Measurement of the $t\bar{t}$ charge asymmetry with lepton+jets events at 8 TeV

The CMS Collaboration

Abstract

The $t\bar{t}$ charge asymmetry is measured in events containing a charged lepton (electron or muon) and at least four jets, one of which is identified as originating from $b$-quark hadronization. The analyzed dataset corresponds to an integrated luminosity of $19.7 \text{ fb}^{-1}$ collected with the CMS detector at the LHC. An inclusive and three differential measurements of the $t\bar{t}$ charge asymmetry as a function of rapidity, transverse momentum, and invariant mass of the $t\bar{t}$ system are presented. The measured inclusive $t\bar{t}$ charge asymmetry is $0.005 \pm 0.007 \text{ (stat.)} \pm 0.006 \text{ (syst.)}$. This result and the three differential measurements are consistent with the predictions of the Standard Model.
1 Introduction

With the 2012 data taking the Large Hadron Collider (LHC) at CERN has become a top quark factory. The abundantly produced top quark pairs enable experiments to precisely measure the various properties of the heaviest elementary particle known to date. One interesting feature of the pairwise top quark production is the difference in the angular distributions of top quarks and top antiquarks. This differing behavior of top quarks and antiquarks in the pp collisions of the LHC is called $t\bar{t}$ charge asymmetry, and calculations within the Standard Model (SM) predict an effect on the order of one percent. Both the CMS and ATLAS collaborations have published results based on the 7 TeV data that are in agreement with these predictions within the still large uncertainties [1–4].

The corresponding quantity in $p\bar{p}$ collisions is the forward-backward asymmetry in $t\bar{t}$ production. One legacy of the Tevatron experiments is the measurement of this asymmetry that deviates from the predicted value at the order of two standard deviations. In certain phase space regions this deviation is even more significant [5, 6].

As the underlying physics process for the two observable asymmetries is the same – interference effects between the amplitudes of different Feynman diagrams for the process $q\bar{q} \rightarrow t\bar{t}$ [7] – one would generally expect that both asymmetries should show the same behavior. There are however also theory models that explain why one could see a deviation from the SM for the forward-backward asymmetry at the Tevatron while the charge asymmetry that is observable at the LHC is not affected at all (see for example Ref. [8]).

The charge asymmetry occurs only in quark-antiquark initial states. Since at the LHC the quarks in the initial state are mainly valence quarks while the antiquarks are always sea quarks, the larger average momentum fraction of quarks leads to an excess of top quarks produced in the forward directions. This makes the difference of the absolute values of the rapidities of top quark and antiquark, $\Delta |y| = |y_t| - |y_{\bar{t}}|$, a suitable observable to measure the $t\bar{t}$ charge asymmetry. We define the charge asymmetry $A_C$ as

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

where $N^+$ and $N^-$ represent the number of events with positive and negative values in the sensitive variable, respectively.

It is not only crucial to measure the inclusive asymmetry but it is of particular importance to measure the differential asymmetry as a function of variables that are suited to enhance the charge asymmetry in certain kinematic regions. In the analysis documented in this note we measure the charge asymmetry as a function of the rapidity, the transverse momentum, and the invariant mass of the $t\bar{t}$ system. Each of these variables is sensitive to a certain aspect of the $t\bar{t}$ charge asymmetry.

The rapidity of the $t\bar{t}$ system in the laboratory frame, $|y_{t\bar{t}}|$, is sensitive to the ratio of the contributions from the $q\bar{q}$ and $gg$ initial states to $t\bar{t}$ production. The charge-symmetric gluon fusion process is dominant in the central region, while $t\bar{t}$ production through $q\bar{q}$ annihilation mostly produces events with the $t\bar{t}$ pair at larger rapidities, which implies an enhancement of the charge asymmetry with increasing $|y_{t\bar{t}}|$ [9].

The transverse momentum of the $t\bar{t}$ pair in the laboratory frame, $p_{T_{t\bar{t}}}$, is sensitive to the ratio of the positive and negative contributions to the overall asymmetry. The interference between the Born and the box diagrams leads to a positive contribution, while the interference between
initial state and final state radiation (ISR and FSR) results in a negative contribution. The presence of additional hard radiation implies on average a higher transverse momentum of the $t\bar{t}$ system. Consequently in events with large values of $p_T^T$ the negative contribution from the ISR-FSR interference is enhanced [9].

The charge asymmetry is expected to depend on the invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$, since the contribution of the $q\bar{q}$ initial state processes is enhanced for larger values of $m_{t\bar{t}}$. This observable is also sensitive to new physics contributions; potential new heavy particles could be exchanged between initial quarks and antiquarks and contribute to the $t\bar{t}$ production (see e.g. Ref. [10] and references therein). The amplitudes associated with these new contributions would interfere with those of the SM processes, leading to an effect on the $t\bar{t}$ charge asymmetry, which increases as a function of the invariant mass of the $t\bar{t}$ system.

2 Data and Simulation

This analysis of $t\bar{t}$ events produced in proton-proton collisions at a centre-of-mass energy of 8 TeV is based on data collected with the CMS detector, corresponding to an integrated luminosity of 19.7 fb$^{-1}$. To translate the distributions measured with reconstructed objects to distributions for the underlying quarks, we use simulated data samples. Top-quark pair events are generated with the next-to-leading order (NLO) generator POWHEG [11–15], simulating the parton shower using PYTHIA version 6.4 [16]. The $t$ and $tW$ channels of electroweak production of single top quarks are also simulated using POWHEG. These samples include also the simulation of spin-correlations in the top quark decay. The production of weak vector bosons in association with jets ($W+$jets and $Z+$jets) is simulated using MADGRAPH [17], with PYTHIA being used to simulate the parton shower. Additional proton-proton interactions (pile-up) are overlaid on the simulated events as observed in the analyzed data.

The samples of generated events are normalized to the corresponding calculated production cross sections. The $t\bar{t}$ NLO production cross section has been calculated as 245.8 pb [18]. The single-top-quark production cross sections are available at approximate NNLO [19]: 56.4 pb (30.7 pb) for top quarks (top antiquarks) in the t-channel and 22.2 pb for the inclusive single-top-quark associated production ($tW$). The production cross section for $W$ ($Z$) bosons decaying into leptons has been determined at NNLO to be 37509 pb (3503.71 pb) using FEWZ [20].

3 Event Selection and Background Estimation

We focus on $t\bar{t}$ events, where one of the $W$ bosons from the decay of a top quark pair subsequently decays into a muon or electron and the corresponding neutrino, and the other $W$ boson decays into a pair of jets. We therefore select events containing one electron or muon and four or more jets, at least one of which is identified as originating from the hadronization of a b quark.

In order to be considered for the offline analysis, the events have to pass single lepton triggers with a $p_T$ threshold for the trigger electron (muon) of 27 GeV/c (24 GeV/c). For the reconstruction of electrons, muons, jets, and any imbalance in transverse momentum due to the neutrino, we use a particle-flow (PF) algorithm [21]. The particle-flow event reconstruction consists in reconstructing and identifying each single particle with an optimised combination of all subdetector information. The reconstructed PF candidates are divided in five classes: electrons, muons, photons, charged hadrons, and neutral hadrons.

Electron candidates are required to have a transverse energy larger than 30 GeV and be within $|\eta| < 2.5$, excluding the transition region between the ECAL barrel and endcaps of 1.4442 <
$|\eta_{sc}| < 1.5660$, where $\eta_{sc}$ is the pseudorapidity of the electron candidate’s supercluster, which corresponds to the cluster of ECAL energy depositions from the electron and any accompanying bremsstrahlung photons. Furthermore, electron candidates are selected based on the value of a multivariate discriminant, which combines various variables related to calorimetry and tracking parameters, but also momentum and $\eta$ of the electron. The electron definition also encompasses a conversion rejection aimed at identifying electrons that are created in the conversion of a photon instead of as part of the hard interaction.

Muon candidates are PF muons with a transverse momentum larger than 26 GeV/$c$ and a pseudorapidity of $|\eta| < 2.1$. Additionally, they also have to be reconstructed as “global” muons. The reduced $\chi^2$ of the global fit has to be smaller than 10 and the number of tracker hits has to be larger than 5. The longitudinal position of the muon track at its closest approach to the beam line is required to lie within 0.5 cm of the longitudinal position of the primary vertex. The global-muon track fit needs to contain at least one muon chamber hit, there must be muon segments in at least two muon stations, and the track must contain at least one pixel hit.

Additionally, electron and muon candidates must be isolated. The lepton isolation variable $I_{\text{rel}}^\ell$ is based on the reconstructed energies of particle-flow objects relative to the lepton transverse momentum ($p_T^\ell$), and it is corrected for pile-up effects using the effective area of the lepton and the energy density in the event. We require electron (muon) candidates to have $I_{\text{rel,cor}}^\ell < 0.1$ ($0.12$).

In both channels (electron+jets and muon+jets) we reject events containing additional more loosely defined electrons or muons. Loose muons need to be global muons or tracker muons, and they must have $p_T > 10$ GeV/$c$, $|\eta| < 2.5$ and corrected relative isolation smaller than 0.2. Loose electrons instead are required to have $p_T > 20$ GeV/$c$, $|\eta| < 2.5$ and corrected relative isolation smaller than 0.15 and a loose cut on the electron ID.

Jets are reconstructed with the anti-$k_T$ [22] jet algorithm with the distance parameter $R = 0.5$ and particle-flow objects as input objects, where the contribution of charged hadrons identified as originating from pile-up vertices has been subtracted. Further corrections to the jet energy are applied depending on the jet area, the median $p_T$ density of the event, jet $\eta$ and the reconstructed jet energy itself. The jets have to lie within $|\eta| < 2.5$ and are required to have $p_T > 30$ GeV/$c$. Jet asymmetry measurements suggest that the jet-$p_T$ resolutions in data are worse compared to MC simulations. To account for this, all jets in the simulated samples are scaled accordingly.

Jets from the hadronization of b quarks are identified using the CSV algorithm [23] at its medium working point.

With the applied event selection we find a total of 375125 events, 176835 in the electron+jets channel and 198290 in the muon+jets channel. For the estimation of the background contributions we make use of the discriminating power of the transverse mass of the W boson, $m_T^W$, and of M3, the invariant mass of the combination of three jets that corresponds to the largest vectorially summed transverse momentum. The transverse mass of the W boson is reconstructed from the four-vector of the charged lepton and the missing transverse energy ($E_{\text{miss}}^T$). We use the missing transverse energy based on the particle-flow algorithm, corrected using Type-I corrections. The Type-I correction is a propagation of the jet energy corrections to the missing transverse energy.

We perform the background estimation individually for the two lepton types to account for small shape differences of most background components as well as for the fact that the QCD multijet contribution in the two channels differs quite strongly – both qualitatively and quan-
Measurement of the $t\bar{t}$ charge asymmetry

4 Measurement of the $t\bar{t}$ charge asymmetry

The measurement of the $t\bar{t}$ charge asymmetry is based on the fully reconstructed four-momenta of $t$ and $\bar{t}$ in each event. We reconstruct the leptonically decaying W boson from the measured charged lepton and $E_T^{\text{miss}}$ and associate the measured jets in the event with quarks in the $t\bar{t}$ decay chain. For a detailed description of the reconstruction procedure see Ref. [24].

The reconstructed top quark and antiquark four-vectors are used to obtain the inclusive (see...
A comparison of the asymmetries calculated from background-subtracted data to values from background. The fit determines also the correlations among the individual background rates. These are taken into account when subtracting the background.

The remaining background-free distributions are translated from the reconstruction level to the particle level after event selection, and from there to the particle level before event selection. The corrected distributions are then independent from the detector environment and analysis specifications. The corrections are achieved by applying a regularized unfolding procedure to the data [25] through a generalized matrix-inversion method. In this method, the disturb-
Measurement of the $t\bar{t}$ charge asymmetry

Figure 3: Migration matrix (top) between the generated and the reconstructed values in $\Delta |y|$, after the event selection (left) and for the measurement differential in $m_{t\bar{t}}$ (right). Selection efficiency (bottom) as a function of generated $\Delta |y|$, defined with respect to inclusive $t\bar{t}$ production (left) and for the measurement differential in $m_{t\bar{t}}$ (right).

The number of bins and especially the bin ranges used for $\Delta |y|$ and the differentiating variables $v_d$ have to be chosen with care. To stabilize the unfolding procedure it is desirable that the number of entries in each bin of the reconstructed distributions is approximately equal. Similarly, the spectrum that results after inversion of the migration matrix – but before inversion of the selection efficiency – is flattened to give comparable statistics and thus uncertainties to all bins involved in the migration. For technical reasons the number of bins in the reconstructed spectra must be twice as high as the number of bins used for the unfolded spectra. We use 16 (8) bins for the reconstructed (unfolded) $\Delta |y|$ distribution and 6 (3) bins in the reconstructed (unfolded) $v_d$ distributions. The ranges for the bins in the unfolded differentiating variables are $[0 - 0.34; 0.34 - 0.75; 0.75 - \infty]$ for $|y_{t\bar{t}}|$, $[0 - 41; 41 - 92; 92 - \infty]$ for $p_T,_{t\bar{t}}$ in GeV/$c$, and $[0 - 430; 430 - 530; 530 - \infty]$ for $m_{t\bar{t}}$ in GeV/$c^2$. 

The smearing effects are described by a smearing matrix $S$ that translates the true spectrum $\vec{x}$ into the measured spectrum $\vec{w} = S \vec{x}$. The technical details on the applied unfolding procedure can be found in Ref. [24]. As reconstruction and selection effects factorize, the smearing matrix $S$ can be calculated as the product of a migration matrix and a diagonal matrix with the selection efficiencies for each of the bins on the diagonal, and all other elements set to zero. Both the migration matrix and the selection efficiency are determined from simulated $t\bar{t}$ events. As the components corresponding to the electron $+\text{jets}$ and muon $+\text{jets}$ channels are found to be very similar, they are combined to yield a method that can be applied to the summed data of both channels. In this combination, the individual components are scaled according to the results of the background estimation.
We use separate migration matrices for the inclusive measurement and the three differential measurements, obtained from simulated $t\bar{t}$ events. Figure 3 shows the migration matrices for the inclusive measurement and for the differential measurement in $m_{t\bar{t}}$. While for the inclusive measurement the migration matrix describes the migration of selected events from true values of $\Delta|y|$ to different reconstructed values, for the migration matrices for the differential measurements not only the migration between bins of $\Delta|y|$ has to be taken into account, but also the migration between bins of $v_d$. The migration matrices for the differential measurements feature on large scale a grid of $6 \times 3$ bins in $v_d$ with each of these bins hosting a $16 \times 8$ migration matrix describing the migration between different $\Delta|y|$ values. The values of $\Delta|y|$ and $m_{t\bar{t}}$ affect the probability for an event to fulfill the event selection criteria. The $\Delta|y|$ and $m_{t\bar{t}}$ dependent selection efficiencies are depicted in Fig. 3.

The performance of the unfolding algorithm is tested in sets of pseudo experiments, each of which provides a randomly-generated sample distribution from the templates used in the background estimation. The normalization of the different processes is determined by throwing random numbers from Gaussian distributions centered around the measured event rates. The average asymmetries from 10000 pseudo experiments for the inclusive as well as for the differential measurements agree well with the true asymmetries in the sample used to model the signal component and the pull distributions agree with expectations, indicating that the uncertainties are calculated correctly. To test the unfolding procedure for different asymmetries, we reweight the events of the default $t\bar{t}$ sample according to their $\Delta|y|$ value, to artificially introduce asymmetries between $-0.2$ and $+0.2$, and then perform pseudoexperiments for each of the reweighted distributions. For the differential measurements this test is performed in each of the three bins of $v_d$ separately. We find a linear dependence of the ensemble mean on the input value.

5 Estimation of systematic uncertainties

The measured charge asymmetry $A_C$ can be affected by several sources of systematic uncertainty. Influences on the direction of the reconstructed top-quark momenta can change the value of the reconstructed charge asymmetry. Systematic uncertainties with an impact on the differential selection efficiency can also bias the result, as well as variations in the background rates. To evaluate each source of systematic uncertainty, we perform a new background estimation and repeat the measurement on data using modified simulated samples. The expected systematic uncertainty for each source is taken to be the shift in the values of the corrected asymmetry between the default measurement and the one using the shifted templates. The corrections on jet-energy scale (JES) and jet-energy resolution (JER) are varied within their $\eta$ and $p_T$-dependent uncertainties to estimate their effects on the measurement. In addition the effect of variations in the frequency of occurrence of pile-up events is estimated. Effects due to uncertainties on b tagging and lepton identification and selection efficiency are also studied by varying the respective scale factors within their uncertainties as a function of $\eta$ (and lepton charge in case of the lepton identification and selection efficiency). The effect of lepton charge misidentification is very small and thus can be neglected.

To estimate the uncertainty resulting from possible mismodelling of the $t\bar{t}$ signal, we compare samples of simulated $t\bar{t}$ events produced with $\text{MC@NLO}$ [26] and samples produced with $\text{POWHEG}$, both interfaced to $\text{HERWIG}$ [27] for the modelling of the parton shower. In a similar way the impact of a possible mismodelling of the parton shower is studied by comparing two different hadronization models, namely the one implemented in $\text{PYTHIA}$ to the one implemented in $\text{HERWIG}$, using $\text{POWHEG}$ in both cases for the generation of the matrix element.
Table 2: Systematic uncertainties for the inclusive measurement of $A_C$ and ranges of systematic uncertainties for the differential measurements.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>shift in inclusive $A_C$</th>
<th>range of shifts in differential $A_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>0.001</td>
<td>0.001 – 0.005</td>
</tr>
<tr>
<td>JER</td>
<td>0.001</td>
<td>0.001 – 0.005</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.001</td>
<td>0.000 – 0.003</td>
</tr>
<tr>
<td>b tagging</td>
<td>0.000</td>
<td>0.001 – 0.003</td>
</tr>
<tr>
<td>Lepton ID/sel. efficiency</td>
<td>0.002</td>
<td>0.001 – 0.003</td>
</tr>
<tr>
<td>Generator</td>
<td>0.003</td>
<td>0.001 – 0.015</td>
</tr>
<tr>
<td>Hadronization</td>
<td>0.000</td>
<td>0.000 – 0.016</td>
</tr>
<tr>
<td>$p_T$ weighting</td>
<td>0.001</td>
<td>0.000 – 0.003</td>
</tr>
<tr>
<td>$Q^2$ scale</td>
<td>0.003</td>
<td>0.000 – 0.009</td>
</tr>
<tr>
<td>W+jets</td>
<td>0.002</td>
<td>0.001 – 0.007</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.001</td>
<td>0.002 – 0.009</td>
</tr>
<tr>
<td>PDF</td>
<td>0.001</td>
<td>0.001 – 0.003</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.002</td>
<td>0.001 – 0.004</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.006</strong></td>
<td><strong>0.007 – 0.022</strong></td>
</tr>
</tbody>
</table>

Differential cross-section measurements [28] have shown, that – in line with theory predictions – the $p_T$ spectrum of the top quarks in $t\bar{t}$ events is significantly softer than the one generated by our simulation programs. To correct for this effect, our simulated $t\bar{t}$ events are reweighted according to scale factors derived from these measurements. As a measure of the resulting uncertainty, the measurement is performed with samples lacking any reweighting and with samples that have been reweighted twice. Finally, the impact of variations in the renormalization and factorization scale ($Q^2$) in the simulated $t\bar{t}$ events is determined using dedicated samples generated at scales shifted systematically by factors of 2.

In order to estimate the influence of possible mismodelling of the $W$+jets background, the measurement is repeated using a data-driven $W$+jets template. The sideband region used for the construction of the template is defined by an inversion of the requirement of a b-tagged selected jet. Due to the very different resulting fraction of heavy quarks in the sample, this approach can be assumed to be a conservative estimate of the uncertainty. The multijet background modelling, while data-driven, is biased towards non-isolated electrons. Thus it will not provide completely correct modelling of the angles between leptons and jets, which also affects the asymmetry. To account for this fact, we perform a conservative estimation of the uncertainty of this background by taking the maximum deviation out of three scenarios of replacing the multijet templates with the $t\bar{t}$ signal template, with the simulated $W$+jets template or by inverting the asymmetry of the multijet template itself.

The systematic uncertainties on the measured asymmetry from the choice of parton distributions functions (PDFs) for the colliding protons are estimated using the LHAPDF [29] package and the CT10 [30], MSTW2008 [31] and NNPDF2.1 [32] PDF sets.

In contrast to the other systematic effects, the uncertainty due to the unfolding method is estimated by performing pseudo experiments. Simulated $t\bar{t}$ events are used as input data for these experiments, reweighted to reproduce the asymmetries observed in the differential measurements on data. The uncertainty of each measurement is estimated as the maximum deviation produced by the unfolding in the three reweighting scenarios corresponding to the three kinematic variables $v_d$. 
The contributions of the different sources of systematic uncertainties to the total uncertainty of the inclusive measurement are summarized in Table 2. It also shows the ranges of systematic uncertainties in the differential measurements to illustrate the magnitudes of the individual contributions.

### 6 Results

Table 3 gives the values of the measured inclusive asymmetry at the different stages of the analysis while the unfolded $\Delta |y|$ distribution itself is shown in Fig. 4 (upper left). The shown theory uncertainty band represents a shape uncertainty, which can account for the apparent width difference between unfolded data and theory. Additionally, one should bear in mind that the unfolding procedure introduces correlations between the individual data points.

Table 3: The measured inclusive asymmetry at the different stages of the analysis and the corresponding theory prediction from the SM.

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>$A_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructed</td>
<td>$0.003 \pm 0.002$ (stat.)</td>
</tr>
<tr>
<td>BG-subtracted</td>
<td>$0.002 \pm 0.002$ (stat.)</td>
</tr>
<tr>
<td>Unfolded</td>
<td>$0.005 \pm 0.007$ (stat.) $\pm 0.006$ (syst.)</td>
</tr>
<tr>
<td>Theory prediction [Kühn, Rodrigo] [9, 33]</td>
<td>$0.0102 \pm 0.0005$</td>
</tr>
<tr>
<td>Theory prediction [Bernreuther, Zi] [34, 35]</td>
<td>$0.0111 \pm 0.0004$</td>
</tr>
</tbody>
</table>

The results of the three differential measurements can be found in Fig. 4 (upper right, lower left and lower right). The measured values are compared to predictions from SM calculations [9, 33–35] and to predictions from an effective field theory [36–38]. The latter theory is capable of explaining the CDF results by introducing an anomalous effective axial-vector coupling to the gluon at the one-loop level. The gluon-quark vertex is treated in the approximation of an effective field theory with a scale for new physics contributions on the order of $1.0 - 1.5$ TeV.

For technical reasons predictions for the asymmetry as a function of $p_T,t\bar{t}$ are not possible for this theory and for one of the SM calculations. In addition we measured the charge asymmetry separately for $m_{t\bar{t}} < 450$ GeV/c$^2$ and $m_{t\bar{t}} > 450$ GeV/c$^2$ (see Fig. 5), as it was done by the Tevatron experiments and the ATLAS collaboration to enable an easier comparison of the results. Within the uncertainties all measured values are consistent with the values predicted by the SM.

### 7 Conclusion

An inclusive and three differential measurements of the charge asymmetry in $t\bar{t}$ production at the LHC have been presented. Events with top-quark pairs decaying in the electron+jets and muon+jets channels were selected and a full $t\bar{t}$ event reconstruction was performed to determine the four-momenta of the top quarks and antiquarks. The observed distributions were then corrected for acceptance and reconstruction effects.

All measured values are within their uncertainties consistent with the predictions of the Standard Model and no hints for deviations due to new physics contributions have been observed. Furthermore, the charge asymmetry in the high-mass region is about 1.5 standard deviations below the predictions from an effective field theory with the scale for new physics at $\Lambda = 1.5$ TeV and about 3.5 standard deviations below the predictions for $\Lambda = 1.0$ TeV.
Figure 4: Unfolded inclusive $\Delta|y|$ distribution (upper left), corrected asymmetry as a function of $|y_{t\bar{t}}|$ (upper right), $p_T^{t\bar{t}}$ (lower left), and $m_{t\bar{t}}$ (lower right). The measured values are compared to NLO calculations for the SM (1: [9, 33], 2: [34, 35]) and to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [36–38]. The inner error bars on the differential asymmetry values indicate the statistical uncertainties while the outer error bars represent the statistical and systematic uncertainties added up in quadrature.

Figure 5: Unfolded asymmetry for $m_{t\bar{t}} < 450 \text{ GeV/c}^2$ and $m_{t\bar{t}} > 450 \text{ GeV/c}^2$. The measured values are compared to NLO calculations for the SM (1: [9, 33], 2: [34, 35]) and to predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [36–38]. The inner error bars on the differential asymmetry values indicate the statistical uncertainties while the outer error bars represent the statistical and systematic uncertainties added up in quadrature.

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