Search for a heavy resonance decaying into a $Z^+$ jet final state in $pp$ collisions at $\sqrt{s} = 1.96$ TeV using the D0 detector

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Heavy resonances decaying into a quark and a gauge boson may signal the existence of excited quarks and thereby indicate quark substructure \[1\]. Searches for excited quarks have been carried out in the past using dijet \[2–4\], photon + jet, and W + jet \[5\] final states. In the analysis described here, we searched for resonances in the \(Z + \text{jet}\) channel, where the \(Z\) boson is detected via its \(Z \rightarrow e^+e^-\) decay mode. This signature is practically free of instrumental background. However, it suffers from the low branching fraction (3.36\%) of the \(Z \rightarrow e^+e^-\) decay channel. The high luminosity delivered by the Fermilab Tevatron collider in Run II makes it possible to present results on this final state for the first time.

For the production and decay of a resonance, we considered the model \[1\] implemented in PYTHIA 6.202 \[6\]. Here, a quark (antiquark) and a gluon from the colliding proton and antiproton form a resonance, \(q'\), which subsequently decays into a \(Z\) boson and a quark: \(q' \rightarrow q + Z\). The model has two free parameters, \(M_{q'}\), the mass of the resonance, and \(\Lambda\), the compositeness scale which determine the production cross section and the natural width of the resonance. The latter scales as \(1/\xi^2\), where \(\xi = \Lambda/M_{q'}\).

The Run II D0 detector \[7\] consists of several layered subdetectors. For the present analysis, the most relevant parts are the liquid-argon/uranium calorimeter \[8\] and the central tracking system. The calorimeter, divided into electromagnetic and hadronic sections, has a granularity of \(\Delta \eta \times \Delta \phi = 0.1 \times 0.1\), where \(\eta\) is the pseudorapidity \((\eta = -\ln[\tan(\theta/2)]\) with \(\theta\) being the polar angle measured from the geometrical center of the detector with respect to the proton beam direction) and \(\phi\) is the azimuthal angle. The third innermost layer, in which the largest electromagnetic energy deposition is expected, has a finer granularity of \(\Delta \eta \times \Delta \phi = 0.05 \times 0.05\). The central calorimeter covers \(|\eta| \leq 1.1\), and the two end calorimeters extend coverage to \(|\eta| = 4.5\). The tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities \(|\eta| < 3\) and \(|\eta| < 2\), respectively.

The data used in this analysis were collected between April 2002 and August 2004, with an integrated luminosity of 370 \(\text{pb}^{-1}\). The selected events were required to pass at least one of several single- or di-electron triggers. The efficiency of the trigger was measured with data and found to reach a plateau of \(e_{\text{trig}} = 0.982 \pm 0.011\) for events satisfying the final event selection criteria.

Offline event selection was based on run quality, event properties, and electron and jet identification criteria. Events were required to have a reconstructed vertex with a longitudinal position within 60 cm of the detector center. Electrons were reconstructed from electromagnetic (EM) clusters in the calorimeter using a cone algorithm. The reconstructed electron candidates were required to satisfy either \(|\eta| \leq 1.1\) or \(1.5 < |\eta| \leq 2.5\). Electron pairs with \(p_T^e \geq 30\ \text{GeV}\) and \(p_T^e \geq 25\ \text{GeV}\) in the event were used to reconstruct the \(Z\) boson candidate. The electron pair was required to have an invariant mass \(M_{ee}\) in the region \(80 < M_{ee} < 102\ \text{GeV}\) near the \(Z\) boson mass of 91.2 GeV.

To reduce background contamination, mainly from jets misidentified as electrons, the EM clusters were required to pass three quality criteria based on shower profile: (i) the ratio of the energy deposited in the electromagnetic part of the calorimeter to the total shower energy had to exceed 0.9; (ii) the lateral and longitudinal shapes of the energy cluster had to be consistent with those of an electron; and (iii) the electron had to be isolated from other energy deposits in the calorimeter with isolation fraction \(f_{\text{iso}} < 0.15\). The isolation fraction is defined as \(f_{\text{iso}} = [E_{\text{EM}}(0.4) - E_{\text{EM}}(0.2)]/E_{\text{EM}}(0.2)\), where \(E_{\text{EM}}(R_{\text{cone}})\) and \(E_{\text{EM}}(R_{\text{cone}})\) are the total and the EM energy, respectively, deposited within a cone of radius \(R_{\text{cone}} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\) centered around the electron. Additionally, at least one of the electrons was required to have a spatially close track with a momentum consistent with the EM shower energy. A total of 24734 events passed these criteria. In Fig. 1, the distribution of the invariant mass, \(M_{ee}\), of the two selected electrons is shown. A very clean, almost background-free \(Z\) boson signal is evident.

Jets were reconstructed using the “Run II cone algorithm” \[9\] which combines cell energies within a cone of radius \(R_{\text{cone}} = 0.5\). Spurious jets from isolated noisy calorimeter cells were suppressed by cuts on the jet shape and by requiring that the charged tracks associated with the jet had to carry a minimum fraction of the jet transverse energy. The transverse momentum of each jet was corrected for offsets due to the underlying event, multiple \(p \bar{p}\) interactions and noise, out-of-cone showering, and the detector energy response as determined from the transverse
energy balance of photon + jet events. Jets were required to have $p_T > 20$ GeV and $|\eta| < 2.5$ and to not overlap with any of the reconstructed EM objects within a distance of 0.4 in ($\eta, \phi$) space. Requiring one or more jets with these selection criteria yielded a sample of 2417 events.

We have considered two kinds of instrumental backgrounds where hadronic jets are misreconstructed as EM clusters and mimic a Z boson events. A background from genuine QCD multijet production arises when both of the EM objects are hadronic jets that fluctuate to electromagnetic final states. This background has been estimated to be $(0.56 \pm 0.02)\%$ of the signal in the mass region of $80 < M_{ee} < 102$ GeV as calculated by comparing the $M_{ee}$ mass distribution of the selected events with a distribution where the lateral and longitudinal shapes of the energy clusters were not consistent with those of an electron and there was no track matching to these clusters. The other source of background is $W \rightarrow e +$ jets events where a hadronic jet is misidentified as an electron. These events are characterized by significant missing transverse energy ($E_T$), and should also appear in the data sample where only one of the EM objects has a matched track. From comparison of the $E_T$ distribution of these events with that where both electrons do have matched tracks, we estimate that this background is an order of magnitude less than the QCD background.

The main standard model (SM) background to the excited quark signal is inclusive $Z/\gamma^* \rightarrow e^+ e^-$ pair production. This process has been simulated with PYTHIA using the CTEQ5L [10] parton distribution functions (PDFs). In order to enhance the statistics for events where the invariant mass of the $Z$ boson and the leading jet, $M_{Zj_j}$, is high, in addition to the so-called $2 \rightarrow 1$ process, where the initial quark and antiquark annihilates into a $Z$ boson, we have also generated events including matrix elements of first order in $\alpha_s$ ($2 \rightarrow 2$ process) where the produced $Z$ boson is accompanied by a quark or a gluon in the final state. The threshold of $M_{Zj_j}$, the invariant mass of the $Z$ boson and the accompanying parton, has been varied. A minimum value of 30 GeV for $p_T$, the transverse momentum of the parton in the $2 \rightarrow 2$ collision, has been set in order to avoid collinear divergences. The leading jet $p_T$ distribution has a mean and an RMS value of 106 GeV and 27 GeV, respectively, at the lowest resonance mass investigated and after the final selection, therefore the $p_T$ cut does not affect the analysis. The shape of the $M_{Zj_j}$ distribution has been compared with that obtained with the ALPGEN program [11] and there is reasonable agreement between them. Any differences in the background level have been taken into account as a systematic uncertainty.

Signal events were generated with PYTHIA using the CTEQ5L PDFs for the following resonance mass values: $M_{q} = 300, 400, 500, 600$ and $700$ GeV with $\xi = \Lambda/M_{q} = 1$. For each mass, except for the lowest one, we also generated events with $\xi = 0.3, 0.5$ and 0.7, in order to vary the natural width of the resonance, $\Gamma_{q'q}$. The form factors associated with the interaction of the quarks with the SM gauge bosons were set to unity. The MC events were passed through the same reconstruction software and selection criteria as the data. The events have been used to estimate the geometrical acceptance and jet and electron identification efficiencies. The combined ac-

![Graph](image.png)

**FIG. 1.** The invariant mass of the two selected electrons in the data events.

**TABLE I.** Measured ($\sigma_{95}$) and expected ($\sigma_{95}^{\text{exp}}$) values of the upper limit on the resonance cross section times branching fraction, signal acceptance $\times$ efficiency, SM background, and number of observed events at the optimal value of the topological cut $k$ for different resonance masses and for $\xi = 1$.

<table>
<thead>
<tr>
<th>$M_{q}$ (GeV)</th>
<th>$k$</th>
<th>$\sigma_{95}$ (pb)</th>
<th>$\sigma_{95}^{\text{exp}}$ (pb)</th>
<th>Acceptance $\times$ efficiency</th>
<th>SM background</th>
<th>Data (events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.1</td>
<td>0.25</td>
<td>0.290</td>
<td>$0.140 \pm 0.009$</td>
<td>$32.8 \pm 2.9$</td>
<td>31</td>
</tr>
<tr>
<td>400</td>
<td>1.2</td>
<td>0.15</td>
<td>0.129</td>
<td>$0.164 \pm 0.010$</td>
<td>$7.5 \pm 0.8$</td>
<td>9</td>
</tr>
<tr>
<td>500</td>
<td>1.3</td>
<td>0.08</td>
<td>0.079</td>
<td>$0.195 \pm 0.012$</td>
<td>$2.9 \pm 0.8$</td>
<td>3</td>
</tr>
<tr>
<td>600</td>
<td>1.8</td>
<td>0.05</td>
<td>0.053</td>
<td>$0.244 \pm 0.014$</td>
<td>$1.6 \pm 0.6$</td>
<td>1</td>
</tr>
<tr>
<td>700</td>
<td>1.7</td>
<td>0.03</td>
<td>0.044</td>
<td>$0.243 \pm 0.014$</td>
<td>$0.64 \pm 0.06$</td>
<td>0</td>
</tr>
</tbody>
</table>
The SM backgrounds generated with PYTHIA are shown in the histograms: $2 \rightarrow 1$ without threshold (solid line), $2 \rightarrow 2$ with various $M_zq$ thresholds (discontinuous lines, as indicated). Each curve with a definite $M_zq$ threshold value stops when the curve of the next threshold value takes over. Also shown with open circles is the signal due to an excited quark of 500 GeV mass and narrow width ($\xi = 1$). The resonance production cross section is taken from Ref. [1].

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Since no significant excess of events is observed, which would indicate the presence of a resonance, we determined the upper limit on the production cross section of a hypothetical resonance as a function of its mass and width. We made use of the fact that in the $p_{TZ}$ vs $M_{Zj1}$ plane, events from the resonance are concentrated for $M_{Zj1}$ around the mass value and for $p_{TZ}$ at about half of the mass value of the resonance, since the resonance is nearly at rest. The SM background does not exhibit a similar structure, as it is shown in Fig. 3. In addition, finite width and mass resolutions wash out the correlation between $p_{TZ}$ and $M_{Zj1}$. We therefore considered events around the peak values $M_{Zj1}^c$ and $p_{TZ}^c$ of the resonance determined by the following condition:

$$
\left( \frac{M_{Zj1} - M_{Zj1}^c}{M_{Zj1}^{rms}} \right)^2 + \left( \frac{p_{TZ} - p_{TZ}^c}{p_{TZ}^{rms}} \right)^2 < k^2
$$

and we optimized the cut value $k$. Here, $M_{Zj1}^{rms}$ and $p_{TZ}^{rms}$ are the RMS values of the corresponding distributions of the resonance. At given values of mass and width, the latter defined by $\xi$, we varied $k$ in Eqn. (1) between 0 and 3 in steps of 0.1.

Based only on the information from the signal and background simulation, for each $k$ we calculated $\sigma_{95}^{ave}$, the expected value of the upper limit on the resonance production cross section times branching fraction at the 95% C.L. using a Bayesian approach [12] and by averaging over possible outcomes of the background-only hypothesis assuming Poisson statistics for the background. The optimum value of $k$ corresponds to the minimum value of $\sigma_{95}^{ave}$. At this value of $k$, using also the data, we derived $\sigma_{95}$, the measured value of the upper limit on the resonance production cross section times branching fraction at the 95%
In this calculation we have taken into account systematic uncertainties in the determination of the luminosity (6.5%), trigger and identification efficiencies, and those of the jet calibration and resolution. Systematic uncertainties due to the modeling of the SM background and to the choice of the PDF, as well as those due to the threshold systematics.

In conclusion, we have searched for a resonance produced by the fusion of a gluon and a quark in $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV which decays into a $Z$ boson and a quark in the $Z\rightarrow e^+e^-$ decay channel. In the absence of a signal, we have determined 95% C.L. upper limits on the cross section times branching fraction as a function of the mass and width of the resonance. The present study is complementary to earlier searches because it has sensitivity to hypothetical models with enhanced couplings to the $Z$ boson.

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[1] U. Baur, M. Spira, and P. M. Zerwas, Phys. Rev. D 42, 815 (1990). NLO corrections for this process have not yet been carried out. In general, they are expected to increase the cross section, but are not expected to exceed 50% for this type of process.


