TOP PAIR PRODUCTION

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We review the most recent results on top quark pair production at the Tevatron including production mechanism, cross sections, forward-backward asymmetry measurements and searches for resonances decaying to top quarks which were available at the time of the 2008 electroweak session of the Rencontres de Moriond conference.

1 Introduction

Since its discovery by the CDF and D0 experiments [1] the Tevatron is the only place where the top quark (t) can be studied. The year 2008 will certainly be the last possible year for such a statement due to the advent of the LHC.

Doing top quark physics means covering a wide spectrum of different subjects including studies of the t (single and pair) production, decay and properties. The present mini-review focuses on top quark pair ($t\bar{t}$) production and the emphasis is put on recent results concerning the $t\bar{t}$ production mechanism, cross section measurements and top quark mass (m_t) measurements from cross sections measurements, forward backward measurement and finally searches of resonances decaying into t quarks. Recent results concerning m_t direct measurements as well as other properties (W helicity, t charge) and the single t production can be found in these proceedings [2]. The Tevatron is performing well and the results reported here correspond to Tevatron integrated luminosities ranging from 1 to 2 fb^{-1}.

At the Tevatron, within the Standard Model (SM), $t\bar{t}$ production is expected to occur via strong interactions namely through $q\bar{q}$ annihilation (85%) and gluon gluon (gg) fusion (15%). Typical next-to-leading (NLO) predictions range from $\sigma(p\bar{p}) \rightarrow t\bar{t} \approx 6.7 \pm 0.4$ pb for $m_t = 175$ GeV to $\sigma(p\bar{p}) \rightarrow t\bar{t} \approx 7.8 \pm 0.5$ pb for $m_t = 170$ GeV [3,4]. The t is expected to decay before it hadronizes. The t decays into a b quark and an on-shell W gauge boson ($t \rightarrow Wb$) with a branching ratio close to 1. The final states corresponding to $t\bar{t}$ production are classified according to the decay of the W gauge boson from the t. The results reported here concentrate on the lepton+jets channels where one W gauge boson decays leptonically i.e. $W \rightarrow l\nu$ where $l = \mu$ or e (amounting to 30% of all the $t\bar{t}$ channels) and dilepton channels where both W decay leptonically (5%). Other channels include all hadronic channels where both W gauge bosons decay hadronically ($W \rightarrow qq'$, 45%) as well as tauonic channels where both W decay leptonically into tau leptons (20%).

The main physics backgrounds from SM processes are also decay channel dependent. The main SM physics backgrounds for $t\bar{t}$ signals in the lepton+jets channel come from W+jets production as well as multijets production where one jet fakes an electron or a muon. In the dilepton channel the main physics backgrounds come from Z gauge boson production decaying into a lepton pair, Drell Yan processes and gauge boson pair production. Typical event selections require high p_T lepton ($>$ 15 to 20 GeV), large missing transverse energy ($>$ 15 to 20 GeV) and jets with large transverse energies ($>$ 15 to 20 GeV). They also include cuts on several kinematical variables. In several analyses the selection uses of b-quark jets identification based either on displaced vertices (with efficiencies ranging from 50 to 60 %) or soft lepton taggers.

2 Production mechanism

The evaluation of the gg fusion process in $t\bar{t}$ production suffers from theoretical uncertainties and can vary up to a factor of 2. This motivates the CDF experiment to perform a measurement of the relative fraction C_f of gluon gluon fusion ($t\bar{t}^{gg}$) versus quark antiquark annihilation ($t\bar{t}^{q\bar{q}}$) by combining two complementary methods which were already reported elsewhere before this conference. The new CDF result presented at this conference concerns the combination.

The first method is a data driven method based on low p_t tracks [5]. Because gluons can radiate other partons and gluons, ($t\bar{t}^{gg}$) should have more low p_t tracks. The shapes of the track p_t distributions of the two components ($t\bar{t}^{gg}$ and $t\bar{t}^{q\bar{q}}$) are derived from inclusive dijets and $W + n$ jets (where $n = 0, 1, 2$) data samples. The background shape is then constructed as a combination of the $t\bar{t}^{gg}$ and $t\bar{t}^{q\bar{q}}$ shapes. The three shapes are then fit to the data sample selected for the t signal in the lepton+jets channel. The second method uses the kinematics of the production and the decay of the $t\bar{t}$ to differentiate the two production mechanisms [6]. The kinematic variables are used to train a neural network (NN) to increase the sensitivity of the method. This analysis relies on Monte Carlo (MC). A large ensemble of pseudo-experiments (PSE) are generated to calculate the statistical and systematical uncertainties and the Feldman-Cousins (FC) [7] method is used to make the measurement. The track method and the NN method are then combined into a combined PSE method [8]. Using a total integrated luminosity of 995 pb^{-1} the CDF experiment finds: $C_f = 0.07^{+0.15}_{-0.07}$ at 68 % confidence level.

3 Top quark pair production cross section and top quark mass from cross sections measurements

3.1 Top quark pair production cross section measurements

The D0 experiment performed a new measurement of the $t\bar{t}$ production cross section in the lepton+jets channel employing two complementary methods for discrimination between signal and background namely using a likelihood discriminant and b-tagging [9]. This new measurement is based on about 0.9 fb^{-1} of data.

Events with $t\bar{t}$ decays differ in their event kinematics from background events. However no single kinematic quantity can separate signal and background very well. This motivates the development of the likelihood discriminant method which uses up to 6 kinematical quantities [9] in each channel to discriminate the $t\bar{t}$ signal from the backgrounds. Four channels are defined

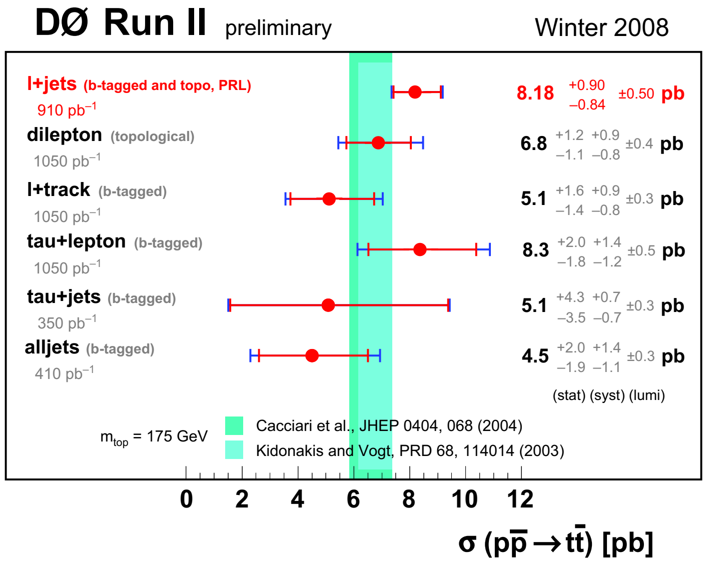

Figure 1: Summary of $t\bar{t}$ production cross-section measurements from the D0 experiment available at the time of the 2008 EW session of the Recnontres de Moriond conference.

by lepton flavor (e, μ) and jet multiplicity ($3, \geq 4$).

The probability density functions of the likelihood discriminant is determined from MC for $t\bar{t}$ signal and prompt lepton backgrounds and from a control data sample for multijets backgrounds (backgrounds without prompt leptons) both using the TMVA method [10]. A maximum likelihood fit to the distribution of the likelihood discriminant from the data is then performed in all four channels simultaneously with the $t\bar{t}$ production cross section as a free parameter.

The b-tagging method exploits the fact that every $t\bar{t}$ decay produces two b quark to distinguish them from the backgrounds. The signal over background ratio is enhanced by requiring at least one b-tagged jet. The $t\bar{t}$ signal and prompt lepton backgrounds are modeled with the MC and the backgrounds from multijets events are determined from the data. The cross section is calculated using a maximum likelihood fit to the number of events in eight different channels defined by the lepton flavor (e, μ), jet multiplicity ($3, \geq 4$) and b-tag multiplicity ($1, \geq 2$).

Combining the likelihood discriminant and the b-tagging methods with the help of the method described in [11], the D0 experiment measures the $t\bar{t}$ production cross section in the lepton+jets channel using a total integrated luminosity of 910 pb^{-1} $\sigma(p\bar{p}) \rightarrow t\bar{t}) = 7.77 \pm 0.54(stat.) \pm 0.47(syst.) \pm 0.47(lumi.)$ pb for $m_t = 170$ GeV and $\sigma(p\bar{p}) \rightarrow t\bar{t}) = 7.42 \pm 0.53(stat.) \pm 0.46(syst.) \pm 0.45(lumi.)$ pb for $m_t = 175$ GeV.

Figure 1 shows that the measurements are consistent with each other and consistent with the SM predictions. New physics would show up as inconsistencies.

3.2 Top quark mass from cross sections measurements

The value of m_t can vary significantly depending on its different possible (and related) definitions from the running m_t definition in the (for example) $\bar{MS}$ scheme (from the 1-loop up to the 3-loop level) to the $m_t pole$ [12] which is itself defined up to some ambiguities such as the known renormalon ambiguity [13].

At the Tevatron, the m_t measurements are performed by using template, ideogram, neutrino weighting or matrix element 'direct' methods [14]. They rely on the detailed description of the $t\bar{t}$ production in the MC simulations which currently contain only matrix elements at the leading order (LO) of quantum chromodynamics (QCD) and higher orders are simulated by applying parton showers thus leaving in principle the m_t convention unknown. Therefore the world average of m_t is extracted in a not very well-defined scheme. The t quark mass can also be measured from the $t\bar{t}$ production cross section measurements. These 'indirect' measurements will thus provide valuable complementary informations on the value of m_t. Although efforts are put in improving their accuracy they are not meant to compete in precision with the 'direct' m_t measurements. The measurement of m_t from the most recent $t\bar{t}$ production cross section measurement from the D0 experiment reported in subsection 3.1 was not available at the time of the 2008 EW session of this conference but can be found in its QCD session [15]. Therefore we will only mention the results obtained with the previous set of cross-section measurements of summer 2007 [16] corresponding to an integrated luminosity of 910 pb^{-1} for the lepton+jets channel and 1.05 fb^{-1} for the dilepton channel. Comparing the cross section measurements in the lepton+jets channel[17] with the predictions of[3], and[4] respectively, leads to $m_t = 166.9^{+5.9}_{-5.2}(stat.+syst.)^{+3.7}_{-3.8}(theory)$ GeV, and $m_t = 166.1^{+6.1}_{-5.3}(stat.+syst.)^{+4.9}_{-6.7}(theory)$ GeV respectively. This can be compared with the direct measurement from the D0 experiment with the matrix element method [19] $m_t = 170.5 \pm 2.4(stat. + JES) \pm 1.2(syst.)$ GeV and with the 2007 world average $m_{top} = 170.9 \pm 1.1(stat.) \pm 1.5(syst.)$ GeV.

Comparing the measurements in the dilepton channel [18] and predictions leads to $m_t = 174.5^{+10.5}_{-8.2}(stat. + syst.)^{+3.7}_{-3.6}(theory)$ GeV and $m_t = 174.1^{+9.8}_{-8.4}(stat. + syst.)^{+4.2}_{-6.0}(theory)$ GeV respectively. This can be compared with the direct measurement from the D0 experiment with the neutrino weighting method [20] $m_t = 172.5 \pm 5.8(stat.) \pm 5.5(syst.)$ GeV.

The CDF experiment performed a new m_t measurement using the $t\bar{t}$ production cross section measurement in the dilepton channel, with an integrated luminosity of 1.2 fb^{-1}, as a constraint. Since the number of $t\bar{t}$ signal events depends on m_t, the observed number of events can therefore be used to measure m_t.

The kinematics of the $t\bar{t}$ system in the dilepton channel data sample is solved using the information on the momentum z-component of the $t\bar{t}$ system taken from the $t\bar{t}$ data sample in the lepton+jets channel. Solving the kinematics of the $t\bar{t}$ system in the dilepton channel allows to reconstruct m_t. The CDF experiment then uses a likelihood fit to get the final m_t measurement. The reconstructed m_t distribution from data is compared to MC signal and backgrounds templates and the number of events is compared to the expected number of events. The result of the likelihood fit gives: $m_t = 170.7^{+4.2}_{-3.9}(stat.) \pm 2.6(syst.) \pm 2.4(theory)$ GeV.

4 Forward backward asymmetry

At the Tevatron the $t\bar{t}$ production is predicted to be charge symmetric at LO in QCD. However NLO calculations predicts asymmetries in the 5%-10% range [23] and next-to-next-to-leading order (NNLO) calculations predict significant corrections for $t\bar{t}$ production in association with a jet [24]. The charge asymmetry arises from the interferences between symmetric and antisymetric contributions under the exchange $t \leftrightarrow \bar{t}$. The charge asymmetry depends on the region of phase space being and, in particular, on the production of an additional jet. The small asymmetries expected in the SM makes this a sensitive probe for new physics [25].

Using a data sample corresponding to an integrated luminosity of about 0.9 fb^{-1}, the D0 experiment performed the first measurement of the forward-backward charge asymmetry in $t\bar{t}$ production in the lepton+jets channel [26]. The forward-backward charge asymmetry can be obtained from the signed difference between the rapidities of the t and $\bar{t}$, $\Delta y = y_t - y_{\bar{t}}$ where the rapidity y is defined as function of the polar angle θ and the ratio of the particle's momentum to its energy β as $y(\theta, \beta) = \frac{1}{2} ln[(1 + \beta cos\theta)/(1 - \beta cos\theta)]$. The asymmetry is defined as:

$$A_{fb} = \frac{N^{\Delta y > 0} - N^{\Delta y < 0}}{N^{\Delta y > 0} + N^{\Delta y < 0}}, \quad (1)$$

where $N^{\Delta y>0}$ ($N^{\Delta y<0}$) is the number of event with positive (negative) Δy.

Using a data sample with one lepton+ n jets,where $n \geq 4$ one jet at least being b-tagged in order to enhance the signal, the kinematics of the $t\bar{t}$ is reconstructed wiht the help a kinematic fitter which varies the 4-momenta of the detected objects within their resolutions and minimizes a χ^2 statistics, constraining both the known W gauge boson mass (M_W) and m_t.

The sample composition, including $t\bar{t}$ signal and W+jets from MC simulations and multijet background from data samples that fail lepton identification, as well as A_{fb} are then extracted from a simultaneous maximum-likelihood fit to data.

The observed asymmetry, uncorrected for acceptance and reconstruction effects, are $A_{fb}^{obs} = 0.12 \pm 0.08(stat.) \pm 0.01(syst.)$ for $n_{jets} \geq 4$, $A_{fb}^{obs} = 0.19 \pm 0.09(stat.) \pm 0.02(syst.)$ for $n_{jets} = 4$ and $A_{fb} = -0.16^{+0.15}_{-0.17}(stat.) \pm 0.03(syst.)$ for $n_{jets} \geq 5$.

Using a lepton+(at least 4) jets sample, where at least one jet is b-tagged, corresponding to an integrated luminosity of 1.9 fb^{-1} and containing 484 candidates events, the CDF experiment performed a forward-backward asymmetry defined by [27]:

$$A_{fb} = \frac{N_{-Q_l Cos\Theta>0} - N_{-Q_l Cos\Theta<0}}{N_{-Q_l Cos\Theta>0} + N_{-Q_l Cos\Theta<0}}, \tag{2}$$

where Θ is the production angle of the t i.e. the angle between the t and the proton beam, and Q_l is the charge of the lepton.

The t production angle in the lepton+jets final state is reconstructed by using a kinematic fitter. In order to compare to the theoretical prediction any bias and smear of the $t\bar{t}$ asymmetry due to backgrounds, acceptance, and reconstruction have to be taken into account. The CDF experiment uses MC simulations to simulate these effects.

Including the reconstruction and acceptance corrections the forward backward asymmetry is measured to be $A_{fb} = 0.17 \pm 0.07(stat.) \pm 0.04(syst.)$

The measured is consistent (at the 2σ) level with the prediction 0.04 from the NLO MC generator MC@NLO [28].

The CDF experiment performed a cross-check to the measurement by reweighting the $t\bar{t}$ MC signal distribution to have a 'true' $A_{fb} = 0.17$. A Kolmogorov-Smirnov test has been performed to compare the shape of the reweighted distribution with backgrounds and data resulting into a probability of 45.6% showing a good agreement.

Due to different A_{fb} definitions and due to the usage (CDF) or not (D0) of acceptance and reconstruction corrections, the D0 and CDF results on A_{fb} are not to be compared.

5 Searches for resonances

The t is known so far as being the heaviest elementary particle. The production of $t\bar{t}$ can be sensitive to physics beyond standard model in particular top-color and unknown heavy resonances [29], heavy Higgs boson decaying to t [30], $t\bar{t}$ condensation [31], massive Z gauge boson in extended gauge theories [32], Kaluza-Klein states of the Z gauge boson or gluon [33] and axigluons [34]. Such new effects may produce resonances in the $t\bar{t}$ invariant mass distribution or may interfere with SM processes and cause distortion to the shape of this invariant mass distribution.

Using the same data sample in the lepton+jets channel as described in section 4 allowing also for a second b-tagged jet, the CDF experiment performed a measurement of the $t\bar{t}$ differential cross section with respect to the invariant $t\bar{t}$ mass $d\sigma/dM_{t\bar{t}}$ [35]. The $t\bar{t}$ invariant mass is reconstructed by combining the 4-momenta of the 4 leading jets, lepton and missing transverse energy. The neutrino momentum is taken from the missing transverse energy, the longitudinal component p_z of the neutrino being obtained by constraining the lepton and the neutrino invariant mass to be equal to M_W.

The reconstructed $M_{t\bar{t}}$ distribution is distorted from the true distribution by detector effects, resolutions and acceptances. These effects are corrected by using a regularized unfolding technique i.e. Singular Value Decomposition (SVD) [36]. The CDF experiment then uses an Anderson-Darling[37] statistic to test for discrepancies from the standard model expectation. No evidence of inconsistencies with the Standard Model is seen, with an observed p-value of 0.45.

Using the same data sample as above the CDF experiment also searched for massive gluons decaying into $t\bar{t}$ [38]. In this search $M_{t\bar{t}}$ is reconstructed event-by-event using the Dynamical Likelihood Method (DLM)[39] also used for one of the CDF experiment m_t measurement[40]. After reconstructing $M_{t\bar{t}}$, an unbinned likelihood fit is performed to extract the coupling strength. The fitted coupling strengths are consistent with the SM prediction within 1.7σ in the width over coupling ratio range from 0.05 to 0.5 for a massive gluon mass range from 400 to 800 GeV.

The D0 experiment searched for a narrow-width heavy resonance X decaying into $t\bar{t}$ using a lepton+jets sample with at least one b-tagged jet corresponding to an integrated luminosity of 0.9 pb^{-1} [41]. The $t\bar{t}$ invariant mass is reconstructed in the same way as described above for the CDF $d\sigma/dM_{t\bar{t}}$ measurement. Model independent upper limits on $\sigma_X Br(X \to t\bar{t})$ have been obtained using a bayesian method [42]. Within a top-color-assisted technicolor model, the existence of a leptophobic Z' boson with $M_{Z'} < 690$ GeV and width $\Gamma_{Z'} = 0.012 M_{Z'}$ is excluded at 95% confidence level.

An updated result was just available for the 2008 QCD session of the Rencontres de Moriond conference [43]. With a data sample corresponding to an integrated luminosity of 2.1 pb^{-1}, the the existence of a leptophobic Z' boson with $M_{Z'} < 690$ GeV and width $\Gamma_{Z'} = 0.012 M_{Z'}$ is excluded at 95% confidence level.

6 Conclusions

We review the most recent results on $t\bar{t}$ production at the Tevatron which were available at the time of the 2008 electroweak session of the Rencontres de Moriond conference and corresponding to about 1 to 2 fb^{-1} of integrated luminosity for each of the CDF and D0 experiments. These results include production mechanism, cross sections and forward-backward asymmetry measurements which are found to be consistent with the SM expectations. The $t\bar{t}$ production cross section measurements allow for complementary m_t measurements which can be compared to direct measurements. There are no evidence so far for resonances decaying into t and model independent limits on masses as well as parameters of the different possible theoretical frameworks have been set. More data and results are expected to come after the winter 2008 as the Tevatron is continuing to perform very well.

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