IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11164-2

Colloquia: LaThuile11

# Search for New Physics at the Fermilab Tevatron $p\bar{p}$ collider

S. Rolli(*)
*Tufts University - 4 Colby St, Medford, MA 02155, USA*

(ricevuto il 29 Settembre 2011; pubblicato online il 2 Febbraio 2012)

**Summary.** — We report on selected recent results from the CDF and D0 experiments on searches for physics beyond the Standard Model using data from the Tevatron collider running $p\bar{p}$ collisions at $\sqrt{s} = 1960\,\text{GeV}$.

PACS 14.80.Bn – Standard-model Higgs bosons.

## 1. – Introduction

Over the past decades the Standard Model (SM) of particle physics has been surprisingly successful. Although the precision of experimental tests improved by orders of magnitude no significant deviation from the SM predictions has been observed so far. Still, there are many questions that the Standard Model does not answer and problems it can not solve. Among the most important ones are the origin of the electro-weak symmetry breaking, hierarchy of scales, unification of fundamental forces and the nature of gravity. Recent cosmological observations indicates that the SM particles only account for 4% of the matter of the Universe. Many extensions of the SM (Beyond the Standard Model, BSM) have been proposed to make the theory more complete and solve some of the above puzzles. Some of these extension includes SuperSymmetry (SUSY), Grand Unification Theory (GUT) and Extra Dimensions. At CDF and D0 we search for evidence of such processes in proton-antiproton collisions at $\sqrt{(s)} = 1960\,\text{GeV}$. The phenomenology of these models is very rich, although the cross sections for most of these exotic processes is often very small compared to those of SM processes at hadron colliders. It is then necessary to devise analysis strategies that would allow to disentangle the small interesting signals, often buried under heavy instrumental and/or physics background. Two main approaches to search for physics beyond the Standard Model are used in a complementary fashion: model-based analyses and signature based studies. In the more traditional model-driven approach, one picks a favorite theoretical model and/or

(*) Currently at: U.S. Department of Energy, Office of High Energy Physics, Washington, DC 20585, USA.

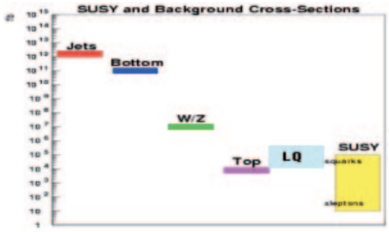


Fig. 1. – Cross sections for typical SM processes at the TeVatron and exotic physics.

a process, and the best signature is chosen. The selection cuts are optimized based on acceptance studies performed using simulated signal events. The expected background is calculated from data and/or Monte Carlo and, based on the number of events observed in the data, a discovery is made or the best limit on the new signal is set. In a signature-based approach a specific signature is picked (*i.e.* dileptons+X) and the data sample is defined in terms of known SM processes. A signal region (blind box) might be defined with cuts which are kept as loose as possible and the background predictions in the signal region are often extrapolated from control regions. Inconsistencies with the SM predictions will provide indication of possible new physics. As the cuts and acceptances are often calculated independently from a model, different models can be tested against the data sample. It should be noticed that the comparison with a specific model implies calculating optimized acceptances for a specific BSM signal. In signature-based searches, there is no such an optimization. Both the experiments have followed a somehow natural approach in pursuing analysis looking at final state signatures characterized by relatively simple physics objects (for example lepton-only final state, where the selection of the leptons is straightforward and can be easily checked with the measurement of electroweak boson production cross sections) and proceeding onto more complex final state, including jets and heavy flavor. Here more sophisticated identification techniques need to be used and issues like jet energy scale calibration play an important role in determining the final result. Given the limited space available for these proceedings, we will focus here on few selected results. Further results are described in `http://ncdf70.fnal.gov:8001/presentations/LaThuile2011_Rolli.pdf`.

## 2. – Search for New Physics in dileptons final states

This is a typical example of a signature-based search for new physics. Final states consisting of dileptons are a straightforward signature where to look for new physics, as several resonant states can appear as enhancement of the Drell-Yan cross section. The analysis strategy is very simple: the invariant mass distribution of the dilepton system is compared to the SM expectations, as shown in figs. 2 and 3. Only identification cuts to select a pair of high $P_T$ leptons are placed.

Both CDF [1, 2] and D0 [3] have been studying the dilepton invariant mass distribution. The most recent result is a search for new dielectron mass resonances using $5.7\,\mathrm{fb}^{-1}$ of data recorded by the CDF II detector. No significant excess over the expected Standard Model prediction is observed, as seen in fig. 2. In this dataset, an event with the highest dielectron mass ever observed ($960\,\mathrm{GeV/c}^2$) has been recorded. The results are intepreted in the framework of the Randall-Sundrum (RS) model [4]. Combined with a similar search performed with $5.4\,\mathrm{fb}^{-1}$ of diphoton data [5] the RS-graviton mass limit

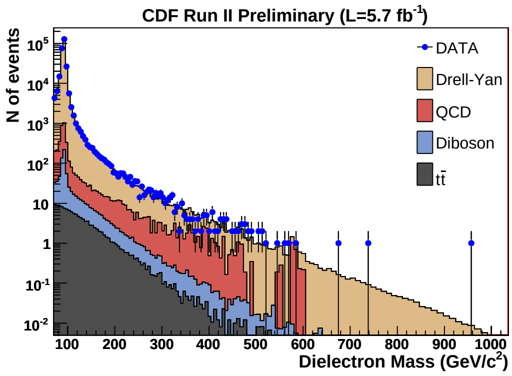


Fig. 2. – Inclusive dielectron mass spectrum at CDF.

for the coupling $k/MP_l = 0.1$ is $1058\,\mathrm{GeV}/c^2$ at 95% CL, making it the strongest limit to date. A similar search is performed in the dimuon channel using $4.3\,\mathrm{fb}^{-1}$ of data and no excess is observed (fig. 3). The result is interpreted in terms of Z′ production and limits are set on several Z′ production scenario: such limits are extending to the kinematical reach of the Tevatron (sequential SM Z′ limit is set for example to $1071\,\mathrm{GeV}/c^2$ at 95% CL, making it one of the most stringent in this channel).

## 3. – Search for extra vector bosons and diboson resonances

A recent result by the D0 Collaboration [6] concerns the search for resonant WW or WZ production. The dataset used corresponds to $5.4\,\mathrm{fb}^{-1}$ of integrated luminosity collected by the D0 experiment. The search for these resonances in the diboson decay channel covers the possibility that their coupling to leptons may be lower than the value predicted by the SM. The data are consistent with the standard model background expectation (figs. 4 and 5), and limits are set on a resonance mass using the sequential standard model (SSM) W boson and the Randall-Sundrum model graviton G as benchmarks. D0 excludes a SSM W′ boson in the mass range 180–690 GeV and a Randall-Sundrum gravi-

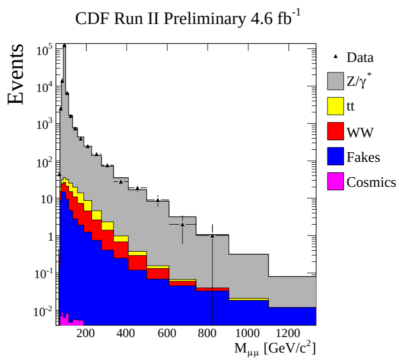


Fig. 3. – Inclusive dimuons mass spectrum at CDF.

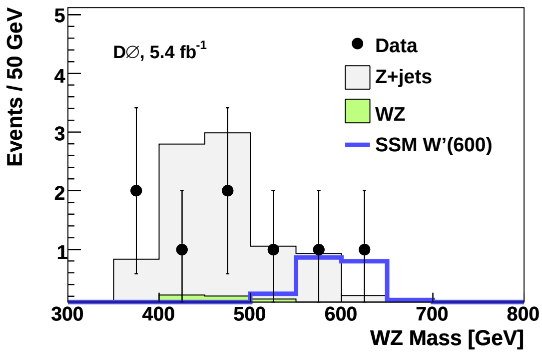


Fig. 4. – Reconstructed WZ mass in the $l\nu jj, lljj, lll\nu$ channels, D0 Collaboration.

ton in the range 300–754 GeV at 95% CL There are two recent direct searches for WZ or WW resonances by the CDF and D0 collaborations [7,8] that exclude WZ resonances with mass below 516 and 520 GeV, respectively, and an RS graviton G→WW resonance with mass less than 607 GeV. Indirect searches for new physics in the WW and WZ diboson systems through measurements of the triple gauge couplings also show no deviation from the SM predictions [9-11] Finally the CDF collaboration has very recently excluded $\mathrm{M(W')} < 1.1$ TeV, when assuming the W′ boson decays as in the SM [12].

## 4. – Search for New Physics in complex final states

**4**˙1. *gamma plus jets*. – Many new physics models predict mechanisms that could produce a $\gamma$+jets signature. CDF searches in the $\gamma$+jets channel, independently of any model, for New Physics using 4.8 $\mathrm{fb}^{-1}$ of CDF Run II data [13]. A variety of techniques are applied to estimate the Standard Model expectation and non-collision backgrounds. Several kinematic distributions are examined, including photon ET, invariant masses, and total transverse energy in the event for discrepancies with predictions from the Standard Model (figs. 6 and 7). The data are found to be consistent with Standard

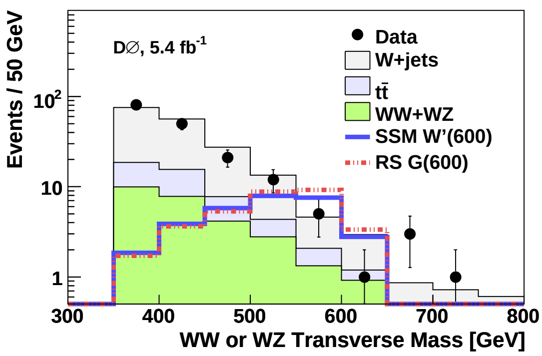


Fig. 5. – Reconstructed WZ or WW transverse mass in the $l\nu jj$ channel, D0 Collaboration.

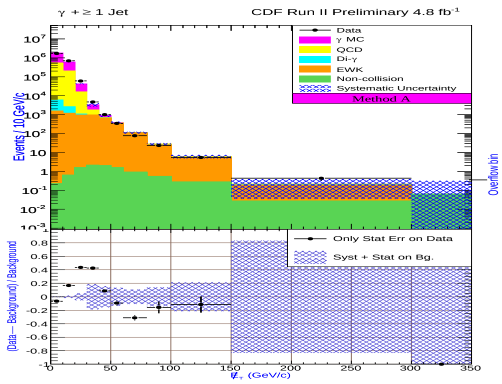


Fig. 6. – Missing energy distribution for $\gamma \pm 1$ jet, CDF Collaboration.

Model expectations. This global search for new physics in $\gamma$+jets channel reveals no significant indication of physics beyond Standard Model.

**4**$\dot{}$2. *gamma plus b-jets plus MET + leptons*. – A search for anomalous production of the signature $l + \gamma + b$-quark+MET ($l\gamma$ MET $b$) has been performed by using $6.0\,\text{fb}^{-1}$ of data taken with the CDF detector [14]. In addition to the $l\gamma$ MET $b$ signature-based search, CDF also presents for the first time a search for top pair production with an additional radiated photon, $t\bar{t} + \gamma$. 85 events of $l\gamma$ MET $b$ *versus* an expectation of $99.1 \pm 7.61$ events. Additionally requiring the events to contain at least 3 jets and to have a total transverse energy of 200 GeV, CDF observes 30 $t\bar{t}\gamma$ candidate events *versus* an expectation from non-top standard model (SM) sources of $13.0 \pm 2.1$. Assuming the difference between the observed number and the predicted non-$t\bar{t}\gamma$ SM total is due to $t\bar{t}\gamma$ production, the collaboration measures the $t\bar{t}\gamma$ cross section to be 0.18 0.07(stat.) $\pm$ 0.04(sys.) $\pm$ 0.01(lum.) pb. We also measure a ratio of the $t\bar{t}\gamma$ cross section to the $t\bar{t}$ cross section to be $0.024 \pm 0.009$.

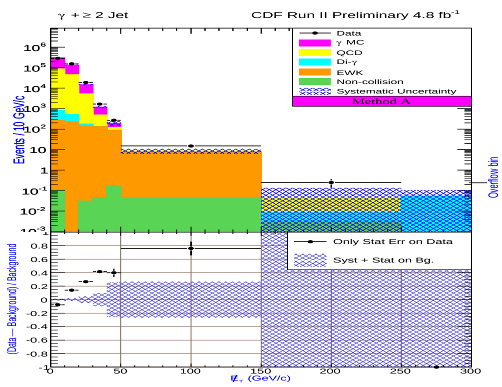


Fig. 7. – Missing energy distribution for $\gamma \pm 2$ jet, CDF Collaboration.

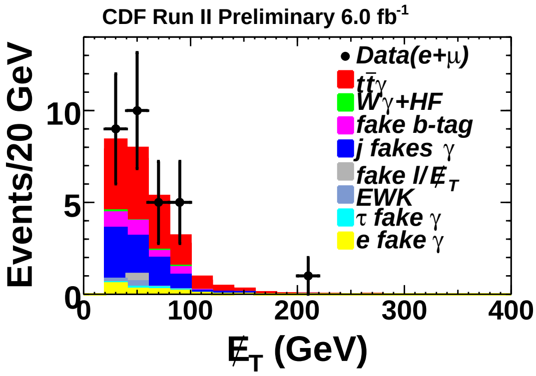


Fig. 8. – Missing energy distribution in $l\gamma$ MET $b$ events, CDF Collaboration.

4˙3. *Multijets resonances.* – A new analysis from CDF has been performed to search for 3-jet hadronic resonances in 3.2 fb$^{-1}$ of data [15]. Typical searches for New Physics require either leptons and/or missing transverse energy, however, they might be blind to new physics which have strong couplings and therefore decay into quarks and gluons. The CDF collaboration used 3.2 fb$^{-1}$ of data in a model-independent search that reconstructs hadronic resonances in multijet final states. Although the analysis is not optimized for a specific model of new physics, we use as a possible benchmark, R-parity violating supersymmetric (RPV SUSY) gluino pairs production, with each gluino decaying into three objects. Since no significant excess is observed in the data a 95% CL limit is set on $\sigma(p\bar{p} \to XX) \times \mathrm{Br}(\tilde{g}\tilde{g} \to$ 3jets+3jets), where X $= \tilde{g}, \tilde{q}$, as a function of the gluino invariant mass (fig. 13). To extract signal from the multijet QCD background, kinematic quantities and correlations are used to create an ensemble of jet combinations. Incidentally, the all-hadronic $t\bar{t}$ decay has a signature similar to the signal searched for in this analysis. The biggest challenge of the analysis is the large QCD background that accompanies multijet resonances. A data driven approach is used to parameterize such background. An ensemble consists of 20 (or more) possible jet triplets from the $\geq 6$ hardest jets in the event. For every event, we calculate each jet triplet invariant mass, $M_{jjj}$, and scalar sum $p_T$, $\Sigma_{jjj}|pT|$. Using the distribution of $M_{jjj}$ *vs.* $\Sigma jjj|pT|$ ensures that the correct combination of jets in pre-defined kinematic regimes is reconstructed, since the incorrect (uncorrelated) triplets tend to have $M_{jjj} = \Sigma jjj|pT|$. The correct (correlated) triplet produces a horizontal branch in the signal at approximately the invariant mass of the signal that is not present for the background as can be seen in figs. 9, 10, 11, 12.

4˙4. *Top + MET.* – We conclude with a search for a new particle T$'$ decaying to top quark via T$' \to$ t + X, where X is an invisible particle [16]. In a data sample with 4.8 fb$^{-1}$ of integrated luminosity collected by the CDF II detector, the search is conducted for pair production of T$'$ in the lepton+jets channel, $p\bar{p} \to t\bar{t} + X + X \to l\nu bqq\bar{b} + X + X$. Such process would produce extra missing energy and the key observable used in the analysis is the transverse mass distribution of the lepton-missing energy system, which in absence of new physics corresponds to the reconstructed W transverse mass. The results are primarily interpreted in terms of a model where T$'$ are exotic fourth generation quarks and X are dark matter particles [17]. Current direct and indirect bounds on such exotic quarks restrict their masses to be between 300 and 600 GeV/$c^2$, the dark matter

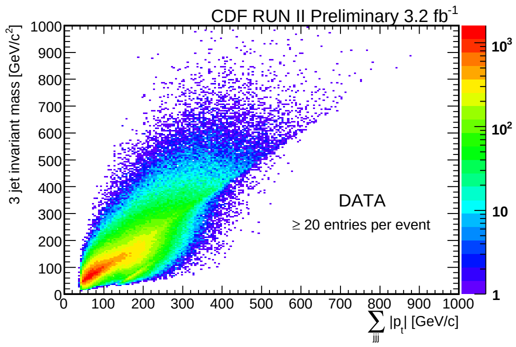


Fig. 9. – Distributions of $M_{jjj}$ *versus* $\Sigma_{jjj}|pT|$.

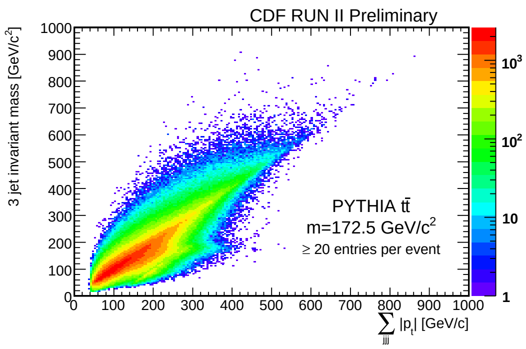


Fig. 10. – Distributions of $M_{jjj}$ *versus* $\Sigma_{jjj}|pT|$.

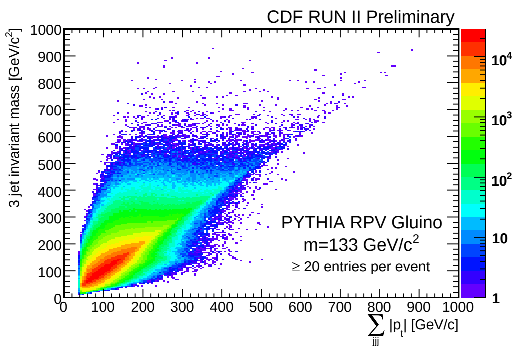


Fig. 11. – Distributions of $M_{jjj}$ *versus* $\Sigma_{jjj}|pT|$.

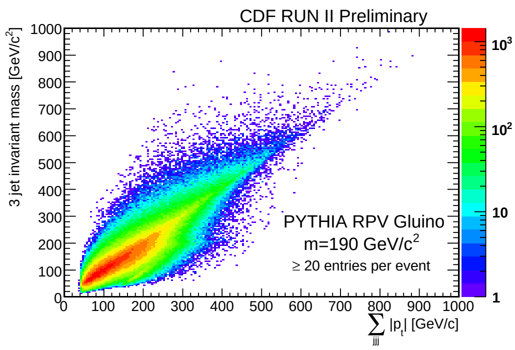


Fig. 12. – Distributions of $M_{jjj}$ *versus* $\Sigma_{jjj}|pT|$ multiple entry($\geq 20$).

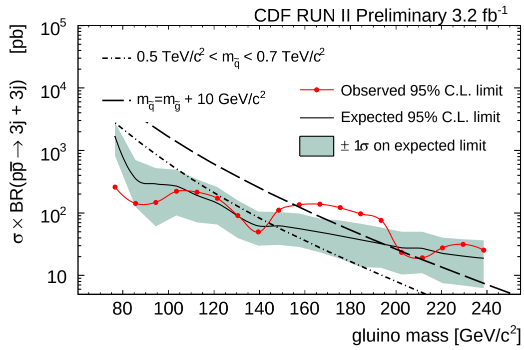


Fig. 13. – The observed and expected limit including systematic uncertainties as well as the theory cross section for $\sigma(p\bar{p} \to XX) \times \mathrm{Br}(\tilde{g}\tilde{g} \to 3\mathrm{jets} + 3\mathrm{jets})$ where X $= \tilde{g}, \tilde{q}$, *versus* gluino invariant mass. The RPV gluino cross-section is from PYTHIA and is corrected by an NLO $k$-factor.

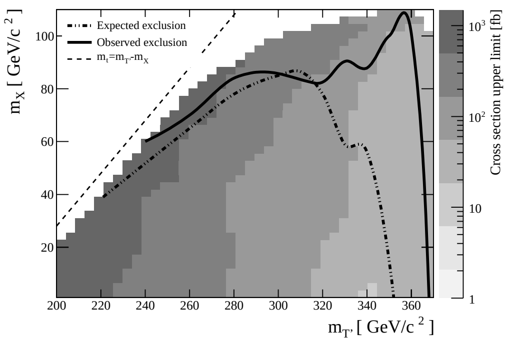


Fig. 14. – Observed *versus* expected exclusion in $(m_{T'}, m_X)$ along with the cross section upper limits.

particle mass can be anywhere below $m_{T'}$. The data are consistent with standard model expectations, and CDF sets a 95% confidence level limits on the generic production of $\mathrm{TT}' \to t\bar{t} + \mathrm{X} + \mathrm{X}$, by performing a binned maximum-likelihood fit in the $m_W$ variable, allowing for systematic and statistical fluctuations via template morphing. The observed upper limits on the pair-production cross sections are converted to an exclusion curve in the mass parameter space for the dark matter model involving fourth generation quarks. The current cross section limits on the generic decay, $T' \to t + X$, may be applied to the many other models that predict the production of a heavy particle $\mathrm{T}'$ decaying to top quarks and invisible particles X, such as the supersymmetric process $\tilde{t} \to t + \chi^0$. Applying these limits to the dark matter model CDF excludes fourth generation exotic quarks $\mathrm{T}'$ at 95% confidence level up to $m_{T'} = 360\,\mathrm{GeV}/c^2$ for $m_X < 100\,\mathrm{GeV}/c^2$ (fig. 14).

## 5. – Conclusions

The CDF and D0 experiments are actively collecting and analyzing data at the Tevatron collider. New physics is searched in a broad manner, using different approaches. In signature based analyses the data are scanned for anomalies pointing to indications of New Physics, while many dedicated searches for specific models are pursued, using the largest possible statistical samples. New results on search for physics beyond the Standard Model are released almost daily. So far there is no evidence for New Physics and numerous limits on new particle masses and cross sections production are set. A broader set of updated results can be found at: `http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm` and `http://www-cdf.fnal.gov/physics/exotic/exotic.html`.

## REFERENCES

[1] Altoonen T. *et al.*, arXiv,1103.4650 (2011).
[2] Altoonen T. *et al.*, *Phys. Rev. Lett.*, **106** (2011) 121801.
[3] Abazov V. M. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 241802.
[4] Randall L. and Sundrum R., *Phys. Rev. Lett.*, **83** (1999) 3370.
[5] Altoonen T. *et al.*, *Phys. Rev. D*, **83** (2011) 011102.
[6] Abazov V. M. *et al.*, arXiv.org, 1011.6278 (2010).
[7] Abazov V. M. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 061801.
[8] Aaltonen T. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 241801.
[9] Abazov V. M. *et al.*, *Phys. Rev. Lett.*, **103** (2009) 191801.
[10] Abazov V. M. *et al.*, *Phys. Rev. D*, **80** (2009) 053012.
[11] The LEP Collaborations, `http://lepewwg.web.cern.ch/` (2005).
[12] Aaltonen T. *et al.*, *Phys.Rev. D*, **83** (2011) 031102.
[13] Aaltonen T. *et al.*, CDF Public Note, 10355 (2011).
[14] Aaltonen T. *et al.*, CDF Public Note, 10437 (2010).
[15] Aaltonen T. *et al.*, arXiv, 1105.2815 (2011).
[16] Aaltonen T. *et al.*, *Phys. Rev. Lett.*, **106** (2011) 191801.
[17] Feng J. *et al.*, arXiv, 1002.3366 (2010).