ and $|\eta| < 2.5$ in the ATLAS analysis or $p_{\mathrm{T}} > 30\,\mathrm{GeV/c}$ and $|\eta| < 2.1$ for the CMS measurement. At least one of the selected jets is required to be identified as a jet originating from a b quark. In the ATLAS analysis, additional cuts are applied on the missing transverse energy and transverse mass of the reconstructed W boson of $E_{\mathrm{T}}^{\mathrm{miss}} > 35\,\mathrm{GeV}$ and $m_{\mathrm{T}}(\mathrm{W}) > 25\,\mathrm{GeV/c}^2$ in the electron+jets channel and of $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$ and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}(\mathrm{W}) > 60\,\mathrm{GeV/c}^2$ in the muon+jets channel to reduce the amount of selected QCD multi-jet events.

The main background processes contributing to the selected $\mathrm{t}\bar{\mathrm{t}}$ signal are W+jets, Z+jets, single top quark and QCD multi-jet production. Except the QCD multi-jet production which is modelled with data from appropriate sideband regions with less well isolated leptons, all background and signal templates are taken from Monte Carlo simulations. To estimate the QCD multijet background, ATLAS uses the so called "Matrix Method". In this approach, the normalisation and shape of the QCD background are determined using a region with inverted QCD rejection cuts together with the selection efficiencies for real and fake leptons, which are also determined in dedicated data control samples. The W+jets background is estimated from the observed difference between numbers of selected events with positively and negatively charged leptons, taking into account the fact that the ratio of cross sections of the $\mathrm{pp} \to \mathrm{W}^+ +$jets and $\mathrm{pp} \to \mathrm{W}^- +$jets processes is greater than one and has relatively small uncertainties. In the CMS analysis,

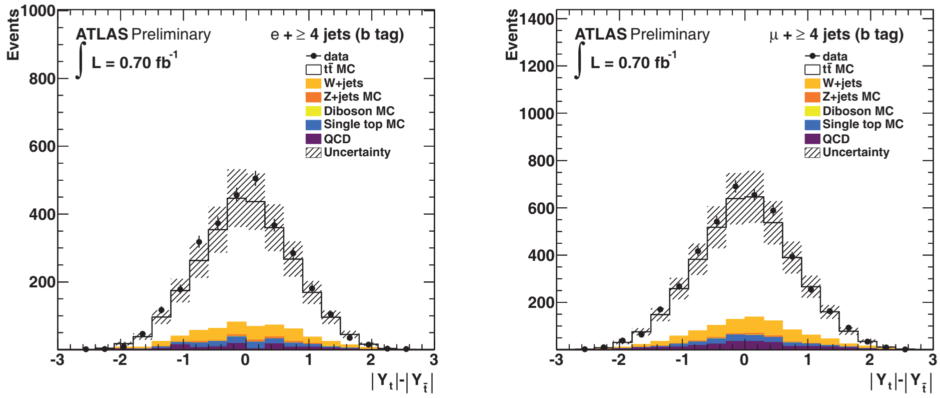

Fig. 1. – The measured $\Delta(|y|)$ distributions in the electron+jets (left) and muon+jets (right) channels in the ATLAS analysis compared to signal and background models.

the background contributions are determined in a binned likelihood fit. The templates for the individual processes in the variables $E_{\mathrm{T}}^{\mathrm{miss}}$ and M3 are fitted to the data. Here, M3 is defined as the invariant mass of the combination of three jets forming the largest vectorially summed transverse momentum. In both analyses, the predictions for the rates of the smaller background processes Z+jets and single top-quark production are taken from Monte Carlo predictions. The background estimations yield a purity of the $\mathrm{t\bar{t}}$ events in the selected data sample of more than 70% in both analyses.

3. – Reconstruction of $\mathrm{t\bar{t}}$ pairs

The measurement of the $\mathrm{t\bar{t}}$ charge asymmetry requires the reconstruction of the top-quark 4-momenta in the selected data sample. In both measurements, the top-quark momenta are obtained by adding the momenta of measurable objects, such as charged leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$. The assignment of objects to the partons in the decay chain of the top-quark pair is ambiguous. Therefore, a criterion has to be found to select one reconstruction hypothesis which matches best the true top-quark momenta. In both analyses, a likelihood function is constructed taking into account the masses of the reconstructed top quarks and W bosons as well as b-tagging information of the jets assigned to the individual quarks from the $\mathrm{t\bar{t}}$ decay. The hypothesis that maximises this likelihood is taken as best approximation of the true top-quark momenta. The resulting distributions for the reconstructed sensitive variables for the $\mathrm{t\bar{t}}$ charge asymmetry measurements are shown in figs. 1 and 2 for the ATLAS and CMS analyses, respectively.

4. – Measurement of the charge asymmetry

The reconstructed top-quark momenta and thus the asymmetries of the distributions presented in figs. 1 and 2 are distorted by several effects and can not be compared to theory predictions directly. First of all, the selected data samples are contaminated with background events. About 20% to 30% of all selected event candidates contain no top-quark pairs. The reconstructed distributions are altered with respect to the true

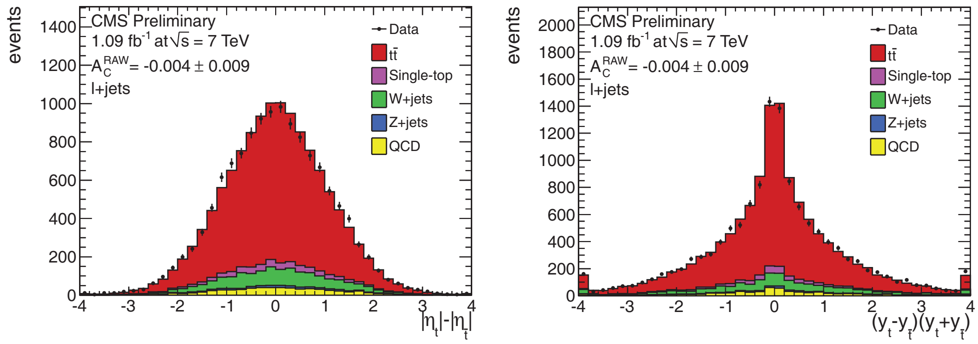

Fig. 2. – The measured $\Delta(|\eta|)$ (left) and $\Delta(y^2)$ (right) distributions in the combined lepton+jets channel in the CMS analysis compared to signal and background models.

distributions due to non-perfect reconstruction techniques. Also non-flat selection efficiencies and acceptances can lead to modified asymmetries in the reconstructed variables. To correct for these effects, the measured distributions are unfolded. In the first step of the unfolding, the background contributions are subtracted from the measured spectra of the sensitive variables according to the background-rate estimations.

The smearing between generated and reconstructed top-quark momenta as well as effects on the measured spectra arising from a non-flat selection efficiency is taken from simulated $t\bar{t}$ events as input for the unfolding techniques. The CMS analysis performs a regularized unfolding procedure based on a generalized matrix inversion, whereas ATLAS uses an iterative Bayesian approach to correct the measured spectra. In the ATLAS measurement, the $\Delta(|y|)$ distributions in the electron+jets and muon+jets channels are unfolded separately. For the CMS analysis, both channels are combined before performing the unfolding of the $\Delta(|\eta|)$ and $\Delta(y^2)$ distributions.

The performance of the unfolding is tested in pseudoexperiments drawn according to the expectation from simulation. In these ensemble tests, the true charge asymmetry is varied by re-weighting the simulated $t\bar{t}$ template in the sensitive variables. The unfolding procedure is found to reconstruct various charge asymmetries correctly in these sets of pseudodata.

The measurement of the charge asymmetry can be affected by several sources of systematic uncertainties. In the ATLAS analysis, the impact of several sources of systematic uncertainties is evaluated by performing the unfolding step on the observed $\Delta(|y|)$ distribution in data with systematically distorted templates for signal and background. The systematic uncertainties in the CMS measurement are estimated by drawing pseudodata from systematically distorted templates. The unfolding is then performed on these pseudoexperiments using the default templates to describe smearing and efficiency corrections. The most dominant systematic uncertainties on the measured charge asymmetries arise from uncertainties on the modelling of the $t\bar{t}$ signal in the simulation. Changes of the used Monte Carlo generator or the used parametrisation of matching threshold between parton-shower and matrix-element simulations, the simulation of initial and final state radiation, and the chosen momentum-transfer scale lead to shifts of the measured charge asymmetry. Furthermore, experimental uncertainties such as the uncertainties in the jet-energy scale and resolution, b-tagging, lepton selection, and trigger efficiencies,

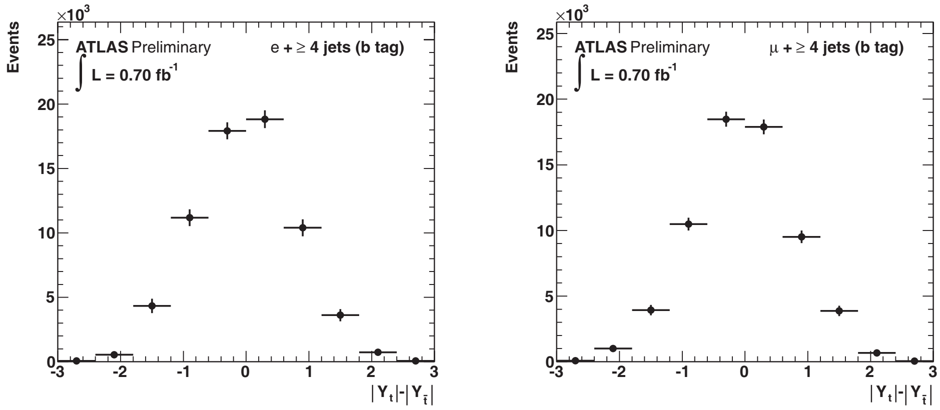

Fig. 3. – The unfolded $\Delta(|y|)$ distributions in the electron+jets (left) and muon+jets (right) channels in the ATLAS analysis.

as well as the modelling of data-driven background templates are taken into account.

The unfolded distributions of the sensitive variables are shown in fig. 3 for the ATLAS measurement and in fig. 4 for the CMS analysis. From these distributions, the charge asymmetry is obtained according to eq. (1). The ATLAS experiment measures

$$A_C^y = -0.009 \pm 0.023(\text{stat.}) \pm 0.032(\text{syst.}) \quad \text{(electron+jets channel)},$$
$$A_C^y = -0.028 \pm 0.019(\text{stat.}) \pm 0.022(\text{syst.}) \quad \text{(muon+jets channel)}.$$

Both channels are combined taking correlations into account. The combined measurement yields

$$A_C^y = -0.024 \pm 0.016(\text{stat.}) \pm 0.023(\text{syst.}).$$

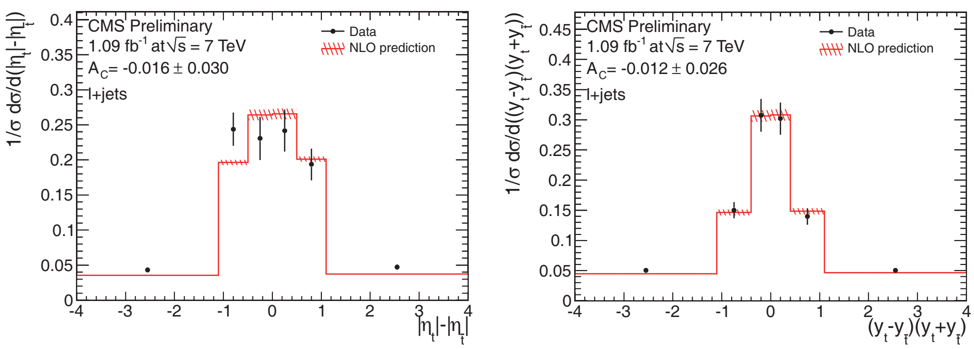

Fig. 4. – The unfolded $\Delta(|\eta|)$ (left) and $\Delta(y^2)$ (right) distributions in the combined lepton+jets channel in the CMS analysis.

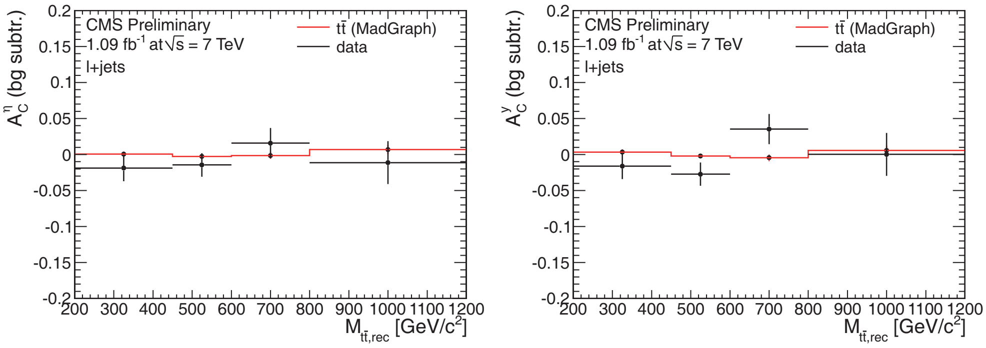

Fig. 5. – Raw asymmetries for $\Delta(|\eta|)$ (left) and $\Delta(y^2)$ (right) for different regions of the reconstructed invariant mass of the $t\bar{t}$ system.

In the CMS measurement, charge asymmetries of

$$A_C^\eta = -0.016 \pm 0.030(\text{stat.})^{+0.010}_{-0.019}(\text{syst.}),$$
$$A_C^y = -0.013 \pm 0.026(\text{stat.})^{+0.025}_{-0.020}(\text{syst.})$$

in the $\Delta(|\eta|)$ and $\Delta(y^2)$ distributions are observed. The results of both analyses show a slight tendency towards negative asymmetries, but within the uncertainties the results are compatible with the theory predictions of approximately +1%.

Within the CMS analysis, also the background-subtracted asymmetry as a function of the reconstructed invariant mass of the $t\bar{t}$ system is measured. Figure 5 shows the results for the two variables, $\Delta(|\eta|)$ and $\Delta(y^2)$, where no change in asymmetry is observed as a function of $M_{t\bar{t}}$ in the non-unfolded distributions. So far, no significant deviations from the SM predictions are found in the measurements of the charge asymmetry in top-quark pair production at the LHC.

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