Searches for Large Extra Dimensions at the Tevatron

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Abstract

The presence of extra dimensions can be probed in high energy collisions via the production or exchange of gravitons. The former corresponds to signatures with missing energy while the latter corresponds to modifications of the final state spectra. Here I review results of analyses performed by the CDF and DØ Collaborations on $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV in signatures sensitive to large extra dimensions. These include analyses of $\gamma + \not{E}_T$ and jet $+ \not{E}_T$ as signatures of graviton production as well as analyses of dilepton and diboson final states sensitive to graviton exchange.

1 Introduction

The standard model of particle physics (SM) does not account for gravitational interactions. A number of theoretical models beyond the SM naturally include gravity and require the existence of extra dimensions where only gravity propagates freely. In particular, a model proposed in Ref. [1] assumes there are large extra dimensions (LED) compactified on a sub-millimeter scale R. In this model gravity can become strong at the TeV scale, which effectively solves the hierarchy problem present in the SM. For n extra dimensions the four-dimensional Planck mass M_{Pl} is related to the $4+n$-dimensional fundamental scale M_D by $M_{\mathrm{Pl}}^2 = 8\pi M_D^2 (M_D R)^n$. For M_D in the TeV range R is of the order of 0.1 mm (10 fm) for $n = 2$ (6). To solve the hierarchy problem M_D should not be too large, which rules out $n = 1$. Tests of the Newton's law constrain R to be below 37 μm for $n = 2$ [2]. Other constraints come from astrophysics (up to $n = 3$) and from high energy colliders [2].

The cross sections of the LED processes depend on M_D and can be at levels detectable at the Tevatron [3]. In $p\overline{p}$ collisions the graviton can be produced in $q\overline{q} \to gG$, $qg \to qG$, or $gg \to gG$ corresponding to a jet $+ \not{E}_T$ final state, and $q\overline{q} \to \gamma G$ corresponding to a $\gamma + \not{E}_T$

detector signature [4]. Graviton exchange can be studied in a range of $2 \to 2$ processes with the best sensitivity in final states with two leptons, photons, or Z bosons.

In this review [5] I first describe searches for graviton production in the $\gamma + \not{E}_T$ and jet $+ \not{E}_T$ signatures reported by CDF and in the $\gamma + \not{E}_T$ signature reported by DØ. Then I briefly describe searches sensitive to graviton exchange in dimuon, dielectron and diphoton final states reported by DØ and in ZZ final states by both CDF and DØ.

2   CDF and DØ detectors

A detailed description of the CDF and the DØ detectors can be found in Ref. [6, 7]. The vertexing and the tracking detectors surrounding the interaction region are used to reconstruct charged particle trajectories. Further out are the calorimeters with electromagnetic and hadronic longitudinal segmentation used to identify and measure photons, electrons, and jets. Outside the calorimeter are the muon detectors used to identify muons from the collisions and cosmic rays.

In analyses of $\gamma + \not{E}_T$ events one of the major backgrounds is from cosmic ray muons misidentified as photons. The detector features used to reject this background are: *photon pointing* available at DØ allowing the reconstruction of direction of the photon from the longitudinal segmentation of the electromagnetic calorimeter [8]; *photon timing* available at CDF from the EMTiming system [9] providing the measurement of the time of the energy deposit and allowing to suppress cosmic-ray background by a factor of 20 or more.

3   Searches for graviton production

The production of gravitons in hadron collisions is probed in events where the final-state hadronic jet or photon recoils against the graviton, which is not detected and results in $\not{E}_T$.

Searches in both the jet $+ \not{E}_T$ and the $\gamma + \not{E}_T$ require exclusive signatures: only a jet or a photon is in the event with a veto on the presence of other objects. These searches have similar backgrounds. The dominant and only irreducible background is production of $Z \to \nu\nu$ in association with a photon or a jet.

A search for LED in jet $+ \not{E}_T$ events has been performed by CDF using 1.1 fb^{-1} of data, updating the analysis in Ref. [10]. Events with high $\not{E}_T$, a high-E_T jet and no second jet with $E_T > 60$ GeV are selected. All major backgrounds are estimated in a data-driven way. The contributions from $Z \to \nu\nu$ and from $W \to \ell\nu$, where the lepton is lost, are estimated using measured $Z \to \ell\ell$ and $W \to \ell\nu$ events. After an *a priori* optimization for the best sensitivity to LED, events with the leading jet

Background	Events
$Z \to \nu\nu$	388 ± 30
$W \to \ell\nu$	362 ± 17
Multi-jet	23 ± 20
γ+jet	17 ± 5
Non-collision	10 ± 10
Total predicted	808 ± 62
Data observed	809

Table 1: The numbers of expected background and observed events in the jet $+ \not{E}_T$ sample used by CDF.

$E_T > 150$ GeV and $\not{E}_T > 120$ GeV are selected. The summary of predicted and observed events is given in Table 1. The constraints on LED are given at the end of this section.

Results for the $\gamma + \not{E}_T$ signature in the Tevatron Run II have been recently reported by CDF in 2 fb^{-1} of data and by DØ in 1.05 fb^{-1} of data [8]. Both analyses use events with high $\not{E}_T$ and a high-E_T photon in the central detector region with $|\eta| < 1.1$ [4]. No jets with $E_T > 15$ GeV are allowed in the event in order to suppress QCD backgrounds. Also, no high-p_T track is allowed, suppressing contributions from leptonic W and Z decays: tracks with $p_T > 10$ GeV/c (isolated with $p_T > 6.5$ GeV/c) are vetoed by CDF (DØ). The contribution from cosmic rays is suppressed based on presence of hits in the muon detectors as well as using the *photon pointing* or the *photon timing* mentioned in Section 2.

Background	CDF	DØ
$Z\gamma \to \nu\nu\gamma$	24.8 ± 2.8	12.1 ± 1.3
$W \to (e \to \gamma)\nu$	2.6 ± 0.4	3.8 ± 0.3
$W \to (\mu/\tau \to \gamma)\nu$	1.0 ± 0.2	–
$W\gamma \to \ell\nu\gamma$	5.0 ± 1.4	1.5 ± 0.2
jet$\to \gamma$	–	2.2 ± 1.5
$\gamma\gamma \to \gamma$	2.3 ± 0.6	-
Non-collision	9.8 ± 1.3	2.8 ± 1.4
Total predicted	46.3 ± 3.0	22.4 ± 2.5
Observed data	40	29

Table 2: The numbers of expected background and observed events in the $\gamma + \not{E}_T$ samples analyzed by CDF and DØ. The contribution from jet$\to \gamma$ in CDF is included in $(W/\gamma)\gamma$ by virtue of the background estimation method.

The background contributions for both analyses are summarized in Table 2. The number of events from $Z \to \nu\nu$ is estimated from simulation. The contribution from $W \to e\nu$, where the electron is identified as the photon, is extracted from the number of events with electrons passing all other requirements applied to the photon signal sample, scaled by the misidentification rate. Contributions from cosmic rays and jets misidentified as photons are estimated at DØ using the *photon pointing* method. The remaining backgrounds in the analysis by DØ are estimated using simulation. The contribution from cosmics at CDF is estimated using events with the photon time significantly different from the collision time. The remaining backgrounds at CDF are from processes where an object is lost. Except for $W \to \tau\nu$, which is estimated from simulation, each of these backgrounds is given by the number of events in data with this object identified, scaled by the simulated rate for it to be lost. This approach implicitly includes contributions from a jet identified as a photon.

After an *a priori* optimization for the best sensitivity, events with a photon with $E_T > 90$ GeV and $\not{E}_T > 50(70)$ GeV are selected in the CDF (DØ) signal sample. Event counts observed in the data are consistent with expectations from the backgrounds. The constraints on the LED model are summarized in Table 3. Since the sensitivity in the $\gamma + \not{E}_T$ is similar to that in the jet $+ \not{E}_T$ mode, the constraints can be improved in a combination. The result of this combination using the CDF data is shown in Table 3. Depending on the number of extra dimensions, the sensitivity to LED at the Tevatron is comparable to or better than that from the LEP experiments [11].

Source	LEP	DØ	CDF		
n	$\gamma + \not{E}_T$	$\gamma + \not{E}_T$	jet $+ \not{E}_T$	$\gamma + \not{E}_T$	combined
2	1600	921	1310	1080	1400
3	1200	877	1080	1000	1150
4	940	848	980	970	1040
5	770	821	910	930	980
6	660	810	880	900	940

Table 3: Lower limits on M_D in GeV/c^2 at 95% C.L. for n from 2 to 6 observed in the jet $+ \not{E}_T$ and $\gamma + \not{E}_T$ signatures and the combination of the two at CDF, and in the $\gamma + \not{E}_T$ signature at DØ, along with the constraints from the LEP experiments [11]. Constraints provided by DØ for n above 6 can be found in [8].

4   Searches for virtual graviton exchange

In hadron collisions the processes most sensitive to virtual graviton exchange in LED are those with two leptons (electrons or muons), two photons, or two Z bosons in the final state, where it is possible to reconstruct the full kinematics of the final state with high precision. The value of the graviton exchange amplitude depends on the cutoff energy Λ, presumably of order M_D [3]. The cross section is proportional to Λ^{-8}.

A search for LED in the dimuon final state has been reported by DØ using 200 pb^{-1} of data [12]. The sample is comprised of events with two opposite charge muons with p_T above 15 GeV/c and both muons passing additional quality and isolation requirements. The dilepton invariant mass and the scattering angle in the dilepton center of mass are analyzed simultaneously to improve sensitivity to the exchange of a graviton (spin 2 particle). A similar analysis using a *di-em* final state where no discrimination is made between electrons and photons has been performed at DØ with 240 pb^{-1} of data [13]. In this case events were selected if they had two *em* objects with $E_T > 25$ GeV passing quality and isolation requirements. No excess over the expected backgrounds is observed. The constraints on the parameter Λ are in the range of 1 to 2 TeV depending on the theoretical parameters.

Both CDF and DØ have recently reported on searches for $p\overline{p} \rightarrow ZZ$ production in a four-lepton final state [14, 15]. The observed number of events is consistent with the SM expectations. Although no constraint has been provided on LED by either experiment, based on Ref. [16] the constraint on Λ is expected to be in the range of 1.5 to 2.5 TeV.

5   Summary

Searches for LED in signatures with direct graviton production and those with virtual graviton exchange are explored by the CDF and the DØ experiments. No evidence of LED has been seen. Additional $p\overline{p}$ collision data currently produced at the Tevatron is expected to give more insight about the possible presence of large extra spacial dimensions.

Acknowledgements

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