PROCEEDINGS OF SCIENCE

Search for heavy resonances decaying into ZZ at CDF

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We report on a search for heavy resonances decaying into pairs of Z bosons using 6 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 2$ TeV collected by the CDF II experiment at the Tevatron.
The analysis explores three final states corresponding to decays of the ZZ system into four charged leptons, two charged leptons plus neutrinos, and two charged leptons plus jets.
The results of the search are interpreted in the framework of theoretical models predicting heavy resonances decaying into ZZ. For heavy resonance masses above 300 GeV/c^2 we are sensitive to production cross-sections times branching ratio to ZZ below 0.2 pb.

XXIst International Europhysics Conference on High Energy Physics
21-27 July 2011
Grenoble, Rhônes Alpes, France

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PoS(EPS-HEP2011)225

1. Introduction

Z pair production is a naturally-motivated place to look for new physics, as new heavy particles may well be expected to decay to the heaviest available known particles. A Higgs boson of mass above around $180\,\mathrm{GeV}/c^2$ can decay to ZZ, and dedicated Higgs searches are reported elsewhere in these proceedings. However, other new physics models can give enhanced decays to ZZ. The original Randall-Sundrum model gives Kaluza-Klein graviton (G^*) excitations decaying mostly to leptons or photons, and searches have ruled out such states to beyond $1\,\mathrm{TeV}/c^2$. But extended models where standard model fields propagate in the bulk can have couplings to light fermions and photons strongly suppressed, and decays to vector boson pairs can dominate [1].

Apart from theoretical motivations, from an experimental perspective the ZZ final state is a very good laboratory for a signature-based search. The decay of ZZ to four charged leptons has been called the 'golden channel' because it is so clean to reconstruct in the detector. Furthermore, any hint of new physics observed in the four-lepton channel may also be confirmable in the leptons plus jets ($\ell\ell jj$) channel, or the leptons plus missing transverse energy ($\ell\ell + \not{E}_T$) channel, in which the $\not{E}_T$ results from the decay of one Z boson to neutrinos.

2. Lepton selection

In the decay mode $\mathrm{ZZ} \to \ell^+\ell^-\ell^+\ell^-$, the need to reconstruct four leptons means that any lepton inefficiency is magnified, and so this analysis implements some improvements to lepton-finding. An improved clustering algorithm is used in the shower-maximum detector embedded in the electromagnetic calorimeter. This increases background rejection for electrons, allowing some standard inefficient electron selections to be loosened. The outermost ring of the calorimeter is included for electron-finding, having verified that the electron energy resolution there is well-modeled. A calorimeter isolation energy cut of $4\,\mathrm{GeV}$ is used, gaining some efficiency compared to a fractional isolation energy cut. We also completely reprocessed CDF's data set of three loosely-selected leptons, using updated tracking code and adding an extra algorithm that adds central tracker hits to forward silicon tracks, to improve charge identification. Overall we significantly improve lepton selection efficiency without increasing the background, as measured by rates of hadronic jets being misidentified as leptons. The reconstruction and selection is verified by measuring the rate of WZ production in the decay $\mathrm{WZ} \to \ell\ell\ell\nu$, as shown in the left plot of Fig. 1.

3. $\mathrm{ZZ} \to \ell^+\ell^-\ell^+\ell^-$

Events are selected that have four leptons, which can be either electrons or muons, with $p_T > 15\,\mathrm{GeV}/c$ and at least one with $p_T > 25\,\mathrm{GeV}/c$. There are ten such events. Requiring a standard Z boson mass window, $76 < M_{\ell\ell} < 106\,\mathrm{GeV}/c^2$, leaves eight events; the two candidates that are rejected each have one lepton pair with $M_{\ell\ell} < 60\,\mathrm{GeV}/c^2$. The lepton pairings that have masses closest to the Z boson mass are same-flavour and oppositely-charged. The background is < 0.01 events. We measure the cross-section for ZZ production assuming a standard model source and find $\sigma(p\bar{p} \to ZZ) = 2.3\,^{+0.9}_{-0.8}\,(\mathrm{stat.}) \pm 0.2\,(\mathrm{syst.})\,\mathrm{pb}$, where the statistical uncertainty is the 68% confidence interval given by the method of Feldman and Cousins. Although the value is high, the large statistical uncertainty means it is consistent with the theoretical prediction 1.4 ± 0.1 pb [2].

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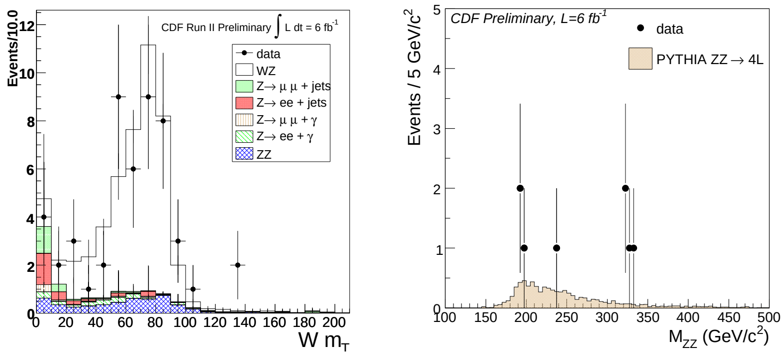

Figure 1: (left) M_T(W) in WZ events as validation of the lepton selection; (right) M_{ZZ} for eight $ZZ \to \ell^+\ell^-\ell^+\ell^-$ candidates (PYTHIA normalized to the standard model prediction).

However, we observe a clustering of events at a mean ZZ mass (M_{ZZ}) of 327 GeV/c^2, as shown in the right plot of Fig. 1. The events are eeee, ee$\mu\mu$, and two $\mu\mu\mu\mu$. At hit- and cluster-level the leptons are well-reconstructed. Splitting the eight events into low- and high-mass samples and comparing kinematic quantities with standard model predictions, it appears that event-level quantities are also well-reconstructed, although the p_T of the ZZ system is higher than expected.

We turn to the other ZZ decay modes to help interpret what is seen in the four-lepton channel.

4. $ZZ \to \ell^+\ell^-\nu\nu$

If the four-lepton events around 327 GeV/c^2 were to be due to a new ZZ resonance, it would also be detectable in the other ZZ decay modes, $\ell\ell\nu\nu$ and $\ell\ell jj$. Z bosons coming from the decay of such a heavy particle would be boosted, so events with one of the Z bosons decaying into neutrinos would have large $\not\!\!E_T$. The expected event yield in the $ZZ \to \ell^+\ell^-\nu\nu$ channel is around ten times higher than in the four-lepton channel, and the sensitivity to new physics at $M_{ZZ} \sim 325$ GeV/c^2 is several times better than in the four-lepton channel.

Optimising sensitivity for a resonance modelled by a G* of mass $M_{G^*} = 325$ GeV/c^2, we define the search region to be $\not\!\!E_T > 100$ GeV, and fix the background model below this value. Background contributions to a search for new physics in this channel come from standard model diboson production processes WW, WZ, and ZZ, as well as from $t\bar{t}$, from Z+jets events that have large $\not\!\!E_T$ due to jet mismeasurement, from W+jets events where a jet is misreconstructed as a lepton, and, in the $ee + \not\!\!E_T$ channel, from $W\gamma$ production with the photon misreconstructed as an electron. Irreducible backgrounds are estimated using simulation, or data events weighted by jet-to-lepton fake rates. The Z+jets contribution is normalized using events in which the $\not\!\!E_T$ is close to a jet or lepton.

In electron and muon channels combined we expect 26 events in the signal selection from standard model processes, and observe 27. Four four-lepton events around $M_{ZZ} = 325$ GeV/c^2 coming from the decay of a new state would imply a production cross section times branching ratio to ZZ close to 1 pb, and for that cross section, a G* signal model predicts around 35 additional events. The muon-channel visible mass ($M_{ZZ}^{\rm vis}$) distribution of Fig. 2(b) shows the predicted signal size, and the data in agreement with the standard model.

5. ZZ $\to \ell^+\ell^- jj$

The decay of a heavy particle into two Z bosons where one of the Z bosons decays into charged leptons and the other to jets has the advantage of being fully reconstructible, and the event yield in the $\ell\ell jj$ channel is expected to be around twenty times higher than in the four-lepton channel.

Events are examined that have $Z \to \ell^+\ell^-$ selected as before, and two or more jets above 25 GeV that form an invariant mass $70 < M_{jj} < 100\,\mathrm{GeV}/c^2$. The total mass $M_{\ell\ell jj} < 300\,\mathrm{GeV}/c^2$ defines a control region for normalising the Alpgen Z+jets background. In the signal region, $M_{\ell\ell jj} > 300\,\mathrm{GeV}/c^2$, the event counts match the standard model expectation and, as shown for the electron channel in Fig. 2(a), there is no evidence of new physics in the form of a mass peak.

6. Limits

To quantify results of the search we compute expected and observed limits on the production cross section times branching ratio $\sigma(p\bar{p} \to G^* \to ZZ)$. The expected sensitivity is determined with a Bayesian technique, using CL_S likelihood test statistics. Although the $\ell\ell + \not{E}_T$ and $\ell\ell jj$ channels have higher backgrounds than the four-lepton channel, they are more sensitive to new physics. Expected and observed limits are consistent with each other, as shown in Fig. 2(c). For $M_{G^*} = 325\,\mathrm{GeV}/c^2$, the 95% CL upper cross section limit is expected to be 0.19 pb and is observed to be 0.26 pb. A second model of a boosted resonance is studied, and for $M_{G^*} = 325\,\mathrm{GeV}/c^2$ the expected limit is 0.17 pb and the observed limit is 0.28 pb, demonstrating that the analysis is not very sensitive to the resonance production mechanism.

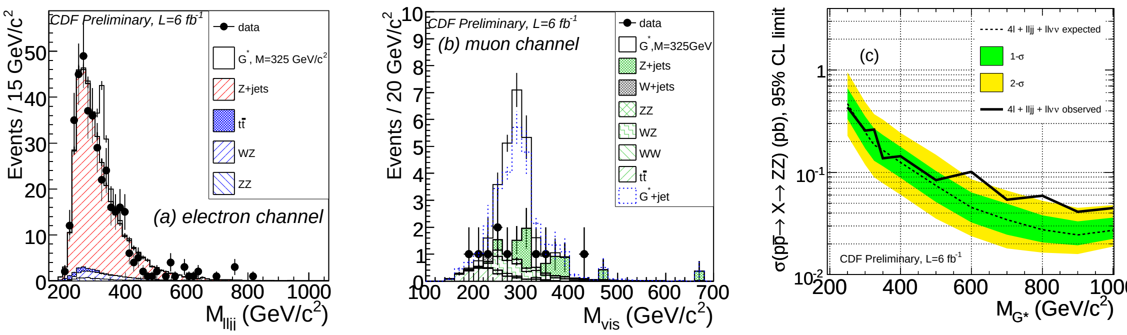

Figure 2: (a) $M_{\ell\ell jj}$ for the Z+jets channel with $Z \to e^+e^-$; and (b) invariant mass M_{ZZ}^{vis} of the sum of the two lepton four-momenta and $(\not{E}_x, \not{E}_y, 0, |\not{E}_T|)$, for the Z+$\not{E}_T$ channel with $Z \to \mu^+\mu^-$; both showing the expected contribution from a graviton of $M_{G^*} = 325\,\mathrm{GeV}/c^2$ and cross section times branching ratio to ZZ of 1 pb. (c) Expected and observed 95% CL limits on $\sigma(p\bar{p} \to G^* \to ZZ)$ from all channels combined.

7. Conclusions

Three distinct final states have been analysed in the search for ZZ resonances. There is a clustering of events at high mass in the four-lepton final state, however new physics is ruled out by the more sensitive $\ell\ell jj$ and $\ell\ell + \not{E}_T$ final states, and limits are set on G^* production.

References: [1] JHEP **0709**, 013 (2007). [2] Phys. Rev. D **60**, 113006 (1999).

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