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SEARCHES FOR EXTRA DIMENSIONS AND Z' BOSONS AT DØ

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We present results on the searches for Extra Dimensions and Z' Bosons conducted at the Tevatron's DØ Detector using dielectron, diphoton, and dimuon final states. The theoretical frameworks of Large Extra Dimensions (LED), Randall-Sundrum Extra Dimensions (RS), TeV^{-1} Extra Dimensions, and Z' bosons are explored in the dielectron and diphoton channels, while LED and Z' bosons are also searched for in the dimuon final state. In the absence of signals we find lower 95% confidence level (CL) limits on the mass of a SM-like Z' boson of 780 GeV and 680 GeV in the dielectron and dimuon channels, respectively. Furthermore, we find a lower 95% CL limit of 1.12 TeV on the TeV^{-1} compactification scale (M_C) in the dielectron channel. In the diEM channel and LED framework we set a lower 95% CL limit of 1.43 TeV (GRW) on the fundamental Planck scale (M_S). Using a dimuon final state we find a lower 95% CL limit of 1.1 TeV (GRW) on M_S. We also find a lower 95% CL mass limit of 785 GeV on a RS graviton decaying into a dielectron or diphoton final state.

1. Large Extra Dimensions

In 1998 an idea was proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) that standard model (SM) particles are confined to a 3-dimensional membrane (D3-brane), as expected in the string theory, and SM gauge interactions are therefore restricted to this brane.[1] At the same time, gravity is allowed to propagate in n extra spatial dimensions, which explains its apparent weakness. The apparent Planck scale of $M_{\mathrm{Pl}} = 1/\sqrt{G_N} \sim 10^{19}$ TeV $\gg M_{\mathrm{EW}} \sim 1$ TeV merely reflects its volume suppression due to the dilution in extra space.

Assuming that the fundamental, $(3+n)$-dimensional Planck scale, M_S, is in the TeV range, suggests for $n = 1$ a very large $R \sim 10^8$ km (of the size of our solar system), which is ruled out by the known $1/r^2$ dependence of the gravitational force at large distances. However, for $n \geq 2$ the expected R is less than 1 mm, and therefore does not contradict existing gravitational experiments. For instance, for $n = 2$ we have $R \sim 1$ mm. For larger n, compactification radius drops as a power law (*e.g.*, ~ 3 nm for $n = 3$). Thus $n = 2$ is the minimum number of these, *large* extra dimensions (LED).

The two main ways of probing LED at colliders is to look for the production of a real graviton recoiling against a gauge boson or a quark in a high-energy interaction (which results in a monojet, or monophoton signature) and to look at the effects of virtual gravitons in the fermion or boson pair production. The effects of virtual graviton exchange are explored in the searches presented here.

2. TeV^{-1} Extra Dimensions

Another interesting model was also proposed, in which matter resides on a p-brane ($p > 3$), with chiral fermions confined to the ordinary three-dimensional world internal to the p-brane and the SM gauge bosons also propagating in the extra $\delta > 0$ dimensions internal to the p-brane.[2,3] It was shown that in this scenario it is possible to achieve the gauge coupling unification at a scale much lower than the usual GUT scale, due to a much faster power-law running of the couplings at the scales above the compactification scale of the extra dimensions.[2] The SM gauge bosons that propagate in the extra dimensions compactified on S^1/Z_2, in the four-dimensional point of view, are equivalent to towers of Kaluza-Klein states with masses $M_n = \sqrt{M_0^2 + n^2/R^2}$ ($n = 1, 2, ...$), where $R = M_C^{-1}$ is the size of the compact dimension, M_C is the corresponding compactification scale, and M_0 is the mass of the corresponding SM gauge boson. In this paper, we study the effects of virtual exchanges of the KK states of the Z and γ.

3. Randall-Sundrum Extra Dimensions

The model proposed by Randall and Sundrum (RS) considers the case of one "small" extra-dimension; where gravity is "localized" on a brane (Planck brane) apart from another brane where the SM fields are confined.[4] The propagation of gravity in the extra-dimension is exponentially damped due to a fine-tuned space-time metric, resulting in the weakness of gravity when observed from the SM brane. Since it propagates in the extra-dimension, the graviton observed in $4d$ manifests itself as a "tower" of Kaluza-Klein (KK) modes, with the zerothmode corresponding to the massless graviton. In models of localized gravity the first graviton excitation $G^{(1)}$ is expected to be heavy, with a mass around the TeV scale. Its coupling to all SM fields is solely determined by a dimensionless model parameter $k/\bar{M}_{Pl}$, in the range $10^{-2} - 10^{-1}$, and is expected to be sizeable. Hence the spin 2 graviton $G^{(1)}$ could be resonantly produced at the Tevatron via a $q\bar{q}$ or a gg fusion.

4. Z' Bosons

A heavy partner of the Z boson, a so-called Z' boson, is found in multiple extensions of the Standard Model (SM). It is particularly popular in extended technicolor models, grand unified theories, models with extra dimensions, and little Higgs models. Depending on the model, couplings of the Z' boson to light fermions could be either SM-like or modified. In some models, Z' couples only to the third generation fermions. A good review of the various extended gauge theory models and references can be found in Ref [5].

5. DiEM and Dielectron Data Selections

The diEM data set correspond to a integrated luminosity of ≈ 200 pb^{-1} and was collected via a suit of single EM and diEM triggers. We require two EM objects in the event, with the transverse energies above 25 GeV, which pass calorimeter energy isolation, EM energy fraction, calorimeter shower shape, and track isolation cuts. The EM clusters are restricted to good fiducial volume of the DØ EM calorimeter: $|\eta_d| < 1.1$ (CC) and $1.5 < |\eta_d| < 2.4$ (EC), where η_d is pseudorapidity, as measured w.r.t. the geometrical center of the DØ detector. The final diEM dataset contains 18,118 events

The dielectron data set used in these searches is based off of the diEM selections detailed above, but with the additional requirement that the two EM objects must have a matched track from the central tracking systems. The final dielectron dataset contains 15,602 events.

The dominant backgrounds for these channels are from Drell-Yan and Z boson as well as QCD events where jets are misidentified as EM objects. Drell-Yan and Z backgrounds are estimated by using monte carlo simulation. The component of the background that comes from QCD misidentification is estimated from data.

6. Dimuon Data Selections

This dimuon data collected corresponds to a integrated luminosity of ≈ 250 pb^{-1} and was collected via a suite of single muon and dimuon triggers. We require at least two muons in the event, with p_T above 15 GeV, which pass data and track quality cuts, have invariant mass greater than 50 GeV, pass cosmic ray muon vetoes and isolation selections. This results in a final data sample of 16,796 dimuon events.

The dominant backgrounds for this channel is from Drell-Yan and Z boson as well as $b\bar{b}$ decays and muons from cosmic ray showers. Drell-Yan and Z backgrounds are estimated by using monte carlo simulation. Isolation requirements and cosmic ray vetoes are utilized to reduce the $b\bar{b}$ and cosmic ray backgrounds to a negligible level.

7. Results and Conclusions

In the models which predict resonances we construct optimum counting windows to search for signal in the mass spectrums. These mass windows are found by optimizing $S/\sqrt{B}$ using established techniques.[6] Summaries of the results of the counting experiments can be seen in Tables 1-2. The table for the dielectron data is not shown for brevity. In all cases we find that the data is fully consistent with background.

In the absence of a Z' signal we proceed to set limits on $\sigma \times BR(Z' \to ee)$ and $\sigma \times BR(Z' \to \mu\mu)$. The limit setting procedure uses a Bayesian approach with flat prior. The systematic errors used in the limit setting are 13% for signal and 14% on background for the dielectron channel. While the dimuon channel has

Table 1. DiEM optimum window sizes and counting results.

RS Graviton Mass	Window	DY bck.	QCD bck.	Total bck.	Bck. Err	Data
200 GeV	190–210 GeV	28.3	36.8	65.1	6.5	49
300 GeV	280–320 GeV	8.4	4.4	12.7	1.3	6
400 GeV	380–420 GeV	2.04	0.39	2.4	0.24	6
500 GeV	450–550 GeV	1.37	0.47	1.84	0.18	1
600 GeV	540–660 GeV	0.50	0.14	0.64	0.06	0
700 GeV	620–780 GeV	0.22	0.14	0.36	0.04	0
800 GeV	700–900 GeV	0.09	0.14	0.23	0.02	0

Table 2. Dimuon optimum windows and counting results.

Z' Mass	200 GeV	300 GeV	400 GeV
Acceptance	0.459±0.005	0.499±0.005	0.521±0.005
Cut Window	151-1500 GeV	202-1500 GeV	226-1500 GeV
Background	91.4±11.9	30.71±4.0	20.2±2.6
Data	76	29	19
Z' Mass	500 GeV	600 GeV	700 GeV
Acceptance	0.534±0.005	0.542±0.005	0.546±0.006
Cut Window	230-1500 GeV	232-1500 GeV	240-1500 GeV
Background	18.3±2.4	18.3±2.4	15.8±2.1
Data	18	18	16

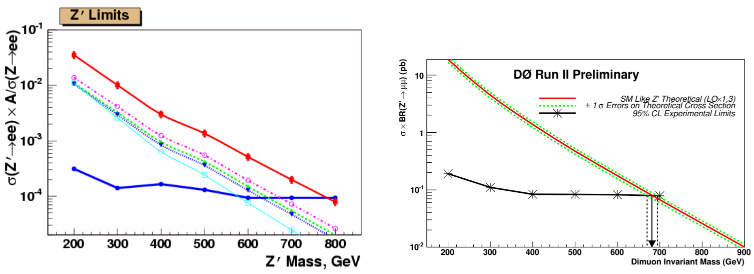

Fig. 1. The left plot shows the 95% CL experimental results found from the dielectron data (black circles) versus Z' mass. Also shown are theoretical curves for various Z' models. The solid red curve is for a SM-like Z' while the other theory curves are for various E_6 GUT models. The right plot shows the 95% CL experimental limits found in the dimuon Z' search as a function of mass. Also plotted is the theoretical $\sigma \times BR$ curve for a SM-like Z' boson with an error band of ±11%, due to k-factor and pdf uncertainties.

systematic errors of 6.5% on the luminosity, 1% on signal acceptance, and 13% on the background estimate. Figure 1 shows the limits found and theoretical $\sigma \times BR$ values. Where the theory values intersect the experimental limits defines our lower mass limits.

Similarly in the absence of a RS graviton signal we set limits on $\sigma \times BR(G \to diEM)$. The limit setting procedure uses a Bayesian approach with flat prior. The systematic errors used for limit setting are 9% for signal and 14% on background. Figure 2 shows the exclusion domain found in this analysis. From the figure we set

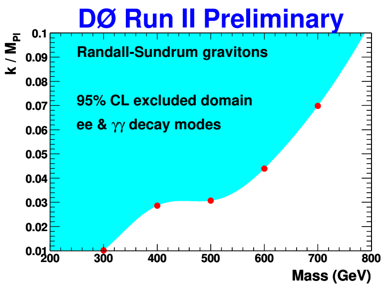

Fig. 2. This plot shows the 95% CL exclusion domain for a RS graviton decaying into a diEM final state as a function of mass and various graviton couplings.

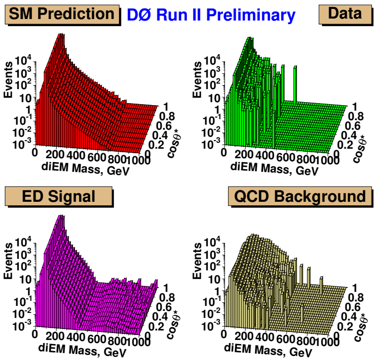

Fig. 3. The plot shows the dielectron distributions for data, backgrounds, and possible signal ($\eta_C = 5.0$ TeV^{-2}) in mass and $|\cos\theta^*|$ space.

a lower mass limit at 95% CL of 785 GeV on a graviton with $k/\bar{M}_{Pl} = 0.1$. This is the best direct experimental limit to date on this model.

The LED and TeV^{-1} searches use 2d distributions shown in Figures 3-4 and fit to the templates illustrated in (1) and (2) to extract the best value of η_C or η_G. Using $|\cos\theta^*|$ as well as mass enhances sensitivity to a signal from a spin 2 object, like the graviton.

$$\sigma = \sigma_{SM} + \eta_C \sigma_{int} + \eta_C^2 \sigma_{KK} \tag{1}$$

$$\sigma = \sigma_{SM} + \eta_G \sigma_{int} + \eta_G^2 \sigma_{KK} \tag{2}$$

In the dielectron channel we find a best fit value for $\eta_C = 0.90 \pm 0.97$ TeV^{-2}. This is not strong evidence for TeV^{-1} extra dimensions, therefore we use a similar Bayesian technique as in the Z' search to set a 95% CL limit on η_C. Using systematic uncertainty of 12% on the calculated cross sections we find $\eta_C^{95\%} < 2.63$ TeV^{-2} which corresponds to a limit of $M_C > 1.12$ TeV.[a]

[a] $\eta_C = \pi^2/3M_C^2$

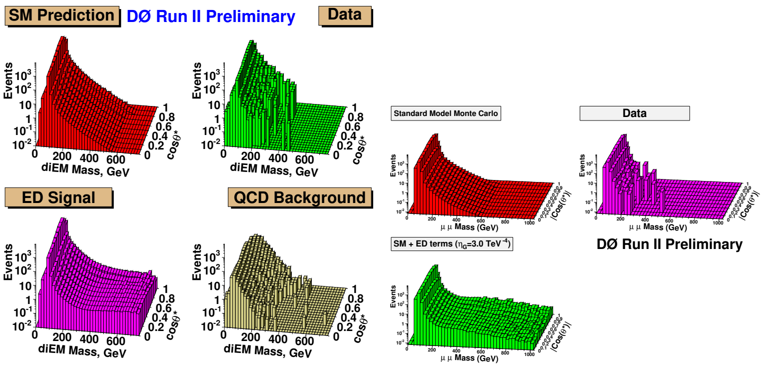

Fig. 4. The left plots show diEM distributions for data, backgrounds, and possible LED signal ($\eta_C = 2.0$ TeV^{-4}) in mass and $|\cos\theta^*|$ space. The right plots show distributions in dimuon mass vs. $|\cos(\theta^*)|$ space for data, background, and signal.

In the diEM channel we find $\eta_G = 0.00 \pm 0.12$ TeV^{-4}. Using the same systematics as above we find $\eta_G^{95\%} < 0.24$ TeV^{-4} which corresponds to a limit of $M_S > 1.43$ TeV (GRW).[b] It should be noted that this limit is the best direct search limit on LED to date and includes DØ 's Run I result in the same channel.

In the dimuon channel we find $\eta_G = 0.00 \pm 0.32$ TeV^{-4}. Using systematic uncertainties of 13% on the calculated cross sections, we find $\eta_G^{95\%} < 0.72$ TeV^{-4} which corresponds to a limit of $M_S > 1.1$ TeV (GRW). This limit is the best direct search limit on LED to date in the dimuon channel.

Table 3. Summary of results.

95% CL Limits	Physics	Channel
780 GeV	SM-like Z' Lower Mass Limit	dielectron
1.12 TeV	Lower limit on M_C	dielectron
1.43 TeV	Lower limit on M_S	diEM
785 GeV	$k/\bar{M}_{Pl} = 0.1$ Graviton lower mass limit	diEM
680 GeV	SM-like Z' Lower Mass Limit	dimuon
1.1 TeV	Lower limit on M_S	dimuon

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[b] $\eta_G = 1/M_S^4$