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Measurement of forward-backward asymmetries at the Tevatron

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Measurements of forward-backward asymmetries in $t\bar{t}$ and $b\bar{b}$ production at the Fermilab Tevatron are reported. Asymmetries in $t\bar{t}$ production are presented both in inclusive and differential form and complemented by leptonic asymmetries. As a cross-check in a different energy regime, $b\bar{b}$ production asymmetries are also studied. All results are based on up to $10\,\mathrm{fb}^{-1}$ of proton-antiproton collisions recorded with the CDF and DØ experiments during Tevatron Run II.

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1. Introduction

The production of heavy quark pairs ($Q\overline{Q}$) in high-energy hadronic interactions allows for detailed tests of quantum chromodynamics (QCD). At leading order (LO) in QCD perturbation theory, $Q\overline{Q}$ production is symmetric under the exchange of the Q and the $\overline{Q}$. However, at next-to-leading order (NLO) the interference of scattering amplitudes stemming from Born and box diagrams and from initial and final state gluon radiation lead to asymmetries in the process $q\overline{q} \to Q\overline{Q}$, whereas $gg \to Q\overline{Q}$ remains symmetric [1]. Additional contributions to the $Q\overline{Q}$ production asymmetry arise from electoweak corrections. The production asymmetries are expected to change significantly in the presence of physics beyond the standard model (BSM), for example color-octet states with axial couplings ("axigluons"), which make their study an interesting goal for collider experiments.

At the Tevatron $p\overline{p}$ collider at Fermi National Accelerator Laboratory (FNAL), $Q\overline{Q}$ production asymmetries can be studied by measuring forward-backward asymmetries

$$A_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B}, \tag{1.1}$$

where N_F (N_B) corresponds to the number of $Q\overline{Q}$ events produced in the forward (backward) direction in some kinematic variable. At the Tevatron, A_{FB} is usually defined in terms of the rapidity difference between the quark and the antiquark,

$$\Delta y = y_Q - y_{\overline{Q}}. \tag{1.2}$$

Note that A_{FB} vanishes for symmetric initial states, for example for pp collisions at the LHC.

Observables that describe forward-backward asymmetries can be constructed at different levels. Asymmetries at *parton level* (also called *production level*) are obtained by correcting the raw reconstructed asymmetries with appropriate unfolding techniques. Parton level asymmetries are directly comparable to calculations, however, the correction introduces some model dependence. Another, complementary, approach is to reconstruct the charge asymmetry of the leptons from heavy quark decays. The resulting *leptonic asymmetries* only show small migration effects that need to be corrected by unfolding.

The results of $t\bar{t}$ asymmetry measurements at the Tevatron have gained considerable interest in recent years. The first results from Tevatron Run II based on datasets corresponding to 1 fb^{-1} to 2 fb^{-1} of integrated luminosity already indicated $A_{\mathrm{FB}}^{t\bar{t}}$ values larger than expected from QCD [2, 3]. By 2011, with about half of the Run II datasets analyzed, the CDF experiment observed discrepancies between the data and NLO QCD expectations at the level of three standard deviations for $t\bar{t}$ invariant masses above 450 GeV [4]. These observations triggered an extensive measurement program on $Q\overline{Q}$ production asymmetries, both at the Tevatron and at the LHC. In around 150 related publications from the theory community, the standard model (SM) calculations have been improved and many BSM physics explanations for the observed discrepancies have been suggested. Further details can be found in a recent review article [5].

In this article the most recent Tevatron results on $t\bar{t}$ and $b\bar{b}$ asymmetries at the Tevatron with various measurement techniques are presented. The measurements are based on the full dataset of $p\overline{p}$ collisions at a center-of-mass energy of 1.96 TeV recorded during Tevatron Run II between 2001 and 2011, corresponding to integrated luminosities between 9 fb^{-1} and 10 fb^{-1}, unless indicated otherwise.

Experiment/Calculation	$A_{\mathrm{FB}}^{t\bar{t}}$	Reference
CDF	0.164 ± 0.047	[6]
DØ	0.106 ± 0.030	[7]
NNLO QCD + NLO EW	0.095 ± 0.007	[9]
aN^{3}LO QCD + NLO EW	0.100 ± 0.006	[10]

Table 1: Measurements of the inclusive $t\bar{t}$ forward-backward asymmetry $A_{\mathrm{FB}}^{t\bar{t}}$ with the full CDF and DØ Run II datasets (top rows) compared to theoretical calculations at NNLO and aN^{3}LO, both including EW corrections at NLO (bottom rows).

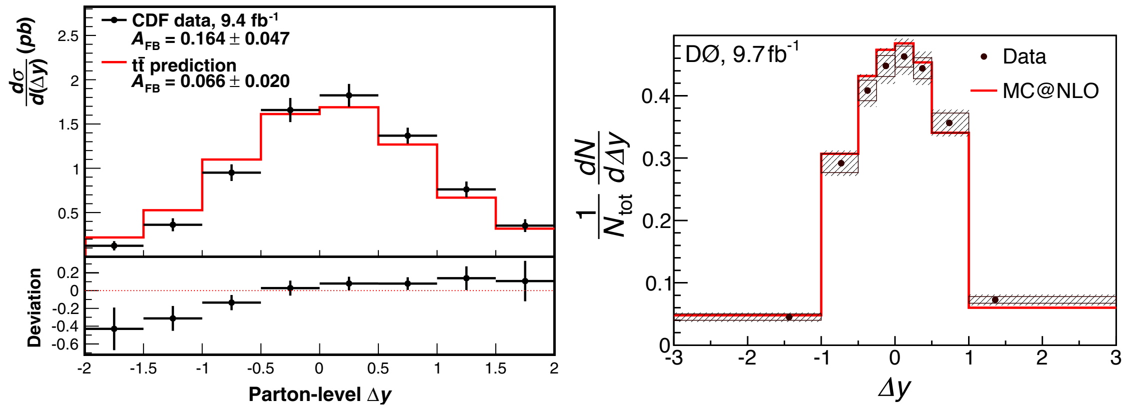

Figure 1: Differential distribution of the $t\bar{t}$ asymmetry observable Δy as measured by the CDF [6] (left) and the DØ experiment [7] (right) compared to NLO QCD predictions from the Monte-Carlo event generator MC@NLO.

2. Inclusive $t\bar{t}$ Asymmetries

Inclusive $t\bar{t}$ asymmetries are studied in the lepton+jets and the dilepton decay channels. In the lepton+jets channel the analysis starts from a kinematic reconstruction of the $t\bar{t}$ system. The top quark and antiquark are distinguished by the charge of the lepton from the semileptonic top decay. Matrix unfolding techniques are applied to correct the raw asymmetries to parton level. The results from the Tevatron experiments on the full Run II datasets are compared with the most precise SM predictions available in table 1. The corresponding differential distributions as a function of Δy, see equation (1.2), are shown in figure 1. The inclusive asymmetries obtained by the CDF and DØ experiments [6, 7] are in good agreement with the most recent SM predictions at next-to-next-to-leading order (NNLO) [9] and approximate next-to-next-to-next-to-leading order (aN^{3}LO) [10], both including electroweak (EW) corrections at NLO.

In the dilepton channel, the DØ collaboration has used a modified version of the matrix-element method, which had been originally employed for precision measurements of the top quark mass [11], to determine $A_{\mathrm{FB}}^{t\bar{t}}$ at parton level [12]. With this method $A_{\mathrm{FB}}^{t\bar{t}}$ and the correlated top quark polarization can be simultaneously. With the top quark polarization fixed to the SM prediction, an asymmetry of $A_{\mathrm{FB}}^{t\bar{t}} = 0.175 \pm 0.063$ is measured. An illustration of the method is shown in figure 2. The CDF collaboration has employed a likelihood-based $t\bar{t}$ reconstruction method and a

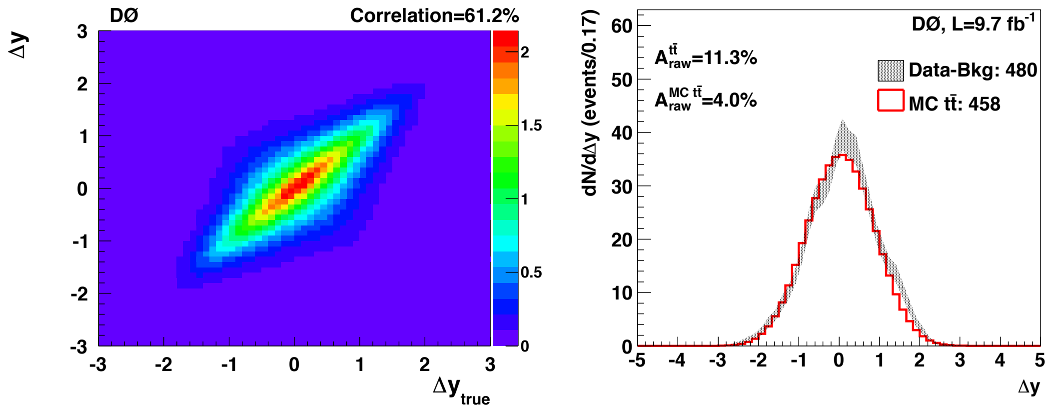

Figure 2: Measurement of $A_{\rm FB}^{t\bar{t}}$ with a modified matrix-element method [12]. Shown are the correlation between the true and the measured Δy (left) and the extracted raw Δy distribution (right).

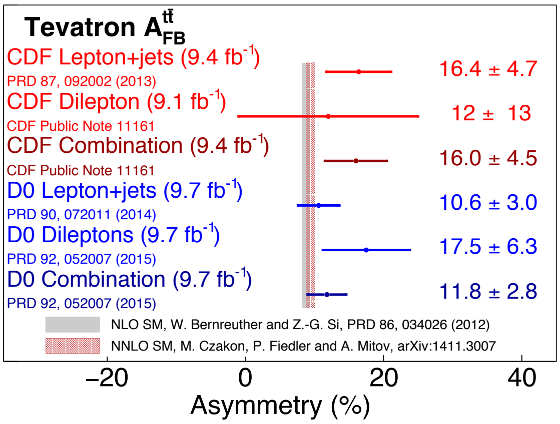

Figure 3: Overview of Tevatron measurements of the inclusive forward-backward asymmetry $A_{\rm FB}^{t\bar{t}}$ in $t\bar{t}$ production. All asymmetry values are given in percent. Figure based on [13], updated for EPS 2015.

Bayesian model to extract $A_{\rm FB}^{t\bar{t}}$ at parton level, resulting in an asymmetry of $A_{\rm FB}^{t\bar{t}} = 0.12 \pm 0.13$ [13], dominated by statistical uncertainties.

In summary, all inclusive measurements of $A_{\rm FB}^{t\bar{t}}$ using the full Tevatron Run II datasets are compatible with the predictions of the SM within 1.5 standard deviations or better, as illustrated in figure 3.

3. Differential $t\bar{t}$ Asymmetries

The forward-backward asymmetry is expected to depend on the kinematics of the $t\bar{t}$ system. In particular, larger asymmetries are expected for larger values of $|\Delta y|$ and for larger invariant masses of the $t\bar{t}$ system, $m_{t\bar{t}}$. For $|\Delta y|$ a linear dependence $A_{\rm FB}^{t\bar{t}} = \alpha|\Delta y|$ is expected. As shown in figure 4, both Tevatron experiments measure slope parameters α consistently larger but still in reasonable agreement with the SM prediction [9]. The largest deviation amounts to approximately two standard deviations. The dependence of $A_{\rm FB}^{t\bar{t}}$ on $m_{t\bar{t}}$ is illustrated in figure 5. The CDF data

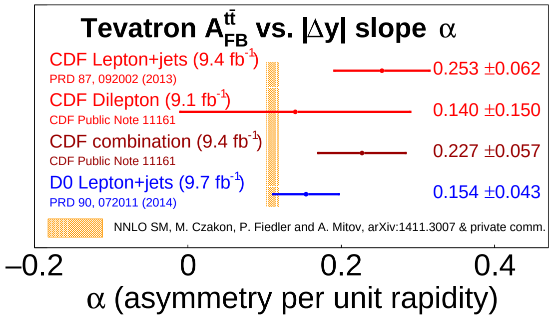

Figure 4: Overview of Tevatron measurements of the slope parameter α for the full Run II dataset. A linear dependence of $A_{\mathrm{FB}}^{t\bar{t}}$ on $|\Delta y|$ is expected: $A_{\mathrm{FB}}^{t\bar{t}} = \alpha|\Delta y|$ [13].

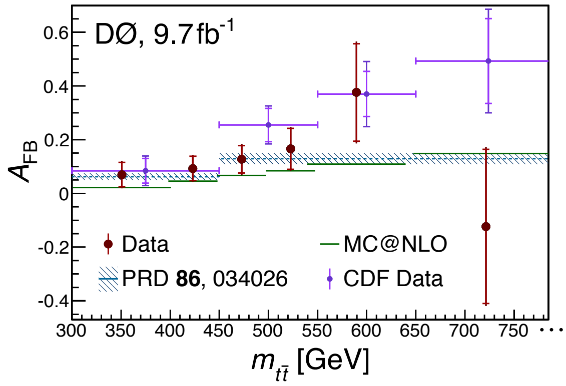

Figure 5: Comparison of $A_{\mathrm{FB}}^{t\bar{t}}$ measurements from the CDF [6] and the DØ experiment [7] as a function of the $t\bar{t}$ invariant mass $m_{t\bar{t}}$ [8].

show a strong increase with $m_{t\bar{t}}$, with an excess above the NLO QCD prediction of more than two standard deviations for large $m_{t\bar{t}}$ [6]. The DØ data, however, agree with the NLO QCD prediction and show only little $m_{t\bar{t}}$ dependence [7].

The $t\bar{t}$ forward-backward asymmetry can also be extracted from a measurement of the normalized differential cross section for $t\bar{t}$ production as a function of top-quark production angle θ_t. The differential cross section can be decomposed in orthonormal Legendre polynomials in $\cos\theta_t$, whose moments a_ℓ are sensitive to the underlying dynamics that generate the asymmetry. In the case of s-channel exchange of (BSM) particles, only a_1 is affected, while for t-channel exchange all a_ℓ are affected. The CDF collaboration has presented a measurement of $A_{\mathrm{FB}}^{t\bar{t}}$ as a function of a_ℓ in the lepton+jets decay channel [14], see figure 6. The measurement suggests that $A_{\mathrm{FB}}^{t\bar{t}}$ is entirely due to a_1, which would point to s-channel dynamics. However, preliminary comparisons of a_ℓ with NNLO computations show overall good agreement [15].

4. Leptonic $t\bar{t}$ Asymmetries

Measurements of the leptonic $t\bar{t}$ production asymmetries A_{FB}^{ℓ} allow a complementary view on $t\bar{t}$ asymmetries. In the lepton+jets decay channel A_{FB}^{ℓ} is usually quoted as an asymmetry in the product of the lepton charge q_ℓ (in units of the elementary charge e) and rapidity y_ℓ or pseudo-

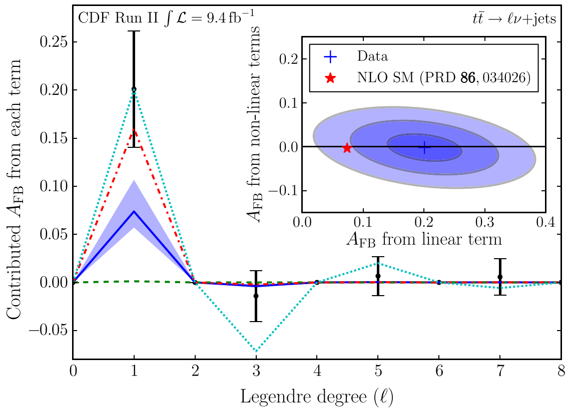

Figure 6: Measurement of $A_{\text{FB}}^{t\bar{t}}$ as a function of Legendre moments of degree ℓ in the cosine of the top-quark production angle, $\cos\theta_t$ [14].

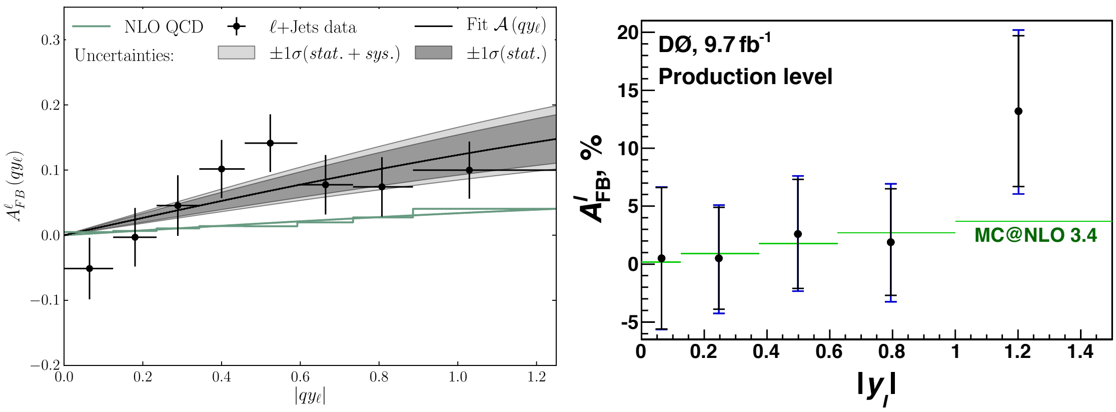

Figure 7: Leptonic $t\bar{t}$ asymmetry A_{FB}^{ℓ} in the lepton+jets channel measured by the CDF [17] (left) and the DØ experiment [18] (right).

rapidity η_ℓ. Recent calculations of A_{FB}^{ℓ} at NLO QCD and including electroweak corrections are performed in a restricted phase space taking into account the lepton acceptance [16]. This results in a very small residual model dependence. The experimental challenges of these measurements include controlling backgrounds with leptonic asymmetries, e.g. W boson production in association with jets, and extrapolating the results to unmeasured η_ℓ with empirical models. Results from the Tevatron experiments, displayed in figure 7, show reasonable agreement with SM expectation [17, 18].

In the dilepton channel, two independent but related leptonic asymmetries can be determined. In addition to A_{FB}^{ℓ}, measured e.g. as a function of $q_\ell\eta_\ell$, also the asymmetry in the difference between the lepton pseudorapidities $\Delta\eta_\ell$, $A_{\text{FB}}^{\ell\ell}$, can be determined [19, 20]. A measurement of the correlation of these two asymmetries is displayed in figure 8. The discrepancy between the observed asymmetries and the NLO QCD prediction including EW corrections amounts to 1.8 standard deviations.

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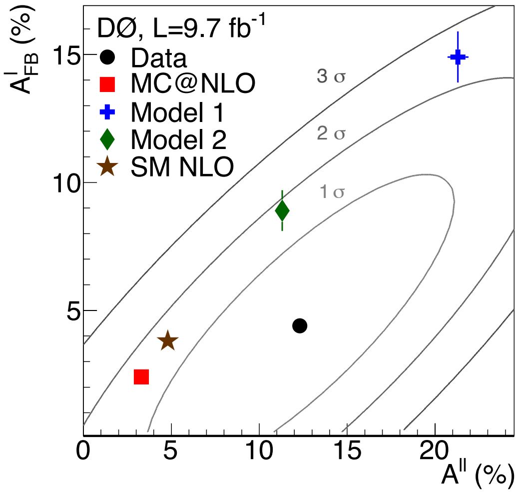

Figure 8: Correlation of the leptonic $t\bar{t}$ asymmetries A^{ℓ}_{FB} and $A^{\ell\ell}_{\mathrm{FB}}$ in the dilepton channel determined by the DØ experiment [19]. The measurement is compared with predictions from the MC@NLO event generator, SM calculations at NLO QCD with EW corrections, and two BSM physics models (Model 1: 200-GeV axigluon with right-handed SM-like couplings, Model 2: 2-TeV axigluon with strong coupling to the top quark).

5. $b\bar{b}$ Asymmetries

Motivated by the deviations from the SM in $t\bar{t}$ asymmetry observables presented above, the Tevatron experiments have also studied asymmetries in $b\bar{b}$ production. The $b\bar{b}$ system offers the opportunity to probe the same physics that gives rise to asymmetries in $t\bar{t}$ production, SM or beyond, but at lower energies.

At very low energies, here defined as b quark transverse momenta below 35 GeV, charged B mesons can be fully reconstructed in the decay $B^{\pm} \to J/\psi\,(\to \mu^+\mu^-)\,K^{\pm}$ [21]. The b flavor can be uniquely assigned by the charge sign of the $K^{\pm}$, as there is no dilution from flavor oscillations like in neutral B mesons. The data are in very good agreement with a recent SM prediction at NLO QCD and including EW corrections [22].

At medium energies, here defined as $b\bar{b}$ invariant masses $m_{b\bar{b}}$ between 40 GeV and 300 GeV, the identification of $b\bar{b}$ pairs is done via soft muons within jets originating from b quarks. The measured asymmetry in 6.9 fb^{-1} of data [23] is consistent with the SM prediction at NLO [24], as shown in figure 9 (left). The asymmetry at high energies, $m_{b\bar{b}} > 150$ GeV, is extracted from the binned difference in jet charge between the b quark and antiquark [25]. As illustrated in figure 9 (right), the results are consistent with a vanishing asymmetry and recent SM predictions [24] and start to constrain the first BSM physics models.

6. Conclusions

The Tevatron experiments CDF and DØ have performed a full suite of measurements on $t\bar{t}$ asymmetries. The measurements constitute a precise test of whether heavy-quark production

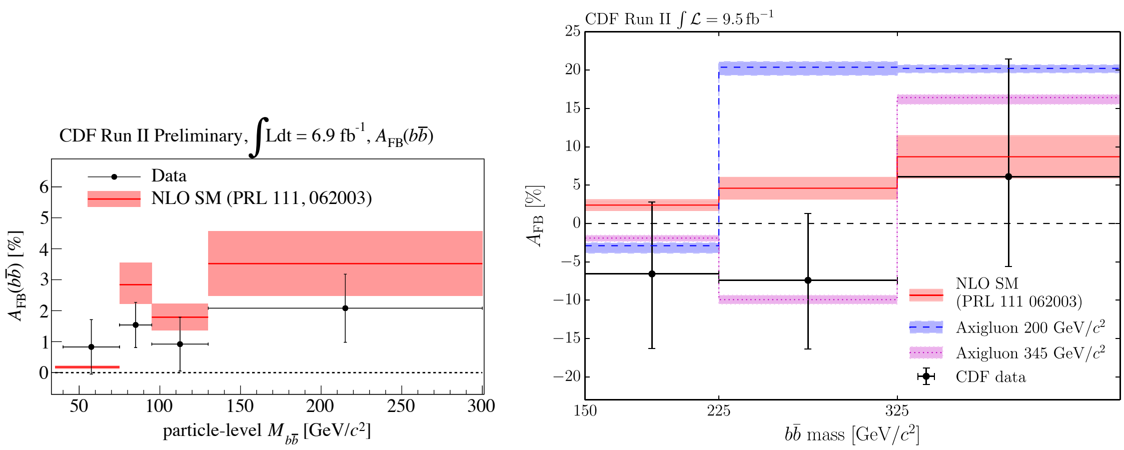

Figure 9: Forward-backward asymmetries in $b\bar{b}$ production as a function of the $b\bar{b}$ invariant mass $m_{b\bar{b}}$ at medium [23] (left) and high $m_{b\bar{b}}$ [25] (right). The data are compared to SM predictions [24] as well as to BSM physics models involving axigluons.

asymmetries are described in the SM or if BSM physics is required. A summary of the most recent measurements with the full Tevatron Run II dataset is presented in figure 10. While there are still measurements that deviate from state-of-the-art SM predictions, there are no strong hints of BSM physics in $t\bar{t}$ asymmetries. An independent look into asymmetries in $b\bar{b}$ production did not reveal any significant deviations from the SM either. A combination of the Tevatron results is ongoing.

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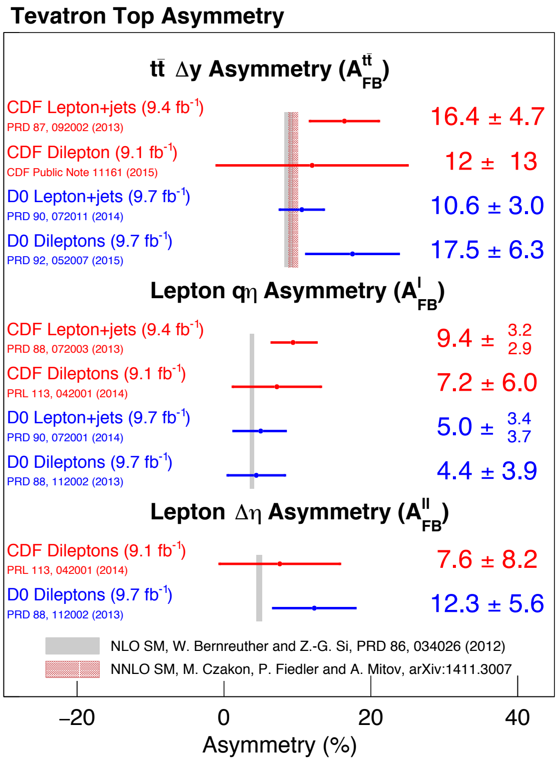

Figure 10: Overview of Tevatron measurements of the asymmetries $A_{\rm FB}^{t\bar{t}}$, $A_{\rm FB}^{\ell}$, and $A_{\rm FB}^{\ell\ell}$ in $t\bar{t}$ production. All asymmetry values are given in percent. Figure based on [13], updated for EPS 2015.

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