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TOP QUARK PHYSICS: FROM TEVATRON TO LHC

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We present an overview of the recent measurements of the top quark production cross sections, top quark properties and searches in the top sector at the Fermilab Tevatron proton-antiproton collider at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV using up to 5.6 fb^{-1} of collision data. We also discuss the prospects of top quark physics with the early LHC proton-proton data being collected at a center-of-mass energy of $\sqrt{s} = 7$ TeV.

1 Introduction

The large sample of top-antitop quark pairs collected by the D0 amd CDF experiments at the Fermilab Tevatron collider allows to perform precision measurements of the fundamental top quark characteristics, such as its production cross section and mass, and to study a broad variety of top quark production and decay properties to address the question whether the top quark is indeed the particle predicted by the standard model (SM). In this paper, we review recent new measurements of top quark cross sections, mass, width, forward-backward charge asymmetry and spin correlations in $t\bar{t}$ production and some direct searches for new physics in the top quark sector. We also present the prospects of the first top quark production and properties measurements at the new energy frontier achieved in the ongoing run of LHC.

2 Top quark production

Within the SM, top quarks are produced either in pairs via strong interactions or as single top events via electroweak interactions. Each top quark decays almost 100% of the time to a W boson and a b-quark. W bosons can decay leptonically into an electron, muon or tau and a corresponding neutrino, or hadronically into quark-antiquark pairs. Thus, the final states of $t\bar{t}$ events are subdivided into the dilepton ($\ell\ell$) channels with both W bosons decaying leptonically, the lepton+jets (ℓ+jets) channels, where one of the W bosons decays leptonically and the other one hadronically, and the all hadronic channel, where both W bosons decay hadronically.

2.1 Top quark pairs

In the Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, top quark pair production occurs via $q\bar{q}$ annihilation (85%) or gluon fusion (15%). In the pp collisions at the LHC top quark pair production is dominated by gluon fusion ($\sim 90\%$). The latest theoretical calculations of the $t\bar{t}$ production cross section [1] have an uncertainty of $\sim 5-8\%$. Any deviation of its measured value from the SM prediction could signal the presence of new physics in top-pair production or decays.

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The most precise measurements of the $t\bar{t}$ cross section have been achieved so far in the ℓ+jets channel which has a good rate and manageable background dominated by the production of W bosons in association with heavy and light flavor jets (W+jets). To discriminate signal from background two approaches are used. The first approach makes use of the distinct kinematic features of a $t\bar{t}$ event arising from its large mass. The second approach requires that at least one of the jets per event is identified as a b-jet. D0 performed $t\bar{t}$ cross section measurement with 4.3 fb^{-1} dataset using both methods [2]. The measured cross section using b-jet identification yields $\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91}(\text{stat} + \text{syst} + \text{lumi})\,\text{pb}$. The measurement that combines kinematic event information into a discriminant using Boosted Decision Trees and performs a fit to data in the same dataset gives a more precise result: $\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70}(\text{stat} + \text{syst} + \text{lumi})\,\text{pb}$. For both methods the measurements are dominated by the systematic uncertainties with the largest contribution coming from the determination of integrated luminosity (6.1%).

The CDF collaboration significantly reduces the dependence on the luminosity measurement and its associated large systematic uncertainty by exploiting the correlation between the luminosity measurements for Z boson and $t\bar{t}$ production [3]. In the CDF analysis, the ratio of the $t\bar{t}$ to Z boson cross section, measured using the same triggers and dataset, is computed and multiplied by the precisely known theoretical Z cross section. Thus, the luminosity uncertainty is replaced with the smaller theoretical and experimental uncertainties on Z cross section. Using this approach in the dataset of 4.6 fb^{-1} the CDF collaboration measures the cross section of $\sigma_{t\bar{t}} = 7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{syst}) \pm 0.15(\text{theory})\,\text{pb}$ combining kinematic event information into a neural network and performing a fit to the data and $\sigma_{t\bar{t}} = 7.32 \pm 0.36(\text{stat}) \pm 0.59(\text{syst}) \pm 0.14(\text{theory})\,\text{pb}$ using b-jet identification. Combination of these two measurements yields the most precise top quark cross section measurement to date of $\sigma_{t\bar{t}} = 7.70 \pm 0.52\,\text{pb}$. All cross sections quoted above assume top quark mass $m_t = 172.5$ GeV.

For the measurements using b-jet identification important uncertainty comes from the flavor composition of W+jets background which is not well modeled by existing event generators. CDF collaboration performed a simultaneous measurement of the $t\bar{t}$ cross section and the normalization of different W+jets background components [4]. The latter are consistent with the existing measurements using other procedures. This approach has an additional advantage of measuring many systematic uncertainties in-situ which inversely scale with integrated luminosity similarly to statistical uncertainties.

Up to now $t\bar{t}$ production cross sections were measured at Tevatron in all channels except for the one with two hadronic taus in the final state. All measurements are in agreement with the theoretical calculations.

2.2 Single top quark

Electroweak production of the single top quarks was predicted [5] ten years before the discovery of the top quark, but it was observed only recently by the CDF and D0 collaborations [6] due to its small production rate and high backgrounds. Single top production allows to probe Wtb interaction since its rate is proportional to the V_{tb} mixing matrix element. At the Tevatron single top quarks are produced by either a t-channel exchange of a virtual W boson which produces a top quark via interaction with a b-quark, or by an s-channel exchange of an off-shell W boson which decays into a top and a b quark. At the LHC single top production via a b-quark or a t-quark exchange, so called Wt channel, also becomes important.

Following the observation of the combined s- and t-channel production, the D0 collaboration published 4.8σ evidence for the t-channel production [7] with a cross section of $\sigma_{t-ch} = 3.14^{+0.94}_{-0.81}$ pb. Figure 1 (left) summarizes combined s+t channel single top cross section measurements [6], and Fig. 1 (right) shows the result of a simultaneaous s- and t-channel cross section extraction.

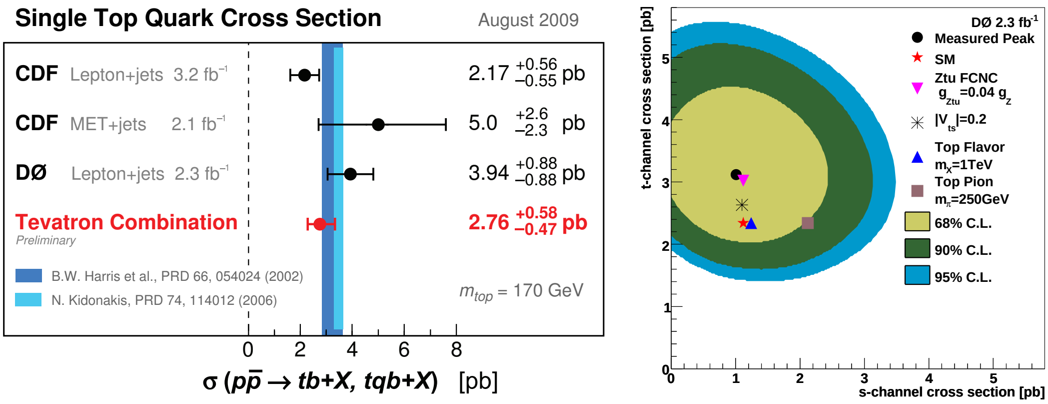

Figure 1: Left: Tevatron single top cross section measurements and their combination. Right: posterior probability density for t-channel and s-channel single top quark production in contours of equal probability density. Also shown are the measured cross section, SM expectation, and several representative new physics scenarios which change the SM ratio of the two production modes.

2.3 Top quark production at LHC

Establishing the top quark signal is one of the key milestones for the early LHC physics program since it requires a good performance and understanding of all detector components and object identification. Given that the production rate of top pairs is about 20 times larger at LHC than at the Tevatron, a dataset of 10 pb^{-1} at the LHC expected towards the end of 2010 will be enough to perform first measurements of the $t\bar{t}$ production. In the ℓ+jets channel approximately 60 $t\bar{t}$ events with four or more jets per lepton flavor per experiment on a background of 40 events are expected. In the dilepton channel 25 signal events are expected with a background of 5.5 in the same dataset [9].

As at the Tevatron, observation of the single top production will be challenging and is expected to be possible with the dataset of 1 fb^{-1} at 7 TeV.

3 Top quark properties

Since the discovery of the top quark in 1995 a substantial effort has gone into measuring its properties. Most of them, such as top quark charge, lifetime, production mechanism, branching fractions and couplings are well defined in the SM, and their measurements provide a probe of its validity. The top quark mass is a free parameter of the SM. Its surprisingly large value suggests a unique role of the top quark in the mechanism of electroweak symmetry breaking.

3.1 Top quark mass

A precise measurement of the top quark mass, together with that of the W boson, allows to constrain indirectly through radiative corrections the mass of the SM Higgs boson [8]. It could also provide a useful constraint to possible extensions of the SM. It is therefore of great importance to continue improving measurements of m_t.

The most precise measurements of the top quark mass have been obtained so far from the matrix element method [10] applied to ℓ+jets events. In this method, the probability for each event to be a signal or a background as a function of m_t is calculated. Event probabilities are then multiplied to extract the most likely mass.

The measurement of m_t is dominated by the systematic uncertainties with the largest one coming from uncertainties in the jet energy calibration (JES). Recent measurements use JES as a second parameter in the fit to data which is constrained by the mass of the hadronically decaying W boson in top quark pair production. This technique has proven to significantly redure the total error due to JES. The most recent measurement from CDF using 5.6 fb^{-1} of data [11] yields $m_t = 173.0 \pm 0.7(\text{stat}) \pm 0.6(\text{JES}) \pm 0.9(\text{syst})$ GeV, corresponding to a total uncertainty of 1.2 GeV and a relative uncertainty of 0.7%. Figure 2 (left) shows the result of the simultaneous fit of the JES and m_t to data.

A summary of the top quark mass measurements at Tevatron and their combination as of July 2010 are presented in Fig.2 (right). They agree between different channels and different methods. Taking correlated uncertainties properly into account the resulting preliminary Tevatron average mass of the top quark is $m_t = 173.3 \pm 1.1$ GeV [12]. The largest uncertainty on the combined mass of 0.46 GeV comes from the statistical component of in-situ JES determined from the fit to data followed by the uncertainties associated with the different aspects of the signal modeling. As the former is expected to go down with the increase of integrated luminosity, the latter will soon become a limiting factor for the precise measurement of m_t.

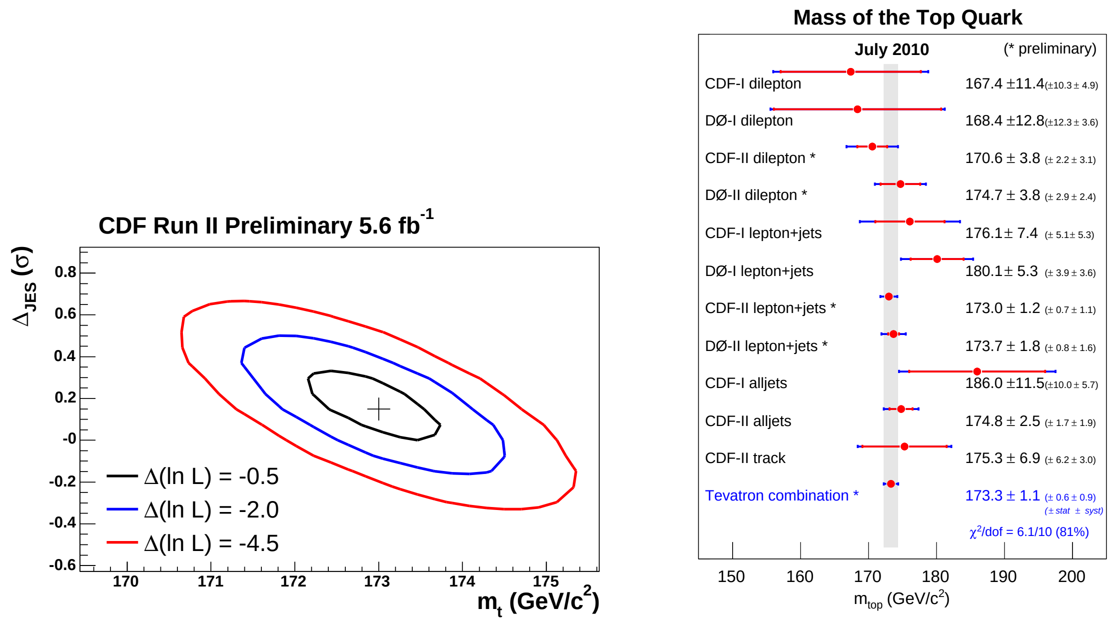

Figure 2: Left: result of the simultaneous fit of the JES and m_t. Right: summary of the top quark mass measurements at Tevatron and their combination.

Top quark mass measurements assume that the top quark mass is equal to the antitop quark mass as demanded by CPT theorem. The measurement of the quark and antiquark mass difference would probe CPT invariance. For all known quarks but the top quark this quantity has been never measured directly because the quarks are never observed in isolation. Top quarks, however, make this measurement possible because they decay before hadronization. D0 has published the first such measurement in 1 fb^{-1} of data using a matrix element technique and found $\Delta M = 3.8 \pm 3.7$ GeV [13]. The CDF collaboration studied the top quark mass difference in 5.6 fb^{-1} of data [14] using a template method. In this method, distributions of variables strongly correlated with m_t and derived from simulations for different m_t hypotheses are used as templates to extract m_t from the fit to the measured distribution in data. CDF finds $\Delta M = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV. Both measurements are in good agreement with the SM within large uncertainties dominated by statistical one which can be significantly reduced by the end of the Tevatron run.

The first top quark mass measurements at LHC are expected to be carried out with $\sim$100 pb^{-1} of integrated luminosity. Both CMS and Atlas experiments plan to use template method in the early data in combination with the jet energy calibration information provided by the hadronically decaying W boson and achieve a systematic uncertainty of 2 GeV in the 1 fb^{-1} dataset. It will take several years for LHC experiments to superseed the current precision of the m_t measurements by the Tevatron experiments.

3.2 Top width

The total width, or lifetime, of the top quark is a fundamental property that has not been measured precisely so far. The top quark, like other fermions in the SM, decays through the electroweak interaction. But unlike b- and c-quarks, which form long-lived hadrons that can be observed through the reconstruction of displaced vertices in a detector, the top quark has an extremely short lifetime. In the SM, the total decay width of the top quark, Γ_t, is dominated by the $t \to Wb$ decay. It depends on m_t and is predicted to be approximately 1.5 GeV for $m_t = 175$ GeV [15] at next-to-leading order.

CDF performed a direct measurement of the top quark width in the ℓ+jets channel using 4.3 fb^{-1} of data by studying the reconstructed top quark mass spectrum [16] which is sensitive to Γ_t. However, since the experimental resolution is much smaller than Γ_t the analysis sets only an upper limit on the width, $\Gamma_t < 7.5$ GeV at 95% C.L.

The D0 collaboration takes a different approach and following Ref. [17] measures Γ_t indirectly from the t-channel single top quark production cross section which is proportional to the partial width $\Gamma(t \to Wb)$. This method assumes that couplings in the top quark production and decay are the same. The total width Γ_t is extracted from the measured partial width and the branching fraction $\mathcal{B}(t \to Wb)$ determined in 1 fb^{-1} dataset [18], and is found to be $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV for $m_t = 170$ GeV corresponding to a top quark lifetime of $\tau = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s [19].

3.3 Spin correlations

Extremely short lifetime of the top quark allows to study the top quark spin at its production since hadronization effects do not deteriorate spin information reflected in the angular distributions of the top quark decay products. While the top and antitop quarks are produced unpolarized at the hadron colliders, their spins are correlated [20]. The strength of the correlation can be expressed as the asymmetry $\kappa = \frac{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}-N_{\downarrow\uparrow}-N_{\uparrow\downarrow}}{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}+N_{\downarrow\uparrow}+N_{\uparrow\downarrow}}$ between the number of events with parallel spins, $N_{\uparrow\uparrow}$ and $N_{\downarrow\downarrow}$ and the number of events with antiparallel spins, $N_{\uparrow\downarrow}$ and $N_{\downarrow\uparrow}$. κ depends on the choice of the quantization axis, referred to as "spin basis".

The CDF and D0 collaborations have measured the spin correlations between t and $\bar{t}$ in the dilepton channel using data with an integrated luminosity of 2.8 fb^{-1} (CDF) and up to 4.2 fb^{-1} (D0), respectively. In both analysis, the double differential distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - \kappa\cos\theta_1\cos\theta_2) \quad (1)$$

is used to extract the correlation parameter κ. Here θ_1 and θ_2 are the angles of a decay product flight direction in the t ($\bar{t}$) rest frame and the chosen quantization axis for t ($\bar{t}$). D0 performed the analysis in the beam basis and extracted the correlation from the angular distributions of leptons [21]. Figure 3 (left) shows the $\cos\theta_1\cos\theta_2$ distribution in data compared to the sum of the background and $t\bar{t}$ signal with the spin correlation parameter set to NLO prediction of 0.777. The open black histogram shows the prediction without $t\bar{t}$ spin correlation. D0 finds a spin correlation strength of $\kappa = -0.09^{+0.59}_{-0.58}$. CDF uses the off-diagonal basis and measures κ using angular distributions of b and $\bar{b}$ quarks as well as leptons. The analysis yields $\kappa = 0.32^{+0.55}_{-0.78}$ to be compared to the NLO prediction of 0.782 for the off-diagonal basis.

In a dataset of 5.3 fb^{-1} CDF measured spin correlations in the ℓ+jets channel in the beam and helicity basis by studying the double differential distributions of Eq.1 for a lepton and a down type quark from the W decay and for a b and a down type quark. This analysis extracts the spin correlation parameter κ by measuring the fraction of $t\bar{t}$ events with the opposite helicity in the helicity basis, and similarly, the fraction of $t\bar{t}$ events with the opposite spin in the beam basis. CDF finds $\kappa_{\rm hel} = 0.48 \pm 0.48(\rm stat) \pm 0.22(\rm syst)$ in the helicity basis, consistent with the NLO prediction of 0.35. In the beam basis $\kappa_{\rm beam} = 0.72 \pm 0.64(\rm stat) \pm 0.26(\rm syst)$. Figure 3 (right) shows the angular distribution of a lepton and a b-quark in data compared to the background model and the sum of the same sign and the opposite sign spin model for $t\bar{t}$, with the normalizations determined by the fit to data. All measurements of the spin correlations

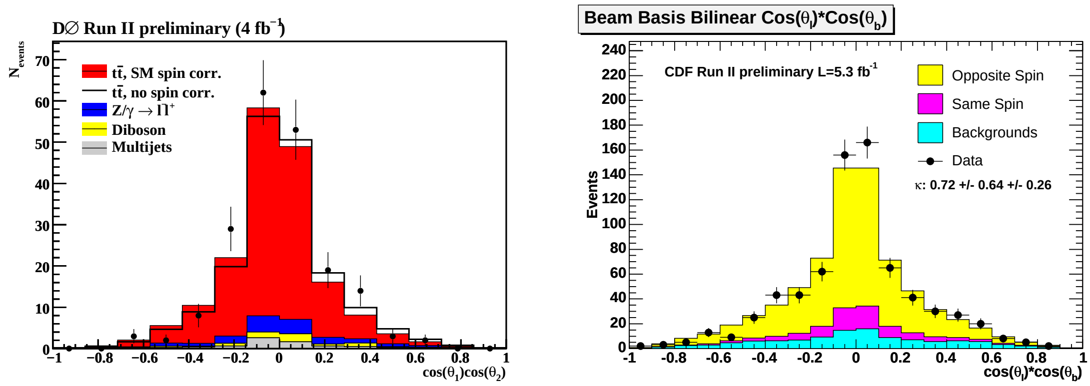

Figure 3: Left: angular distribution in data compared to the sum of the background and $t\bar{t}$ signal with and without spin correlation. Right: angular distribution in data compared to the sum of the background model and the sum of the same sign and the opposite sign spin contribution for $t\bar{t}$.

performed at the Tevatron so far are consistent with the SM within large uncertainties dominated by the statistical one.

3.4 Forward-backward production asymmetry

In QCD at LO, the top quark production angle is symmetric with respect to the beam direction. In NLO a small charge asymmetry arises from interference effects. It can be observed at the Tevatron as a forward-backward asymmetry defined as $A_{fb} = \frac{N(-Q\times Y_{had}>0)-N(-Q\times Y_{had}<0)}{N(-Q\times Y_{had}>0)+N(-Q\times Y_{had}<0)}$, where Q is the lepton charge and Y_{had} is the rapidity of the top quark decaying hadronically. According to MCFM calculation [22], $A_{fb} = 0.038$ ($A_{fb} = 0.058$) in the laboratory ($t\bar{t}$ rest) frame. Asymmetry increases with the rapidity separation of the two quarks.

Measurements of the forward-backward assymetry sparked a large interest among theorists because previous inclusive measurements by the CDF and D0 collaborations have found large positive asymmetries that were nevertheless consistent with the NLO predictions within large uncertainties [23]. The deviation of the observed forward-backward asymmetry from the SM prediction can indicate the contribution from the unexpected new $t\bar{t}$ production channels.

A new CDF analysis studies forward-backward asymmetry using reconstructed semileptonic $t\bar{t}$ events with at least one identified b-jet in a dataset of 5.6 $\rm fb^{-1}$ [25]. Asymmetry is determined at the parton level to be $A_{fb} = 0.150 \pm 0.050(\rm stat) \pm 0.024(\rm syst)$ in the laboratory frame and $A_{fb} = 0.158 \pm 0.072(\rm stat) \pm 0.017(\rm syst)$ in the $t\bar{t}$ rest frame, in agreement with the previous measurements. Figure 4 (left) presents the distribution of the reconstructed rapidity of the top quark y_t (which is equal to $-y_{\bar{t}}$ in the laboratory frame) in data compared to the sum of signal and background. The legend shows the reconstructed A_{fb} before correction for the resolution and reconstruction effects.

Additionally, CDF measures A_{fb} for the rapidity difference

$$A_{fb} = \frac{N^{\pm}(\Delta y > 0) - N^{\pm}(\Delta y < 0)}{N^{\pm}(\Delta y > 0) + N^{\pm}(\Delta y < 0)}\,, \tag{2}$$

where $\Delta y = y_{lep} - y_{had}$, in two regions of the $t\bar{t}$ rapidity difference: $A_{fb}(|\Delta y| < 1.0) = 0.026 \pm 0.104(\text{stat}) \pm 0.055(\text{syst})$ and $A_{fb}(|\Delta y| > 1.0) = 0.611 \pm 0.210(\text{stat}) \pm 0.141(\text{syst})$, to be compared to the MCFM model predictions 0.039 $\pm$0.006 and 0.123 $\pm$0.018 for the inner and outer rapidities, respectively. Figure 4 (center) shows the asymmetry in the $t\bar{t}$ rest frame at small and large $|\Delta y|$, including correction to the parton level and comparison with the MCFM prediction.

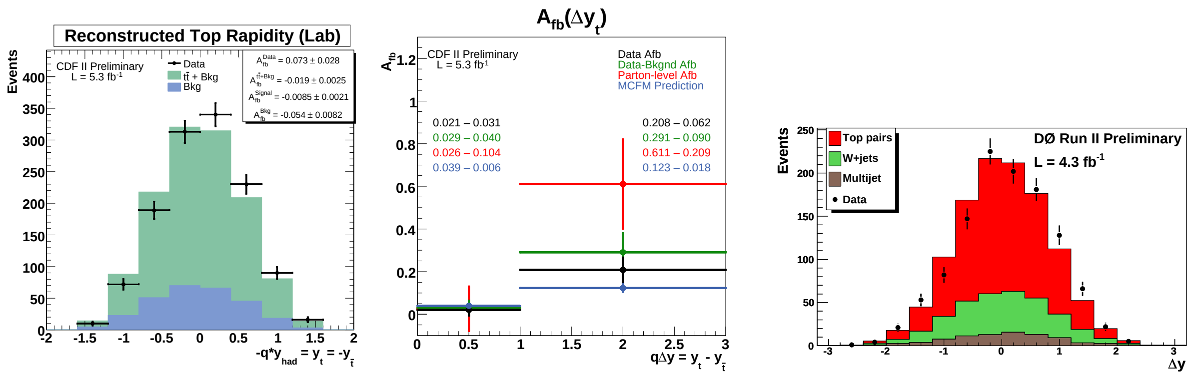

Figure 4: Left: distribution of the reconstructed rapidity of the top quark y_t in data compared to the sum of signal and background. Center: the asymmetry in the $t\bar{t}$ rest frame at small and large $|\Delta y|$. Right: reconstructed Δy in data compared to the signal and background model.

Using the 4.3 fb^{-1} dataset D0 recently updated the previous measurement where A_{fb} was defined according to Eq.2 and found reconstructed $A_{fb} = (8 \pm 4)$ %[24]. Figure 4 (right) compares reconstructed Δy in data with the signal and background model. Distributions shown in the right and left plots of Fig. 4 show the difference in shapes between the asymmetry predicted by the simulation and the observed one in data.

4 Searches in the top quark sector

The uniquely large mass of the top quark distinguishes it from the other fermions of the SM and stimulates searches for new physics in the top quark sector. One of the recent searches preformed by both CDF and D0 collaborations in datasets of 4.6 fb^{-1} and 4.3 fb^{-1}, respectively, is a search for heavy top (t') quark pair production with t' decaying to a W boson and a down-type quark $q = d, s, b$. The earlier analysis by CDF using 2.8 fb^{-1} dataset excluded a fourth-generation t' quark with mass below 311 GeV at 95% C.L.[27] but showed an interesting deviation of the observed limit from the expected one at the level of 2σ for $m_{t'}$ above 370 GeV.

The t' quark is assumed to be produced in pairs via strong interactions, to have mass greater than m_t and decay promptly to Wq final states with branching ratio 100%. Such a particle appears, for example, in Little Higgs models[26] that require the existence of a vectorlike quark T as a partner of the top quark. The analysis considers the ℓ+jets final state, reconstructs the mass of the t' quark and performs a two-dimentional fit of the observed mass and the sum of jets and lepton transverse momenta and missing transverse energy of the event. The data show no t' presence, and the CDF and D0 experiments exclude a fourth-generation t' quark with mass below 335 GeV[28] and below 296 GeV[29] at 95% C.L., respectively. The rise of the observed limit over expected at high $m_{t'}$ is still present in both searches.

4.1 Top quark properties and searches at LHC

The majority of the top quark properies measurements and direct searches for new physics are statistically limited at the Tevatron, and they will benefit from the large samples of $t\bar{t}$ events expected to be collected at LHC. The sensitivity exceeding the one of Tevatron can be achieved already in the dataset of approximately 500 pb^{-1} at $\sqrt{s} = 7$ TeV which will become available in 2011. Therefore by the end of LHC 7 TeV run one can expect more precise measurements of the basic top quark properties such as width, charge and couplings. However, some measurements, like forward-backward asymmetry and spin correlation, will be different and thus complementary to the ones from the Tevatron since $t\bar{t}$ pairs at LHC are mostly produced by gluon fusion rather than by $q\bar{q}$ annihilation as at the Tevatron.

A search for the $t\bar{t}$ resonances is one of the first searches for new physics to be performed at LHC [30]. Its discovery potential depends significantly on the ability to reconstruct highly boosted top quarks. The technique developed by the CMS collaboration to distinguish top jets from light quark and gluon jets allows to reduce dijet background to heavy $t\bar{t}$ resonances by $\sim 10,000$ [31]. The first search for boosted top quarks at the Tevatron was reported recently by the CDF collaboration [32].

5 Conclusion

Top quark physics today has achieved unprecedented precision on the top quark pair production cross section and top quark mass measurements, significantly beyond the Tevatron goals. Tevatron experiemnts achieved impressive sensitivity in measurements of the top quark properties and studied such new ones as top quark width and spin correlations. A broad program of searches for new physics in the top quark sector is ongoing. So far no significant deviations from the SM have been observed. First top quark measurements from the LHC expected in 2011 will be an important milestone towards top quark physics at the new energy and precision frontier.

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