Search for Pair Production of Strongly Interacting Particles Decaying to Pairs of Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for the pair production of a narrow nonstandard-model strongly interacting particle that decays to a pair of quarks or gluons, leading to a final state with four hadronic jets. We consider both nonresonant production via an intermediate gluon as well as resonant production via a distinct nonstandard-model intermediate strongly interacting particle. We use data collected by the CDF experiment in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of 6.6 fb^{-1}. We find the data to be consistent with nonresonant production. We report limits on $\sigma(p\bar{p} \to jjjj)$ as a function of the masses of the hypothetical intermediate particles. Upper limits on the production cross sections for nonstandard-model particles in several resonant and nonresonant processes are also derived.

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One of the few hints of possible physics beyond the standard model (SM) at the TeV scale is the anomalous top-quark forward-backward asymmetry A_{fb} observed at the Fermilab Tevatron collider [1–3]. This asymmetry could be generated by non-SM physics through the production of top-quark pairs via a light axigluon [4], a particle with axial couplings to quarks, that interferes with SM $t\bar{t}$ production to produce the observed asymmetry. The axigluon would be visible in its alternate decay mode to low-mass strongly interacting particles, each of which decays to a pair of jets [5] yielding a four-jet final state. This final state is of broad interest, as various models predict the pair production of strongly interacting particles decaying to jet pairs with no intermediate resonance [6,7], and R-parity-violating supersymmetric theories [8] predict the pair production of light partners of the top quark (top squarks), each decaying into to pairs of light quarks.

The masses of the axigluon and its strongly interacting decay products are not predicted but must be fairly light ($< 400\ \text{GeV}/c^2$) to explain the A_{fb} measurement [9]. The CERN Large Hadron Collider experiments have excellent sensitivity at high mass due to the large center-of-mass energy but difficulties at low mass due to high background rates. The ATLAS experiment ruled out masses between 100 and 150 GeV/c^2 [10]; CMS ruled out masses between 250 and 740 GeV/c^2 [11]. No experimental bounds exist for such non-SM particles with masses below 100 GeV/c^2 for the nonresonant pair production of dijet resonances; there are no current limits on resonant production.

In this Letter, we report a search for both nonresonant and resonant production of pairs of strongly interacting particles, each of which decays to a pair of jets. Rather than probing a specific theory, we construct a simplified model with the minimal particle content. In the nonresonant case, we consider the production process $p\bar{p} \to YY \to jjjj$, with the mass of the hypothetical Y state m_Y as a single free parameter. In the resonant case $p\bar{p} \to X \to YY \to jjjj$, we also explore the mass of the X state m_X (Fig. 1). In both cases, we assume that the natural width of the particles is small compared to the experimental resolution.

We analyze a sample of events corresponding to an integrated luminosity of $6.6 \pm 0.5\ \text{fb}^{-1}$ recorded by the CDF II detector [12], a general purpose detector designed to study $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV produced by the Fermilab Tevatron collider. The tracking system consists of a silicon microstrip tracker and a drift chamber immersed in a 1.4 T axial magnetic field [13]. Electromagnetic and hadronic calorimeters surrounding the tracking system

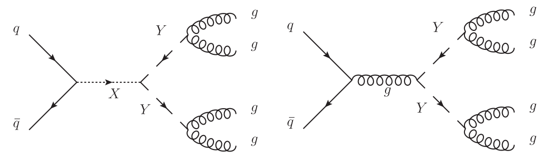

FIG. 1. Diagrams for the resonant (left, via X) and nonresonant (right) pair production of Y particles, with subsequent decays to pairs of gluons. Other models, with final-state quarks, are also considered.

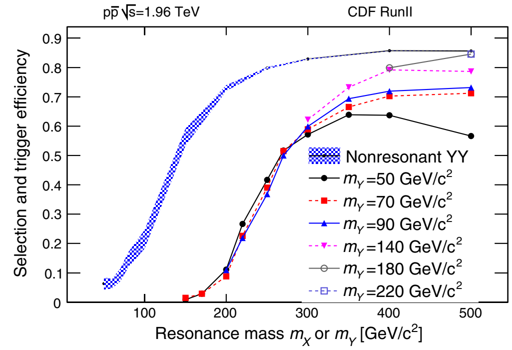

FIG. 2 (color online). Overall efficiency, including trigger and selection requirements. Efficiency is shown for several simulated nonresonant $YY \to jjjj$ samples with varying m_Y. The shaded band shows the uncertainty. In addition, efficiency is shown for several simulated resonant $X \to YY \to jjjj$ samples with varying m_X and m_Y. The uncertainty is not shown but is similar to the nonresonant case. The turn-on curve is determined largely by the trigger requirement that $\Sigma_{\text{jets}} E_T > 130$ GeV.

measure particle energies, with muon detection provided by an additional system of drift chambers located outside the calorimeters.

We reconstruct jets in the calorimeter using the JETCLU [14] algorithm, with a clustering radius of 0.4 in $\eta - \phi$ space [15] and calibrated using the techniques outlined in Ref. [16]. Events are selected online (triggered) by the requirement of three jets, each with $E_T > 20$ GeV and with $\Sigma_{\text{jets}} E_T > 130$ GeV [15]. The data set used in this search is limited to 6.6 fb^{-1} because the trigger selection was not available in early data. After trigger selection, events are retained if at least four jets are found with $E_T > 15$ GeV and $|\eta| < 2.4$.

We model resonant and nonresonant production with MADGRAPH5 [17] version 1.4.8.4 using models provided by the authors of Refs. [6,7] and the CTEQ6L1 [18] parton distribution functions (PDFs). The parton shower, hadronization, and underlying-event modeling are described by PYTHIA [19] version 6.420. The detector response for all simulated samples is modeled by the GEANT-based CDF II detector simulation [20].

The trigger and selection requirements have an efficiency on the signal up to 90% (Fig. 2) if $\Sigma_{\text{jets}} E_T$ exceeds significantly the 130 GeV trigger threshold. For events with smaller $\Sigma_{\text{jets}} E_T$, the efficiency decreases rapidly. In the nonresonant-production model, the $\Sigma_{\text{jets}} E_T$ is strongly correlated with m_Y. In the resonant-production model, it is correlated with m_X; additionally, if $m_X - 2m_Y$ is large, the p_T of the resulting Y is large, which leads to a small opening angle of its decay products and a loss of efficiency due to merged jets. The trigger efficiency is measured in simulated events, and uncertainties are derived from validation in disjoint samples; the measured trigger efficiency and uncertainty are applied to the signal model.

To reconstruct the dijet resonance, we consider the four highest E_T jets and evaluate the invariant mass of each of the dijet pairs in the three permutations, choosing the permutation with the smallest mass difference between the pairs. Invariant masses are computed as those from the sum of the four-vectors of the jet pairs. As the pair masses are correlated, we take the mean of the two pair masses as the estimate of the dijet resonance mass. To reduce backgrounds, we require that the relative mass difference between the two pairs is less than 50% and that the production angle θ^* of the dijet resonance in the YY pair center-of-mass frame satisfies $\cos(\theta^*) < 0.9$. In the resonant-production analysis, we calculate the four-jet invariant mass. No specific m_Y-dependent selections are made; the requirement that the relative dijet mass difference be small ensures compatibility with the $X \to YY$ hypothesis. Figures 3 and 4 show the observed dijet and four-jet spectra, respectively.

The dominant background originates from standard QCD multijet production. We model this background contribution using a parametric function which is fit to the reconstructed mass spectrum of the observed data. The function is a piecewise combination of a third-order polynomial to describe the turn-on region, a third-order polynomial to describe the peak region, and a double

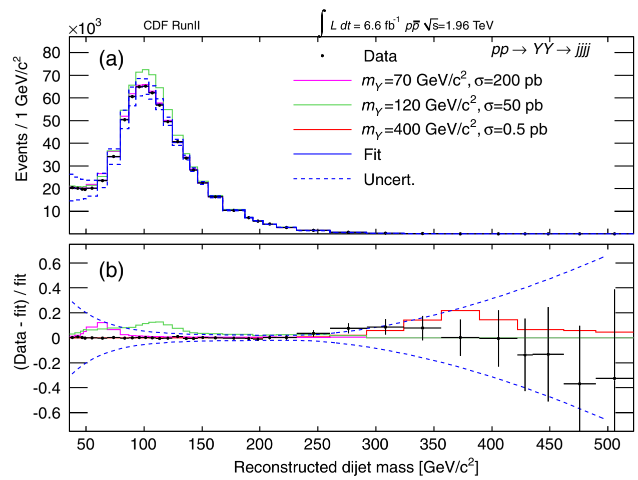

FIG. 3 (color online). Reconstructed mean dijet mass in events with four jets. Parametric fit and several signal hypotheses are overlaid in (a). Relative difference between the observed data and the fit in each bin are shown in (b).

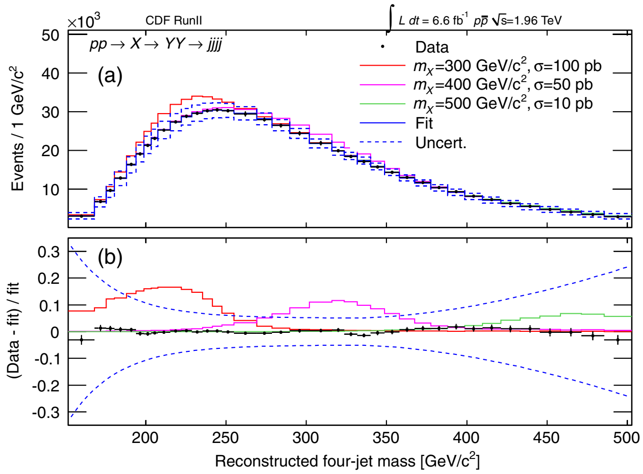

FIG. 4 (color online). Reconstructed four-jet mass in events with four jets. Parametric fit and several signal hypotheses are overlaid in (a). Relative difference between the observed data and the fit in each bin are shown in (b).

exponential of the form $f(m) = a_1 e^{-(m-a_2)^{a_3}/a_4}$ to describe the falling spectrum. The parametric functional form was chosen to be flexible enough to describe the multijet mass spectrum but rigid enough to avoid accurately describing a spectrum which includes a narrow resonance, so that in the presence of a narrow feature, a signal-plus-background hypothesis would be preferred. For the dijet mass, the ranges used are [35, 82.5], [82.5, 140], and [140, 700] GeV/c^2; for the four-jet mass, the ranges used are [115, 185], [185, 330], and [330, 800] GeV/c^2. The functional form and ranges were chosen based on their ability to accurately describe the mass spectra of simulated multijet events generated by ALPGEN [21] version 2.10.

The dominant source of systematic uncertainty is due to the multijet background model. The functional form is an approximation, which even in the absence of a narrow feature may deviate from the observed spectrum. We estimate the impact of these potential deviations by measuring their magnitude in two background-enriched control samples. These two control samples are adjacent to the signal region and capture the expected deviations in two independent directions. The first requires a large relative dijet mass difference, greater than 50%, and the second requires $\cos(\theta^*) > 0.9$. The observed relative deviations are then applied to the observed spectrum in the signal region to estimate the magnitude of spurious deviations due to possible mismodeling. In addition, we verify that the fitting procedure gives an unbiased estimate of the signal rate.

An additional uncertainty is due to knowledge of the trigger efficiency [22] extracted from the simulated signal samples, varying from 20% relative at $\Sigma_{\mathrm{jets}} E_T = 120$ GeV to 10% above $\Sigma_{\mathrm{jets}} E_T = 200$ GeV. Uncertainties in the levels of parton radiation [23] and in the calibration of the jet energy and resolution modeling [16] also contribute to uncertainties in the trigger and selection efficiency and reconstructed mass spectrum of the signal samples. These uncertainties are small (< 10%) relative to the fitting and trigger uncertainties.

In the nonresonant analysis, for each Y mass hypothesis, we fit the most likely value of the Y pair-production cross section (σ_{YY}) by performing a maximum likelihood fit of the binned dijet mass distribution, allowing for systematic and statistical fluctuations via template morphing [24]. The likelihood takes the form of

$$L(\sigma_{YY}) = \prod_{\mathrm{bin}\,i} f^i_{\mathrm{bg}}(\vec{a}) + \sigma_{YY}\mathcal{L}\epsilon f_{\mathrm{sig}},$$

where $f_{\mathrm{bg}}(\vec{a})$ is the parametric function with nuisance parameters $\vec{a}$ defined above to describe the background spectrum, f_{sig} is a normalized template of the expected shape of the signal determined from simulated events, and $\mathcal{L}\epsilon$ is the product of the integrated luminosity and efficiency. No evidence is found for the presence of the pair production of dijet resonances, and upper limits on Y pair production at a 95% confidence level (C.L.) are set.

Limits are calculated using the C.L. [25] method by repeating the measurement on sets of simulated experiments that include signal contributions corresponding to various hypothetical production cross sections and variation of systematic uncertainties. The values of nuisance parameters are varied but are not fit in the experiments. The observed limits are consistent with expectation for the background-only hypothesis. The resonant analysis is very similar but is done as a function of the X mass hypothesis, fitting the four-jet mass distribution for the most likely value of the X production cross section σ_X.

In the nonresonant case, this analysis sets limits on coloron or top-squark pair production, excluding 50–125 GeV/c^2 and 50–90/c^2, respectively; see Table I and the top of Fig. 5. The uncertainty on the theoretical cross-section prediction comes from two sources summed

TABLE I. Observed and expected 95% C.L. upper limits on $\sigma(p\bar{p} \to YY \to jjjj)$ for several values of m_Y. Also shown are theoretical predictions for coloron pair production [6,7] or top-squark pair production with R-parity-violating decay $\tilde{t} \to qq'$ [26].

Mass (GeV/c^2)	Expected (pb)	Observed (pb)	Coloron (pb)	Top squarks (pb)
50	240	250	320	570
70	75	62	180	100
90	8.2	5.9	62	26
100	11	17	37	15
125	14	11	11	4.4
150	37	46	3.7	1.5
200	4.5	2.0	0.60	0.25
250	2.7	1.5	0.11	5.4×10^{-2}
300	2.0	3.0	2.9×10^{-2}	1.3×10^{-2}
400	1.1	1.5	1.7×10^{-3}	7.2×10^{-4}
500	0.3	0.3	8.5×10^{-5}	3.6×10^{-5}

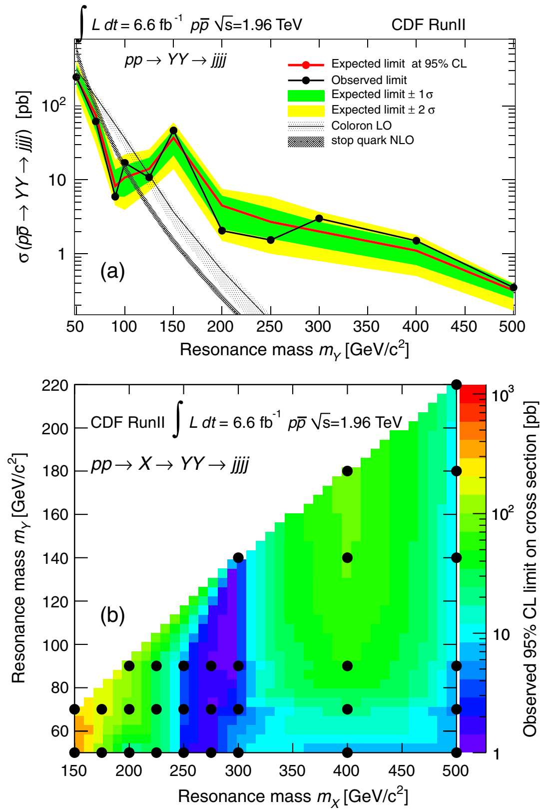

FIG. 5 (color online). Upper limit on signal production rate at 95% C.L. Expected and observed upper limits on $\sigma(p\bar{p} \to YY \to jjjj)$ versus m_Y in the nonresonant analysis are shown in (a). Two signal hypotheses are shown, at leading-order (LO) and next-to-leading-order (NLO) in α_s; see text for details. Observed limits on $\sigma(p\bar{p} \to X \to YY \to jjjj)$ versus m_X and m_Y are shown in (b). Circles indicate the true values of the parameters used in each ensemble of simulated samples used to evaluate the limits; intermediate values are interpolated.

in quadrature. The first uncertainty is the envelope of the PDF uncertainties from the CTEQ6L1 uncertainties and an alternative PDF choice MSTW2008LO [27] (5% relative). The second uncertainty comes from a variation of the renormalization and factorization scales by a factor of 2 in each direction from their default values of the per-event mass scale. These theoretical uncertainties are illustrated in Fig. 5.

In the resonant case, this analysis excludes axigluon (A) production, leading to pairs of σ particles and a four-gluon final state for $m_A \in [150, 400]$, $m_\sigma \in [50, m_A/2]$ in the case of coupling to quarks $C_q = 0.4$ (see Table II and the bottom of Fig. 5), which is close to the value required to explain the top-quark $A_{\rm fb}$ result [9]. To be consistent with this analysis, the couplings would have to be smaller by an order of magnitude. Maintaining consistency with the top-quark $A_{\rm fb}$ result would require different couplings to light quarks and heavy quarks, with the heavy-quark coupling approaching the perturbative limit $C_q < 1$.

TABLE II. Observed and expected 95% C.L. upper limits on $\sigma(p\bar{p} \to X \to YY \to jjjj)$ for several values of m_Y and m_X. Also shown are theoretical predictions for axigluon production assuming coupling to quarks of $C_q = 0.4$ [5,9].

m_X (GeV/c^2)	m_Y (GeV/c^2)	Expected (pb)	Observed (pb)	Axigluon (pb)
150	50	641.2	431.1	5600
	70	209.6	270.6	
175	50	66.8	78.9	3500
	70	111.5	163.9	
200	50	13.8	9.5	2200
	70	30.4	91.5	
	90	17.8	100.4	
225	50	18.0	26.0	1750
	70	20.7	25.0	
	90	20.9	25.3	
250	50	6.2	2.0	1000
	70	4.0	3.6	
	90	5.1	2.8	
275	50	6.5	1.2	850
	70	7.7	1.3	
	90	9.7	1.4	
300	50	5.0	7.1	540
	70	2.4	2.6	
	90	1.7	1.0	
	140	1.8	1.2	
400	50	15.5	6.8	170
	70	15.0	20.2	
	90	30.6	52.8	
	140	41.0	74.6	
	180	46.9	79.1	
500	50	20.7	6.8	60
	70	15.9	4.7	
	90	17.7	5.9	
	140	25.2	7.0	
	180	26.7	8.0	
	220	29.7	9.3	

In both cases, a particle with width larger than the experimental resolution would evade these limits.

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