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Searches for resonant production of top anti-top quarks at the Tevatron

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Summary. — A review of the measurements pertaining to searches for resonant production of top and anti-top quarks from the CDF and D0 Collaborations is presented, using different methods to reconstruct the top anti-top quark invariant mass.

PACS 14.65.Ha – Top quarks.
PACS 12.60.Nz – Technicolor models.

1. – Introduction and motivation

As the heaviest particle known so far, the top quark participates in many beyond the standard model (SM) scenarios. Such scenarios might include extended gauge theories with massive Z-like bosons and Kaluza-Klein (KK) states of gluons, weak bosons and gravitons. Some of these models predict an enhanced coupling to third generation quarks and $t\bar{t}$ is the dominant decay mode. A resonant production of a top and anti-top quark would appear as an unexpected structure in the spectrum of the invariant mass of $t\bar{t}$ pairs $M_{t\bar{t}}$.

Models are grouped according to the spin of the object, its color content and CP parity [1]. There can also be non-trivial interferences effects between new resonances and SM $t\bar{t}$ production. Experimentally the approach is to obtain the reconstructed $M_{t\bar{t}}$ and to look for any deviation from the SM $t\bar{t}$ production. Most results extract limits for a topcolor leptophobic Z' of narrow width (spin 1 and color singlet), while one result quotes a limit for a massive gluon production (spin 1, color octet).

Looking at the current differential cross-section of SM $t\bar{t}$ production [2], there are very few events found at very large $M_{t\bar{t}}$ values, making the signal of a resonant production at high mass potentially possible to observe. However, current CDF and D0 results are focused on a non-boosted topology for the final state, which is less efficient at very large

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mass. The boosted topology refers to a situation where the high boost given to the top and anti-top quarks collimate the decayed objects (the daughters of the W boson and the b-jet) into a single jet. Also discussed here is a CDF result focused on looking for SM $t\bar{t}$ pairs produced in the boosted topology. Finally, the current precision for the SM $t\bar{t}$ production leaves open the possibility of non-SM contributions.

There are various methods used for reconstructing $M_{t\bar{t}}$. Identifying which objects come from the $t\bar{t}$ pair can be done using a χ^2 kinematic fit, which also provides the full neutrino momentum. This neutrino momentum can also be estimated using the W mass constraint. The most sophisticated reconstruction techniques involve the use of Matrix Elements (ME) and Dynamical Likelihood Methods (DLM).

2. – Lepton+jets event selection

As four out of the five reported results make use of the lepton+jets channel (where one of the W decayed leptonically, while the other decayed into hadronically), the event selection is presented here. First, for the trigger selection, CDF requires an electron (muon) trigger with $E_T(p_T) > 18\,\text{GeV}$ while D0's trigger requests an electron (muon) and a jet. CDF requires an isolated electron (muon) with $E_T(p_T) > 20\,\text{GeV}$, while D0's muon requirement is that the $p_T > 25\,\text{GeV}$ and $|\eta| < 2.0$. The Missing E_T ($\not{E}_T$) is the usual vector sum of calorimeter energy deposits, corrected for identified objects. The CDF requirement is that for both electron and muon $\not{E}_T > 20\,\text{GeV}$, while for D0 the electron (muon) requirement is $\not{E}_T > 20$ (25) GeV. CDF uses the anti-k_T with $R = 0.4$ algorithm for jet clustering while D0 uses the cone algorithm with $R = 0.5$. The jet p_T and eta requirements are analyses dependent. The identification of b-jets is done using the displaced vertex algorithm SECVTX for CDF which has an identification efficiency of 50% for b-jet and 2% for light jets. D0 uses its neural network (NN) (discriminating variables are d_0, m_{vtx}, displacement significance and the number of tracks within the secondary vertex) with a requirement of NN > 0.65, which results in a b-jet identification efficiency of 55% and a light jet efficiency of less than 1%. Finally, both collaborations apply some standard event cleaning requirements.

The backgrounds in this channel are the same that are involved in the $t\bar{t}$ cross-section measurements. The most important ones are the W+jets production and the multijets production. Both are estimated using data-driven methods. The electroweak backgrounds (diboson, single top quark) are estimated using Monte Carlo predictions.

3. – CDF: Search for new color-octet vector particle

This analysis [3] uses $1.9\,\text{fb}^{-1}$ of Tevatron data and searches for a massive generic gluon G. It is assumed that the coupling between the massive and massless gluon is 0, while there can be interference between G and the process $qq \to g \to t\bar{t}$. The coupling of G to quarks is assumed to be parity-conserving. In $t\bar{t}$ production there are three observable parameters: the product of massive gluon coupling strength $\lambda = \lambda_q\lambda_t$, the mass M and the width Γ. The SM process $gg \to g \to t\bar{t}$ is a background. The $M_{t\bar{t}}$ is reconstructed from the parton level momenta event by event using the Dynamical Likelihood Method, which was also used for a top mass measurement. A path integral is built, which includes a transfer function treated as a probability density function (pdf) from the observed to the parton kinematics, and each event is the average over all the possible paths. It is assumed that the transfer functions are independent of the $t\bar{t}$ production matrix and so at reconstruction it is removed from the likelihood. A signal $g + G$ pdf is built and fed

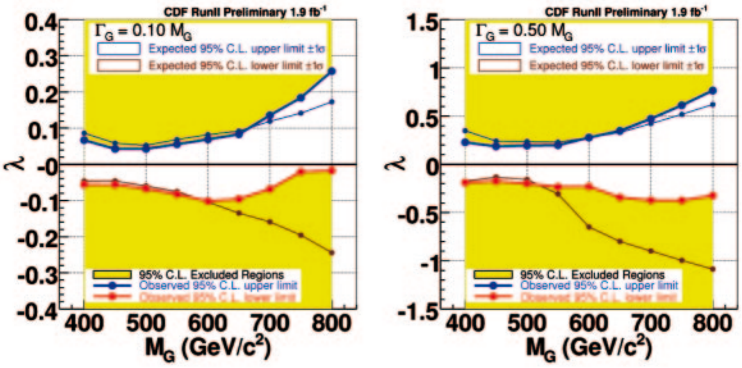

Fig. 1. – Upper and lower limits on the strength of the coupling with 95% CL as a function of the mass of the massive gluon. The limits become worse at the larger width.

into an unbinned maximum likelihood. The pdf contains a term which is the ratio of $g + G$ to SM $t\bar{t}$ production, which implies that Parton Density Functions (PDF), top propagators, decay ME and final state densities will cancel out. Another term of the pdf is the resolution function which translates from reconstructed to true $M_{t\bar{t}}$. Examples of the excluded regions for the coupling parameter is shown in fig. 1. In summary, no significant indication of the existence of a massive gluon with $|\lambda| > 0.5$ is observed in the search region of $400\,\mathrm{GeV}/c^2 < M < 800\,\mathrm{GeV}/c^2$ and $0.05 < \Gamma/M < 0.5$.

4. – D0: Search for top anti-top quark resonances using 3.6 fb^{-1}

This analysis [4] uses the lepton+jets channel and obtains results separately for the 3-jet signal region and for the greater or equal to 4-jet region. The product of acceptance, efficiency and branching ratio after the event selection is 3.4% and 4.4%, respectively, for the SM $t\bar{t}$ events and 2.8% and 3.9% for events from a Z' with mass of $650\,\mathrm{GeV}/c^2$. The analysis obtains $M_{t\bar{t}}$ from using up to four leading jets and uses the W mass constraint for obtaining the z component of the neutrino momentum. If two solutions are found, the smallest one is used and if no real solutions are found p_z is set to 0. This procedure provides better sensitivity at large values of $M_{t\bar{t}}$ than using a kinematic fit. Limits are obtained using a Bayesian approach with a Poisson probability for the number of events in each bin, and a flat prior for σB. The $M_{t\bar{t}}$ distribution in the greater than or equal to four jet signal region is shown in fig. 2 alongside the exclusion limit plot. In summary, a topcolor leptophobic Z' is excluded at 95% CL below $820\,\mathrm{GeV}/c^2$.

5. – CDF: Search for resonant production of $t\bar{t}$ pairs in 4.8 fb^{-1}

This analysis [5] uses the lepton+jets channel and for each event the $t\bar{t}$ hypothesis is applied by mapping the observed event kinematics to the parton level using the Matrix Element for $t\bar{t}$ production and decay. A pdf is constructed representing $M_{t\bar{t}}$ which includes a sum over jet-parton assignments. The pdf also contains a transfer function mapping jets to partons. These functions are obtained from Monte Carlo and have 10 bins in jet E_T and five bins in jet η. The probability for an event is a function of the signal fraction and the signal and background templates. The likelihood is written as the product of the per-event probabilities. The total probability density is shown in fig. 3

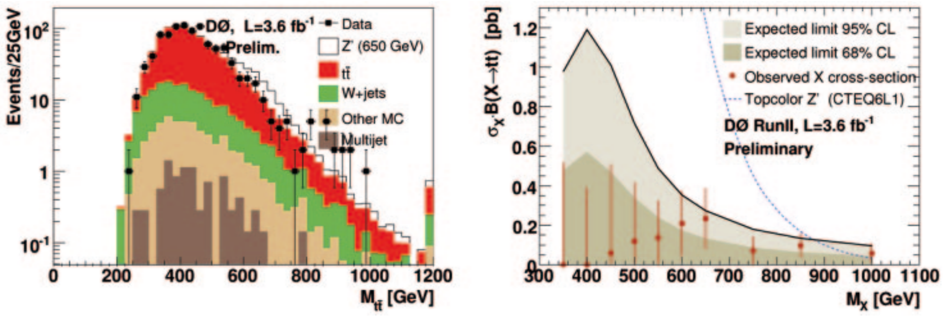

Fig. 2. – Left: $M_{t\bar{t}}$ distribution in the greater than or equal to four jet signal region. Right: the data points show the measured $\sigma_X \cdot B(X \to t\bar{t})$ for a narrow resonance obtained for the full data set. The shaded areas indicate the 68% and 95% fluctuation bands expected under the assumption of pure SM $t\bar{t}$ production.

alongside the expected and observed limit. In summary, a topcolor leptophobic Z' is excluded at 95% CL below 900 GeV/c^2.

6. – CDF: Search for resonant production of $t\bar{t}$ decaying to jets

This analysis [6] uses the all hadronic channel and 2.8 fb^{-1}. The advantages of the all hadronic channel are the high branching ratio, the good mass resolution and the complementarity of this result compared to the lepton+jets channel. The all hadronic event selection starts with requesting a jet trigger (at least 4 jets of $E_T > 10$ GeV, which has a signal efficiency of 80%). It vetoes leptons and $\not{E}_T$ and asks for either six or seven jets with $E_T > 15$ GeV and $|\eta| < 2.0$. The b-jet identification algorithm is SECVTX described above. To suppress the overwhelming multijets background a neural net is used containing 10 variables that discriminate between multijet events and $t\bar{t}$ events. A requirement of NN > 0.93 is applied. The leftover multijet background seeping into the signal region is estimated from the tag rate matrix from four or five jet bins and tested on various control samples, built from looser requirement on the NN value. A likelihood is calculated by integrating the signal matrix elements, which allows not only to calculate $M_{t\bar{t}}$ but also to suppress the background. The $M_{t\bar{t}}$ distribution is shown in fig. 4 alongside the limit obtained. In summary a topcolor leptophobic Z' is excluded at 95% CL below 805 GeV/c^2.

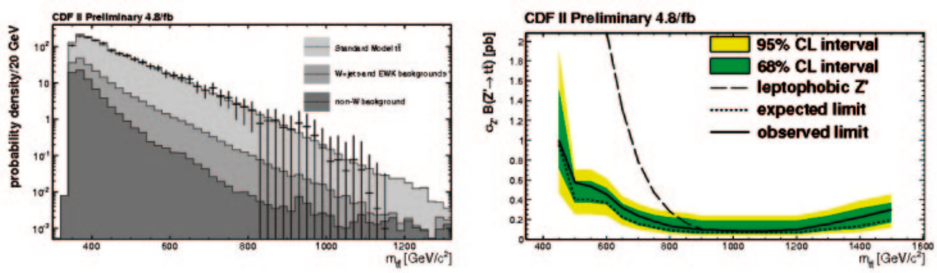

Fig. 3. – Left: total probability density for the 1366 $t\bar{t}$ events observed in 4.8 fb^{-1}. Right: expected and observed 95% CL upper limit for $\sigma(p\bar{p} \to Z') \times BR(Z' \to t\bar{t})$.

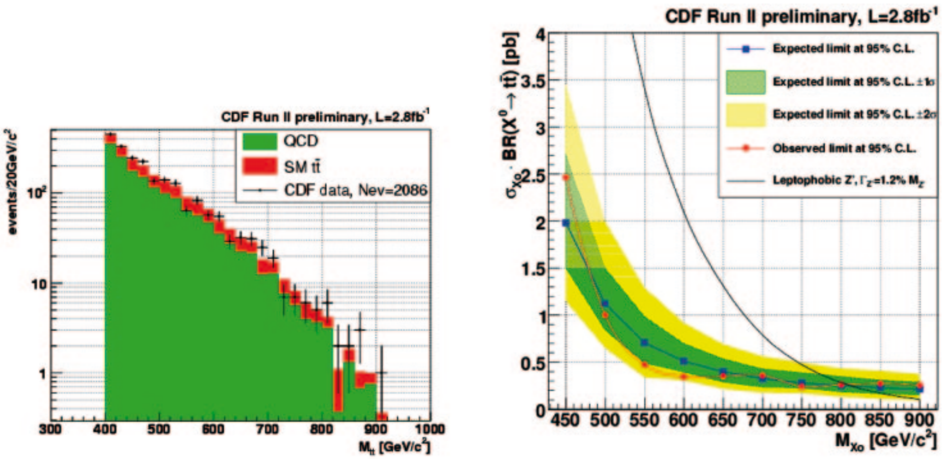

Fig. 4. – Left: Reconstructed $M_{t\bar{t}}$ distribution *vs.* the SM expectation. Right: Expected and observed upper limits on leptophobic topcolor Z' in $2.8\,\text{fb}^{-1}$.

7. – CDF: A search for boosted top quark using $5.95\,\text{fb}^{-1}$

This analysis [7] is the first observation of boosted top quarks at the Tevatron. The observation of massive collimated jets is an important test of perturbative QCD, helps tune the Monte Carlo event generators, gives insight into the parton showering mechanism, and opens the door to resonant top anti-top searches in the boosted topology. It is the first measurement probing the $t\bar{t}$ sample with top quark $p_T > 400\,\text{GeV}/c$. It is interesting to note that for a Lorentz boost greater than three the top decay products collimate into a single massive jet. The jet trigger requested expects at least one jet with $E_T > 100\,\text{GeV}$. The jets are reconstructed using the Midpoint algorithm with $R = 1.0$ and the calorimeter towers are turned into four-vectors using the so-called "E-scheme". A jet energy scale correction as well as a multiple interaction correction are applied. At least one of such reconstructed jets with $p_T > 400\,\text{GeV}/c$ and $|\eta| < 0.7$ is requested.

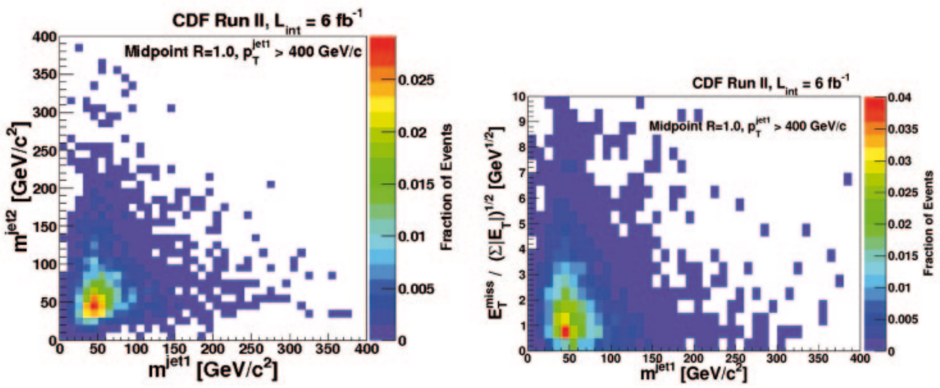

Fig. 5. – Left: the m^{jet2} *vs.* m^{jet1} distribution for all data events. Right: the S_{MET} *vs.* m^{jet1} distribution for all data events.

At that value of p_T, the typical jet energy scale is 1.12 with a 3% uncertainty. Finally the requirement on the $\not{E}_T$ significance is

$$S_{\mathrm{MET}} = \frac{\not{E}_T}{\sum E_T} < 10. \tag{1}$$

The total number of events passing all of the event selection is 4230. The expected cross-section is $4.55^{+0.50}_{-0.41}$ fb (based on recent NNLO calculation [8]) which represents 5.6×10^{-4} of the total cross-section. In the all hadronic channel, the $\not{E}_T$ significance requirement is $S_{\mathrm{MET}} < 4$, and four regions in the 2D plane of the variables m^{jet1} and m^{jet2} are used to evaluate the multijet background in the signal region, see fig. 5. Since there is a slight correlation between those two variables, the expression used to obtain N_D is

$$R_{\mathrm{mass}} = \frac{N_B N_C}{N_A N_D}\,, \tag{2}$$

where $R_{\mathrm{mass}} = 0.89 \pm 0.03(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$. The estimated amount of multijet background is 14.6 ± 2.76. In the lepton+jets channel the $\not{E}_T$ significance required is $4 < S_{\mathrm{MET}} < 10$. In this channel the variable m^{jet2} is no longer discriminating between the multijet events and the $t\bar{t}$ events and so the four regions are defined in the S_{MET} *vs.* m^{jet1} plane to extract the multijet background, see fig. 5. This estimate is 31.3 ± 8.1. Combining the all hadronic and lepton+jets channel 57 data events are selected compared to an expectation of $46 \pm 8.5(\mathrm{stat.}) \pm 13.8(\mathrm{syst.})$. An upper limit on the cross section is obtained by using a Bayesian treatment with a flat prior. The expected limit is $\sigma < 33$ fb at 95% CL and the observed limit is $\sigma < 38$ fb at 95% CL. These numbers are an order of magnitude larger than the SM predicted cross section, and are dominated by the background prediction. The analysis also makes use of the all hadronic channel to put a limit on the resonant top anti-top quark production: a limit on the cross-section, $\sigma < 20$ fb at 95% CL is obtained.

8. – Conclusion

Several searches for resonant production of a top and anti-top quark at the Tevatron were presented. The best limit obtained for a leptophobic topcolor Z' is $M_{Z'} > 900\,\mathrm{GeV}/c^2$ (for $\Gamma = 1.2\%$). A search for a massive gluon was also presented and limits put on its coupling strength. This massive gluon is generic although assumes parity conservation. The first boosted $t\bar{t}$ analysis at the Tevatron was also presented, providing the most stringent limit on boosted top quark cross-section.

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