Heavy resonance searches at Tevatron

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Abstract. We present a selection of beyond-the-standard-model searches of heavy resonances from the CDF and D0 experiments at the Tevatron collider. The data used are part or all of the Run IIa Tevatron data giving more than 1 fb^{-1} per experiment. The searches have been performed for spin 0, spin 1/2, spin 1 and spin 2 resonances. All the searches and the limits on the different cross section times branching fractions are model independent. They have been interpreted using different models, such as : spin 0 third-generation neutrino, spin 1/2 excited quark, spin 1 W' and Z' and also spin 2 Randall-Sundrum graviton. No evidence of new physics or deviations from the standard model were observed. Limits on particle masses are thus extracted.

1. Introduction

The Tevatron collider at Fermilab, near Chicago in the United States of America, is the most powerful collider in the world. It collides protons (p) and anti-protons ($\bar{p}$) with a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. Its RunIIa phase from 2002 to 2006 delivered about 1.3 fb^{-1} to both the experiments CDF [1] and D0 [2]. In this paper we present a selection of beyond-the-standard-model (SM) searches for heavy resonances with the CDF and D0 detectors. Section 2 describes the results of the search for a spin 0 resonance decaying to an electron and a muon, including limits on a third-generation neutrino in Supersymmety (SUSY) with R-parity (Rp) violation. A spin 1/2 resonance production is presented in section 3. This search is for a resonance decaying to a Z^0 and a quark, where the Z^0 decays to e^+e^-. Limits are set on excited quarks in the compositeness model. In section 4 we discuss spin 1 resonance production. The decay modes analysed are $t\bar{b}$ ($\bar{t}b$), $e\nu$, e^+e^- and $t\bar{t}$. We use the left-right ($SU(2)_L \times SU(2)_R$) and E(6) GUT models to interpret the results in the context of W' or Z' production. In section 5 we present spin 2 resonance production. The decay modes studied are the $\gamma\gamma$ and e^+e^-. The model used for interpreting the results is the Randall-Sundrum model of extra-dimensions. All the analyses use the parton density functions (PDF) CTEQ5L [3] except the $W' \to e\nu$ which uses CTEQ6L [4]. All the extracted limits either on cross sections or on masses are at 95% Confidence Level (CL).

2. Spin 0 resonance search ($\tilde{\nu}_\tau$)

The CDF experiment searched for third-generation SUSY Rp-violating neutrinos ($\tilde{\nu}_\tau$), produced via $d\bar{d}$ annihilation and decaying to an electron and an oppositely charged muon:

$d\bar{d} \to \tilde{\nu}_\tau \to e\mu$ [5]. The search covers the mass range from 50 GeV[1] to 800 GeV and uses a luminosity of 344 pb^{-1}. The event selection requires : 2 high E_T isolated leptons, with 1 electron with $E_T \geq 20$ GeV and 1 oppositely charged muon with $p_T \geq 20$ GeV, and a common vertex for the electron and the muon tracks. All the signal and background processes are simulated using the event generator PYTHIA [6].No significant excess of data over the prediction is observed. An upper limit on the cross section times the branching fraction (BF or BR) $\sigma(p\bar{p} \to \tilde{\nu}_\tau) \times BF(\tilde{\nu}_\tau \to e\mu)$ is extracted. This is shown in the Figure 1 as a function of the mass of the final $e\mu$ system, where the black curve is the observed limit and the blue curve is the expected limit using only background and signal expectations. On the same figure we compare those limits to a theoretical NLO $\tilde{\nu}_\tau$ production cross section, using the current best values [7] of the couplings λ'_{311} and λ_{132}. The crossing of this curve with the observed limits allows us to exclude $\tilde{\nu}_\tau$ masses lower than 460 GeV.

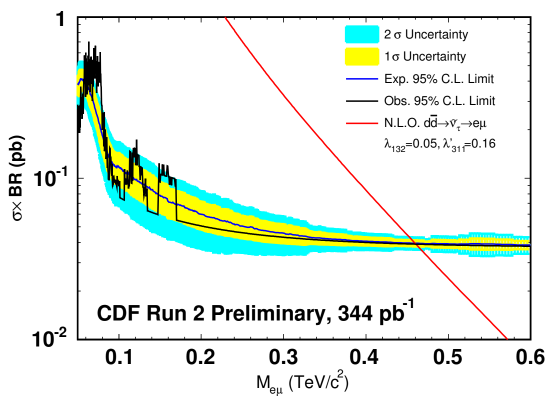

Figure 1. $\sigma(p\bar{p} \to \tilde{\nu}_\tau) \times BF(\tilde{\nu}_\tau \to e\mu)$ upper limits and also theoretical cross section.

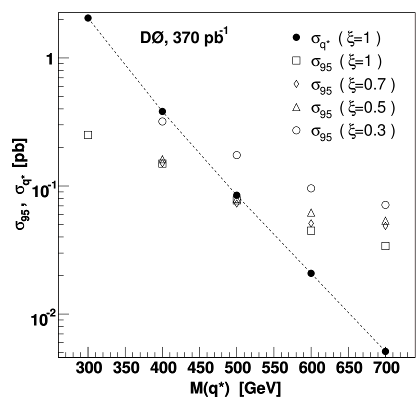

Figure 2. $\sigma(p\bar{p} \to q^*) \times BF(q^* \to Z^0 + q; Z^0 \to e^+e^-)$ upper limits as a function of the M_{q^*}

3. Spin 1/2 resonance search (q^*)

Excited fermions occur in compositeness models where the known fermions are bound states of more fundamental particles [8]. Their production and decay could be either via contact or gauge interactions. The relevant parameters in the process are the excited fermion mass M_{f*} and the compositeness scale Λ. In D0 we searched for a spin 1/2 resonance produced via quark-gluon fusion and decaying to a Z^0 and a quark, the Z^0 decaying to e^+e^- [9]. It uses a luminosity of 370 pb^{-1}. The selection is based on : 2 high E_T isolated electrons with $E_T^1 \geq 30$ GeV and $E_T^2 \geq 25$ GeV; the invariant mass of the e^+e^- system must be around the Z^0 mass : 80 GeV $\leq M_{e^+e^-} \leq$ 120 GeV and the event must contain at least 1 high E_T jet with $E_T \geq 20$ GeV. The background and the signal have been simulated using PYTHIA 6.1. Since there is no significant excess of the data compared to the expected SM background we put upper limits on $\sigma(p\bar{p} \to q^*) \times BF(q^* \to Z^0 + q; Z^0 \to e^+e^-)$ as a function of the q* mass. We see that in the Figure 2. The open signs are the observed limits for different values of $\xi = \frac{\Lambda}{M_{q*}}$. The black points are the theoretical cross sections for a q* produced with $\Lambda = M_{q*}$. From that we can extract a limit on the q* mass : $M_{q*} \geq 510$ GeV if $\Lambda = M_{q*}$.

[1] All the energies and momenta are expressed in GeV, we assume $c = 1$.

4. Spin 1 resonance search (W', Z')

The left right symmetry models predict heavier W's and Z's : W' and Z' [10]. The E(6) Grand Unified Theories [11] predict the existence of 4 Z' : $Z'_I, Z'_\Psi, Z'_\chi, Z'_\eta$. In the following analyses we searched for massive $W'(Z')$ as massive $W(Z)$-like bosons with SM-like couplings.

4.1. $W' \to t\bar{b}$ $(\bar{t}b)$

CDF looked for a W' decaying to $t\bar{b}$ $(\bar{t}b)$ [12]. The search covers the mass range from 300 GeV to 950 GeV and uses a luminosity of 1 fb^{-1}. The final state is a lepton, a neutrino and 2 or 3 jets, selected as follows (à la single top): 1 high E_T lepton with $E_T \geq 30$ GeV; a large missing E_T ($\not\!\!E_T$) coming from the neutrino $\not\!\!E_T \geq 25$ GeV; 2 or 3 energetic jets with $E_T \geq 15$ GeV; at least one displaced secondary vertex for the b tagging. No significant excess of data compared to the expected background is seen. Figure 3 shows the upper limit on the $\sigma(p\bar{p} \to W') \times BF(W' \to t\bar{b})$ as a function of the W' mass. The observed limit is the black curve and the expected limit is the gray curve with the shaded plus or minus one standard deviation. The purple and blue curves are the theoretical cross sections for a SM-like W' with $M(W') \geq M(\nu_R)$ and $M(W') \leq M(\nu_R)$ respectively. From that we can extract limits on the mass of a W': $M(W') \geq 760$ GeV if $M(W') \geq M(\nu_R)$ and $M(W') \geq 790$ GeV if $M(W') \leq M(\nu_R)$.

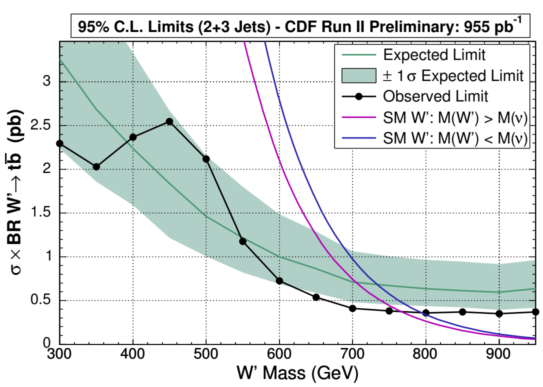

Figure 3. $\sigma(p\bar{p} \to W') \times BF(W' \to t\bar{b})$ upper limits and theoretical cross sections.

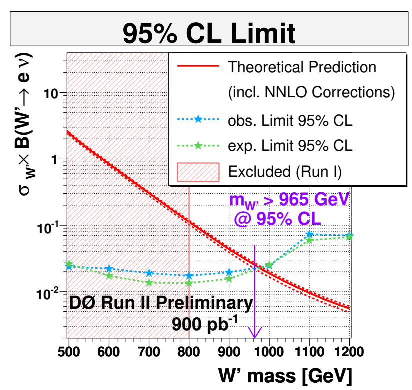

Figure 4. $\sigma(p\bar{p} \to W') \times BF(W' \to e\nu)$ upper limits and theoretical cross section.

4.2. $W' \to e\nu$

D0 searched for a W' decaying to $e\nu$ [13]. The luminosity used is 0.9 fb^{-1}. The selection is based on : 1 high E_T isolated electron with $E_T \geq 30$ GeV; a large $\not\!\!E_T$ for the neutrino with $\not\!\!E_T \geq 30$ GeV; the $\not\!\!E_T$ must balance the electron energy and be almost back-to-back to it with $0.7 \leq E_T/\not\!\!E_T \leq 1.3$; any produced jet must not be back to back to the electron or the $\not\!\!E_T$. The Backgrounds and the signal have been produced with PYTHIA 6.323. No significant excess of data compared to the different expected backgrounds is observed, we extract upper limits on the $\sigma(p\bar{p} \to W') \times BF(W' \to e\nu)$. This is shown in the Figure 4 as a function of the W' mass. The magenta curve is the observed limit, the green one is the expected one. The red curve represents the theoretical cross section with NNLO correction of the production of a W', from that we can exclude a W' with a mass lower than 965 GeV.

4.3. $Z' \to e^+e^-$

CDF searched for a narrow resonance decaying to e^+e^- : $qq' \to Z' \to e^+e^-$ [14]. The search covers the mass range from 150 GeV to 950 GeV. The data used are the full set of delivered luminosity 1.3 fb^{-1}. The selection is based on : 1 high E_T isolated electron in the Central Calorimeter (CC) with $E_T \geq 25$ GeV; 1 high E_T electron in the CC or in the plug calorimeter with $E_T \geq 25$ GeV; 1 photon conversion veto. The event generator used is PYTHIA. Since there is no significant excess, we can put upper limits on the $\sigma(p\bar{p} \to Z') \times BF(Z' \to e^+e^-)$. Figure 5 shows those limits as a function of the Z' mass. The black curve is the observed limit, the dashed one is the expected limit. The colored curves are the theoretical cross sections for the SM-like Z' and the 4 E(6) model Z''s.

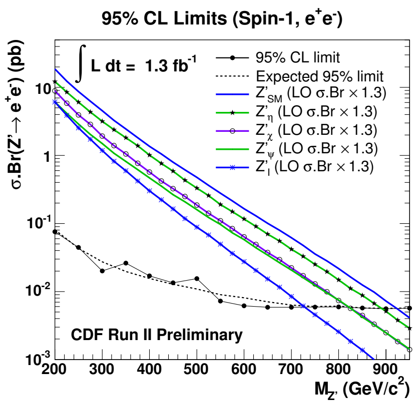

Figure 5. $\sigma(p\bar{p} \to Z') \times BF(Z' \to e^+e^-)$ upper limits and theoretical cross sections.

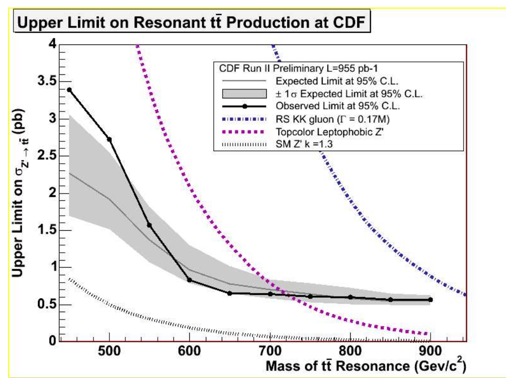

Figure 6. $\sigma(p\bar{p} \to Z') \times BF(Z' \to t\bar{t})$ upper limits and theoretical cross sections.

4.4. $Z' \to t\bar{t}$

CDF studied the $t\bar{t}$ system invariant mass and set independent limits on a new resonant $t\bar{t}$ production interpreted as a Z' : $q\bar{q} \to Z' \to t\bar{t}$ [15]. The luminosity used is 1 fb^{-1}. The selection is a standard b-tagged top mass selection : 1 central high E_T lepton with $E_T \geq 20$ GeV; a high $\not{E}_T$ with $\not{E}_T \geq 20$ GeV; 4 jets with $|\eta| \leq 2.0$ in which 3 jets have $E_T \geq 15$ GeV, the 4^{th} jet has $E_T \geq 8$ GeV; at least 1 jet with a secondary vertex. The background has been simulated using HERWIG generator[16]. The signal was generated with PYTHIA as a Z^0-like neutral boson. The search covers the mass range from 450 GeV to 900 GeV. The width of the resonance is 1.2% of the mass. No significant excess of data with respect to the background expectations is observed, we can set upper limits on $\sigma(p\bar{p} \to Z') \times BF(Z' \to t\bar{t})$. Figure 6 shows this limit as a function of the Z' mass. The black curve is the observed limit and the shaded area is the expected limit with one standard deviation. The dashed curves are different theoretical models cross sections : A massive Z' SM-like is out of the range of our sensitivity (black curve). With more luminosity, we can exclude a Randall-Sundrum Kalusa-Klein gluon of about a TeV (blue curve) and we can already exclude a leptophobic topcolor Z' with a mass lower than 720 GeV (purple curve).

5. Spin 2 resonance search (*RS G*)

Additional models have been proposed to explain the hierarchy scale between the electroweak (EW) symmetry breaking scale ($\simeq 1$ TeV) and the Planck scale ($M_{pl} \simeq 10^{16}$ TeV). The Randall-Sundrum (RS) model [17] proposes that the gravity is in a (3+1)-dimensional brane, called the Planck brane. This brane is separated from the SM brane by a 5^{th} extra-dimension with a warped metric. Gravitons are the only (spin 2) particles propagating in that extra-dimension. The graviton (G) wave functions are suppressed exponentially from the Planck brane to the SM brane, this explains why the gravity is so weak in the SM world. The RS gravitons are towers of Kaluza-Klein excitations with different modes. The zero mode RS graviton decays in the SM brane in di-photon or di-lepton. This graviton is characterized by its mass M_1 or M_G and its coupling to the SM fields $k/\bar{M}_{pl}$. Where k is the warp factor giving the extra-dimension curvature, and $\bar{M}_{pl} = M_{pl}/\sqrt{8\pi}$. The coupling is constrained with EW data and perturbative models to be between 0.01 and 0.1.

5.1. $G \to e^+e^-$

The e^+e^- resonance search interpreted as a Z' (paragraph 4.3) is used also for RS-G search. Figure 7 shows same upper limits as in Figure 5 but compared with theoretical curves from the RS model with different couplings.

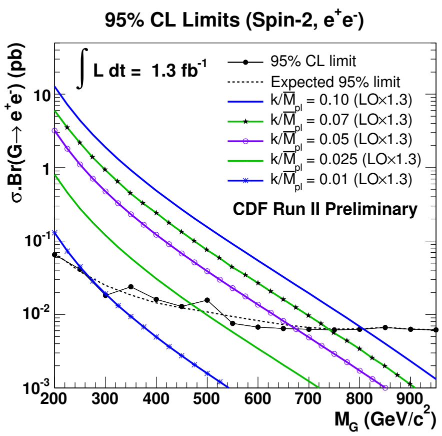

Figure 7. $\sigma(p\bar{p} \to G) \times BF(G \to e^+e^-)$ upper limits and theoretical cross sections.

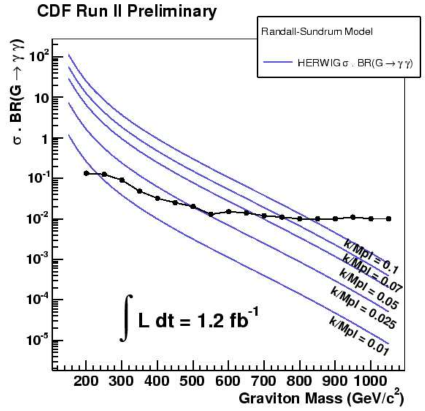

Figure 8. $\sigma(p\bar{p} \to G) \times BF(G \to \gamma\gamma)$ upper limits and theoretical cross sections.

5.2. $G \to \gamma\gamma$

CDF searched for RS graviton decaying to $\gamma\gamma$ [18]. The luminosity used is 1.2 fb^{-1}. The selection is based on 2 high E_T isolated photons with $E_T \geq 15$ GeV and a cut on the $\gamma\gamma$ system invariant mass $M_{\gamma\gamma} \geq 30$ GeV. The $\gamma\gamma$ background was generated by the DIPHOX NLO generator [19] plus PYTHIA. The signal was generated with HERWIG. The Figure 8 shows the observed upper limit on $\sigma(p\bar{p} \to G) \times BF(G \to \gamma\gamma)$ as a function of the RS-G mass. The theoretical cross sections with different coupling values is also shown.

5.3. $G \to \gamma + \gamma$ *or* e^+e^-

D0 searched for an RS graviton decaying to two photons or electrons [20]. The luminosity used is 1.1 fb^{-1}. The selection is based on 2 high E_T central electromagnetic (EM) objects with $E_T \geq 25$ GeV and a high invariant mass of the 2 objects $M_{EM-EM} \geq 50$ GeV. No significant excess is observed and we set upper limits on the $\sigma(p\bar{p} \to G) \times BF(G \to \gamma\gamma \text{ or } e^+e^-)$. Figure 9 shows those limits as a function of the RS graviton mass compared to the theoretical RS model predictions for different values of the coupling. From that, we can extract a RS graviton mass lower limit of 240 GeV for a coupling of 0.01. This limit is 865 GeV for a coupling of 0.1. The combined CDF and D0 coupling versus RS graviton mass exclusion plane is shown in Figure 10.

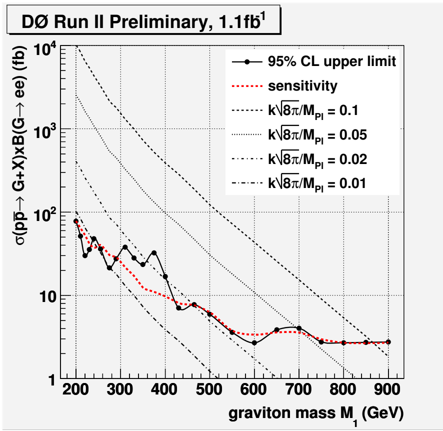

Figure 9. $\sigma(p\bar{p} \to G) \times BF(G \to \gamma\gamma \ or \ e^+e^-)$ upper limits and theoretical cross sections.

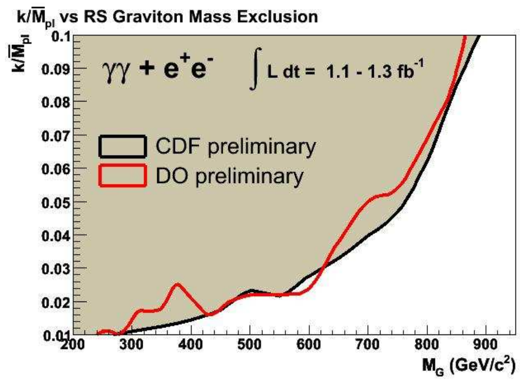

Figure 10. CDF/D0 combined plot RS graviton limits.

6. Conclusion

The CDF and D0 experiments searched for heavy resonances in the Tevatron RunIIa data, representing more than 1 fb^{-1}. No evidence for new physics or deviations from SM was found. We set model independent limits on $\sigma \times BF$ of such resonances, and also interpreted them using different models and extracted limits on the masses of particles like $\tilde{\nu}_\tau$, q^*, W', Z' and RS graviton. D0 and CDF are taking data and the Tevatron could deliver 8 fb^{-1} to each experiment by the end of 2009. This will be certainly a great opportunity for the searches beyond the Standard Model.

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