TEVATRON SEARCHES FOR LARGE EXTRA DIMENSIONS AND LEPTOQUARKS*

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This paper presents searches for large extra dimensions and leptoquarks in $p\overline{p}$ collisions from Run 1 at the Tevatron. Large extra dimensions are searched for in real graviton production with a monojet or monophoton and in virtual graviton exchange processes with electron or photon pairs. Results from leptoquark searches are presented for three generations of leptoquarks. No evidence of signal is found in any searches for large extra dimensions or leptoquarks and limits are placed. Prospectives for these searches in the Tevatron's Run 2 are discussed and initial Run 2 data is presented.

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1. Large extra dimensions

The possibility of more than three spatial dimensions has been raised by a number of theories including string theories with six or seven extra dimensions compactified at distances of the order of 10^{-32} m. Larger extra dimensions can be used to solve the hierarchy problem and bring the effective Planck scale ($M_{\rm S}$) down to the TeV scale. In a model where gravity is the only force allowed to propagate in the extra dimensions, Arkani–Hamed, Dimopoulos and Dvali [1] show that if the extra dimensions are large enough, the apparent weakness of gravity in the observed three dimensions can be explained by the surface area added to the Gaussian surface by the extra dimensions. In order to make $M_{\rm S} \sim 1\,{\rm TeV}$, the size of the extra dimensions must be

$$R \approx \frac{1}{M_{\rm S}\left(\frac{M_{\rm P}}{M_{\rm S}}\right)^{2/n}} \approx 10^{\left(\frac{32}{n}\right)-19}\ {\rm m} \qquad (1)$$

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where, M_{P} is the Planck scale, n is the number of extra dimensions and all extra dimensions are assumed to have the same size.

Cosmological observations [2] and recent results from gravity experiments at sub-millimeter distances [3] give constraints of $M_{\mathrm{S}} > \sim 100\,\mathrm{TeV}$ for $n = 2$ and $M_{\mathrm{S}} > \sim 5\,\mathrm{TeV}$ for $n = 3$ while the orbits of the planets in our solar system show the Newtonian $1/r$ nature of the gravitational potential, ruling out $n = 1\,(R \sim 10^{13}$ m). Clearly, $n = 2\,(R \sim 1$ mm) is significantly constrained, however for $n > 2$, the required sizes of the extra dimensions can be microscopic. Probing these short scales can be accomplished at high energy colliders where the effects of gravity may be enhanced by the accessibility of numerous excited Kaluza–Klein graviton states which wind around the compactified dimensions.

Large extra dimensions may be observed at colliders through real graviton production or virtual graviton exchange [4–7]. The typical signature of real graviton production is a monojet or single vector boson with large transverse momentum as well as missing energy from a graviton that escapes the detector. The cross section for real graviton production has a $1/(M_{\mathrm{S}})^{n+2}$ dependence: strongly dependent on the number of extra dimensions.

Virtual graviton exchange produces fermion–antifermion or diboson pairs with large invariant mass. A number of different formalisms describe this cross section in the presence of large extra dimensions [4, 5, 7]. The cross section formalisms have weak or no dependence on the number of extra dimensions. Calculations of virtual graviton effects require an ultraviolet cutoff to keep the divergent sum over the graviton excitation modes finite. This cutoff is expected to be of the order of the effective Planck scale and is quoted as M_{S} for limits on virtual graviton effects in this paper [8]. The limits on M_{S} in this paper are presented using the formalism of [7], which has no dependence on n and uses the parameter $\lambda = \pm 1$ to denote constructive or destructive interference between Standard Model and graviton-mediated production.

In a recent study [9], the CDF collaboration reports a search for virtual graviton effects in $p\overline{p} \to \gamma\gamma$ with $E_{\mathrm{T}}^{\gamma} > 22\,\mathrm{GeV}$ and $|\eta_{\gamma}| < 1$. A total of 287 events pass these cuts in 110 pb^{-1} of data from the Tevatron's Run 1 data-taking period. No deviation from the Standard Model description of the invariant mass of the $\gamma\gamma$ system is observed and limits of $M_{\mathrm{S}}(\lambda = +1) > 0.899\,\mathrm{TeV}$ and $M_{\mathrm{S}}(\lambda = -1) > 0.797\,\mathrm{TeV}$ are extracted. An e^+e^- final state is also explored with $E_{\mathrm{T}}^{e^{\pm}} > 25\,\mathrm{GeV}$ and $|\eta| < 1$, 3298 events being accepted. Again, no deviation from the Standard Model is observed and limits of $M_{\mathrm{S}}(\lambda = +1) > 0.826\,\mathrm{TeV}$ and $M_{\mathrm{S}}(\lambda = -1) > 0.808\,\mathrm{TeV}$ are extracted. The results from the $\gamma\gamma$ and e^+e^- final states have been combined to increase the limits to $M_{\mathrm{S}}(\lambda = +1) > 0.939\,\mathrm{TeV}$ and $M_{\mathrm{S}}(\lambda = -1) > 0.853\,\mathrm{TeV}$.

Similarly, DZero searches for virtual graviton effects by combining both the $\gamma\gamma$ and e^+e^- final states and searching for events with a final state consisting of two electromagnetic showers in the calorimeter [10]. The electromagnetic showers are required to have greater than 45 GeV of transverse energy and satisfy $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. A total of 1250 events are found in 127 pb^{-1} of Run 1 luminosity. Instead of comparing to the one-dimensional invariant mass distribution, this analysis fits to the two-dimensional distribution of the invariant mass *versus* $|\cos\theta^*|$, where θ^* is the scattering angle of the di-electron or di-photon system. This method provides greater sensitivity because the Standard Model contributions to high invariant mass final states tend toward large $|\cos\theta^*|$, while contributions from virtual graviton exchange tend toward low $|\cos\theta^*|$. Events in the data with high invariant mass occur at large $|\cos\theta^*|$, consistent with Standard Model production. Limits of $M_{\mathrm{S}}(\lambda = +1) > 1.1\,\mathrm{TeV}$ and $M_{\mathrm{S}}(\lambda = -1) > 1.0\,\mathrm{TeV}$ are extracted.

A search for real graviton production has been conducted by the DZero collaboration in the $q\overline{q} \to gG$ channel [11]. Events are required to have 150 GeV of missing transverse energy, a jet with $E_{\mathrm{T}} > 150\,\mathrm{GeV}$ and $|\eta| < 1.0$; if a second jet is found it must have $E_{\mathrm{T}} < 50\,\mathrm{GeV}$ and not point at the missing transverse energy. The search is conducted in $\sim$79 pb^{-1} of Run 1 data and 38 events are found with an expected background of 38 events. No deviation from the Standard Model is found, and limits on M_{S} from 0.886 TeV for $n = 2$ to $\sim$0.650 TeV for $n \geq 5$ are set.

The CDF collaboration has performed a search for $q\overline{q} \to \gamma G$ [12]. Events are required to have a photon with $E_{\mathrm{T}} > 55\,\mathrm{GeV}$ and $|\eta| < 1.0$, missing transverse energy greater than 45 GeV, no jets with $E_{\mathrm{T}} > 15\,\mathrm{GeV}$ and no tracks with $p_{\mathrm{T}} > 5\,\mathrm{GeV}$. From 87 pb^{-1} of Run 1 luminosity, 11 events are found with an expected background of 11 ± 2 events. Limits of $M_{\mathrm{S}}(n = 4) > 0.550\,\mathrm{TeV}$ to $M_{\mathrm{S}}(n = 8) > 0.600\,\mathrm{TeV}$ are extracted.

The sensitivities of the Tevatron searches for large extra dimensions are all limited by the statistics available in Run 1. The Tevatron upgrade for Run 2 increases the center-of-mass energy as well as the instantaneous luminosity, and both the DZero and CDF detectors have been improved for Run 2. Whereas in Run 1, 130 pb^{-1} of luminosity were delivered Runs 2a and 2b will consist of 2 fb^{-1} and 20 fb^{-1} of data. The luminosity increase in Run 2a will approximately double the sensitivity of Tevatron searches for large extra dimensions relative to the Run 1 searches, and the Run 2b luminosity will triple the sensitivity relative to Run 1.

In a search for virtual graviton effects in events with two electromagnetic objects in the initial 10 pb^{-1} of Run 2 data, the DZero collaboration has found events with invariant masses up to 286 GeV. The events have large $|\cos\theta^*|$ and are consistent with Standard Model production.

2. Leptoquarks

The possible existence of leptoquarks is suggested by the apparent symmetry between the lepton and quark sectors. Leptoquarks appear in technicolor, R-parity violating supersymmetry, compositeness and grand unified theories [13]. A leptoquark would couple directly to both leptons and quarks and carry fractional electric charge. A leptoquark could be either a vector or scalar boson. Strict limits on flavor changing neutral currents imply that a leptoquark can only couple within a single generation of leptons and quarks, *i.e.* a first generation leptoquark could only decay to eq or $\nu_e q$.

Many searches for leptoquarks have been performed at CDF and DZero and are summarized in Table I [14]. The limits on leptoquark masses depend on which type (scalar or vector, generation number) of leptoquark was investigated, the assumed couplings between the leptoquark and its generation's leptons and quarks, and the branching ratio, β, of the leptoquark's decay to leptons. Limits on the mass of first generation leptoquarks run from 79 GeV to 345 GeV with a recent combined limit from CDF and DZero constraining the mass of first generation scalar leptoquarks to above 242 GeV for $\beta = 1$. Limits on second and third generation leptoquarks tend to be somewhat lower.

TABLE I

Tevatron limits on first/second/third generation leptoquark masses (in GeV/c) for scalar and vector leptoquarks assuming minimal and Yang–Mills couplings. The branching ratio of the leptoquark to leptons is denoted as β.

Experiment	β	Scalar	Vector: *Minimal coupling*	Vector: *Yang–Mills coupling*
DZero	1	225/200/–	292/275/–	345/325/–
	0.5	204/180/–	282/260/–	337/310/209
	0	98/ 98/98	238/238/238	298/298/298
CDF	1	220/202/99	280/–/170	330/–/225
	0.5	202/–/–	265/–/–	310/–/–
	0	–/123/148	–/171/199	–/222/250
Combined CDF/DZero	1	242/–/–		

In a recently released study, DZero conducts a generation-independent search for production of two leptoquarks which both decay to νq [15]. Events are required to have greater than 40 GeV of missing transverse energy, two jets with $E_{\rm T} > 50\,{\rm GeV}$ and $\Delta R_{\rm jets} = \sqrt{\Delta\phi^2_{\rm jets} + \Delta\eta^2_{\rm jets}} > 1.5$. In 85 pb^{-1} of data, 231 events are found with a background estimated to be 242 $\pm$ 18.9 events. No deviation from the Standard Model is seen and the improved DZero limits for all generations of leptoquarks at $\beta = 0$ are shown in Table I.

The increased center-of-mass energy and luminosity available in Run 2 will increase the sensitivity of Tevatron searches for leptoquarks by about 100 GeV in leptoquark mass. A DZero search for di-leptoquark production with the leptoquarks decaying to $e^{\pm}q$ in the first 10 pb^{-1} of Run 2 data has found 5 events with two electromagnetic showers in the calorimeter with $E_{\rm T} > 25\,{\rm GeV}$ and two jets with $E_{\rm T} > 20\,{\rm GeV}$. One of these events has tracks matched to the calorimeter electromagnetic objects. The scalar sum of transverse energy and the electron-jet invariant masses in these events is consistent with Standard Model production.

3. Summary

Searches for the effects of large extra dimensions in data from the Tevatron's Run 1 constrain $M_{\rm S}$ to greater than about 1 TeV, while searches for leptoquarks constrain their masses to be greater than $\sim$ 100–350 GeV, depending on the type of leptoquark. The increased energy and luminosity of Run 2 at the Tevatron will initially double and eventually triple the sensitivities of searches for large extra dimensions, and the sensitivity to leptoquark masses will be increased by about 100 GeV.

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