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Search for extra dimensions at hadron colliders

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Abstract. To explain the large difference between the Planck scale and the electroweak scale, models in which gravity propagates in more than four dimensions have recently been proposed. In this paper, results from searches for extra dimensions at the Tevatron p$\bar{\text{p}}$ collider are presented. Limits are set on the higher dimensional Planck scale, and expectations for the LHC pp collider are given.

1 Introduction

Precision tests have shown a remarkable agreement between experimental data and predictions from the Standard Model, especially in the electroweak sector [1]. However, the Standard Model does not explain the huge value of the Planck scale (M_{Pl}) with respect to the electroweak scale (M_{EW}): $M_{\text{Pl}}/M_{\text{EW}} \sim 10^{16}$. It has recently been pointed out that this hierarchy problem can be solved if gravity propagates in more dimensions than the Standard Model particles.

Arkani-Hamed, Dimopoulos and Dvali (ADD) proposed a model [2] in which gravity propagates freely in n extra, compact spatial dimensions. In their model, the electroweak scale is the only fundamental scale, and the apparent large Planck scale follows directly from the existence of extra dimensions. From a generalization of the gravitational potential in $4 + n$ dimensions, they find for the radius R of these extra dimensions: $R \sim \frac{1}{M_{\text{S}}}(M_{\text{Pl}}/M_{\text{S}})^{2/n}$, where M_{S} is the fundamental scale in $4+n$ dimensions, and M_{Pl} is the apparent 4-dimensional Planck scale. Taking $M_{\text{S}} \simeq M_{\text{EW}}$, $R \simeq 1$ mm for $n = 2$ and $R \lesssim 1$ nm for $n \geq 3$. It is remarkable that from direct gravitational measurements, only $n \leq 2$ has been excluded at present [3]. Note that in the ADD approach, the size of the extra dimensions is "large" with respect to $1/M_{\text{EW}}$.

Randall and Sundrum (RS) propose a 5-dimensional model [4] in which the 4-dimensional metric is multiplied by an exponential "warp" factor $e^{-2kr_c\phi}$, where k is the 5-dimensional Planck scale. The fifth dimension appears as a finite interval $0 \leq \phi \leq \pi$ whose size is given by r_c. Even if r_c is small, a large hierarchy can be generated by this exponential factor. In other words, the size of the extra dimension in the RS model is relatively small compared to the size of the extra dimensions in the ADD approach.

In both models, effects of the extra dimensions could become visible in collider experiments at the TeV scale.

1.1 Experimental signatures

In hadron-hadron collisions, real gravitons can be produced in association with a jet or a photon [5]. The graviton propagates in the extra dimensions and is therefore invisible in a detector. It will manifest itself as missing transverse energy ($E\!\!\!/_{\text{T}}$).

Virtual graviton exchange will modify the cross section for di-lepton and di-photon production. The exact experimental observation is different for the two models. In the RS model, the size of the extra dimension is small and thus the separation between the Kaluza-Klein modes (quantized energy levels in the finite extra dimension) of the graviton is large. Therefore, the graviton will be produced resonantly. However, in the ADD model the separation between the graviton Kaluza-Klein modes is small (as small as 2 keV for $n = 4$ [5]) due to the size of the extra dimensions. This will lead to an overall modification of the cross section at high di-lepton or di-photon invariant mass.

The cross section for di-lepton or di-photon production in the presence of extra dimensions can be written as

$$\frac{\text{d}^2\sigma}{\text{d}M\text{d}\cos\theta^*} = f_{\text{SM}} + f_{\text{int}}\eta_G + f_{\text{KK}}\eta_G^2, \qquad (1)$$

with $\eta_G = \mathcal{F}/M_{\text{S}}^4$. The parameter M is the invariant mass of the two particles and θ^* is the scattering angle in the centre-of-mass frame. The term f_{SM} describes the Standard Model cross section, f_{int} the interference of the graviton-induced amplitude with that of the Standard Model processes, and f_{KK} describes the pure graviton exchange term. Different formalisms exist for the dimensionless parameter $\mathcal{F}$:
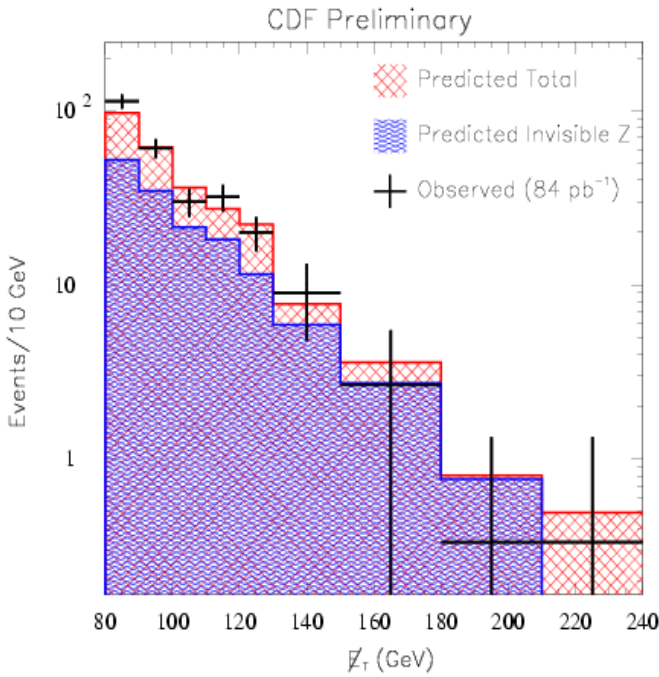
Fig. 1. Distribution of $\not{E}_T$ in jets + $\not{E}_T$ events in CDF Run I data

$$\mathcal{F} = 1, \quad \text{(GRW [5])}; \tag{2}$$

$$\mathcal{F} = \begin{cases} \log(\frac{M_S^2}{M^2}) & n = 2 \\ \frac{2}{n-2} & n > 2 \end{cases}, \quad \text{(HLZ [6])}; \tag{3}$$

$$\mathcal{F} = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, \quad \text{(Hewett [7])}. \tag{4}$$

In the remainder of this paper, experimental searches for graviton emission and exchange at the Tevatron $p\bar{p}$ collider will be presented. During Run I, the $p\bar{p}$ centre-of-mass energy was 1.8 TeV whereas during the ongoing Run II, it has been increased to 1.96 TeV, with higher instantaneous and integrated luminosities. In addition, a brief overview of prospects at the LHC pp collider ($\sqrt{s} = 14$ TeV) is given. This is discussed in more detail in [8].

2 Experimental results

2.1 Graviton emission in the ADD model

The CDF collaboration has searched for graviton emission in the jets + $\not{E}_T$ channel, based on an integrated luminosity of 84 pb^{-1} collected during Run I. The main background in this channel is Z + jets production, where the Z boson decays invisibly in a neutrino-antineutrino pair. As can be seen from the $\not{E}_T$ distribution in Fig. 1, the data agree well with expectation in the absence of extra dimensions.

This leads to lower limits on M_S of 1 TeV, 770 GeV, 710 GeV for $n = 2, 4, 6$, respectively[1]. These results are

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[1] All limits are given at 95% confidence level.

Table 1. Lower limits on M_S in GeV (Hewett convention) in the di-electron, di-photon and combined samples from CDF Run I

	$\lambda = -1$	$\lambda = +1$
ee	826	808
$\gamma\gamma$	899	797
di-EM	939	853

very similar to the previously established DØ limits in this channel [10]. A similar search by the CDF collaboration in the $\gamma + \not{E}_T$ channel gives no excess above the expectation from the Standard Model and thus lower limits on M_S of 549 GeV, 581 GeV, 602 GeV for $n = 4, 6, 8$, respectively. The sensitivity in the jets + $\not{E}_T$ sample is higher due to the larger cross section.

At the LHC, with 100 fb^{-1} of integrated luminosity, discovery of extra dimensions in the jets + $\not{E}_T$ channel is possible up to high mass scales. As shown by the ATLAS collaboration [8], significant signals can be found up to values of M_S of 9.1 TeV, 7.0 TeV, 6.0 TeV for $n = 2, 3, 4$.

2.2 Graviton exchange in the ADD model

Both the CDF and DØ collaborations have searched for virtual graviton exchange in the ADD model. CDF analyzed the invariant mass spectrum of photon pairs from an integrated luminosity of approximately 95 pb^{-1}, collected during Run I. The selected sample agrees well with the expectation from Standard Model induced di-photon production and from misidentified di-photon events. A similar agreement was found in a di-electron sample, leading to lower limits on M_S in the Hewett convention (see (4)) given in Table 1.

The DØ collaboration presented results on di-muon events in 30 pb^{-1} of integrated luminosity in Run II. Background to graviton exchange in this decay mode is mainly caused by Standard Model di-muon production, estimated from a Monte Carlo simulation, and by heavy quark decay, estimated from the data itself. Similarly, di-photon and di-electron events were studied in 120 pb^{-1} of integrated luminosity in Run II. Background from Standard Model di-photon and di-electron production was estimated from Monte Carlo simulations, and background from misidentified QCD events was derived from the data sample. In both channels, a good agreement between data and background estimates was observed in distributions of both the invariant mass and the scattering angle.

A 10-15% higher sensitivity to graviton exchange is expected from fitting the data in the M versus $\cos\theta^*$ plane [9] instead of in M only. This is illustrated in Fig. 2. In the di-muon sample, such a two-dimensional fit (see (1)) yields $\eta_G = 0.02 \pm 1.35$ TeV^{-4} and in the combined di-photon, di-electron sample $\eta_G = 0.0 \pm 0.15$ TeV^{-4}. This translates into lower limits on M_S given in Table 2.
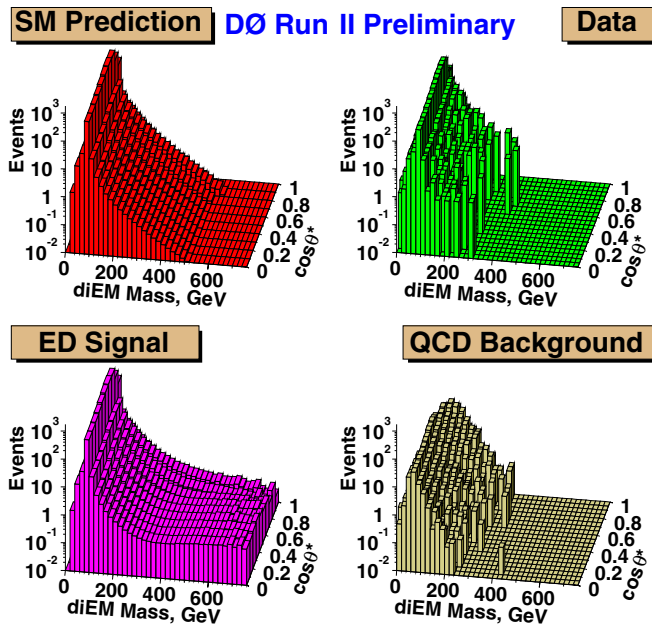
Fig. 2. Distributions of invariant mass of electron and photon pairs versus scattering angle in DØ Run II data for *(top-left)* Standard Model expectation, *(top-right)* data, *(bottom-left)* Standard Model plus an extra dimensions signal, and *(bottom-right)* QCD background

Table 2. Lower limits on M_S in TeV in the combined di-electron and di-photon sample and in the di-muon sample from DØ Run II data

	GRW	HLZ $n=2$	HLZ $n=7$	Hewett $\lambda=+1$
di-EM	1.28	1.42	1.01	1.14
$\mu\mu$	0.79	0.68	0.63	0.71

Table 3. Lower limits on RS graviton mass in GeV for $k/M_{\mathrm{Pl}} = 0.1$, in the di-electron and di-muon channels, and combined, from CDF Run II data

ee	$\mu\mu$	combined
535	370	550

2.3 Graviton resonance production in the RS model

The CDF collaboration has performed a search for graviton resonance production in the di-muon and di-electron decay channels, using an integrated luminosity of 72 pb^{-1} collected during Run II. The invariant mass distribution found in this data in both channels agrees well with the expectation from the Standard Model, as shown in Fig. 3 for the di-electron channel. This leads to lower limits on the RS graviton, given in Table 3. The ATLAS collaboration expects a sensitivity up to a mass of 2 TeV in 100 fb^{-1} of integrated luminosity at the LHC [8].
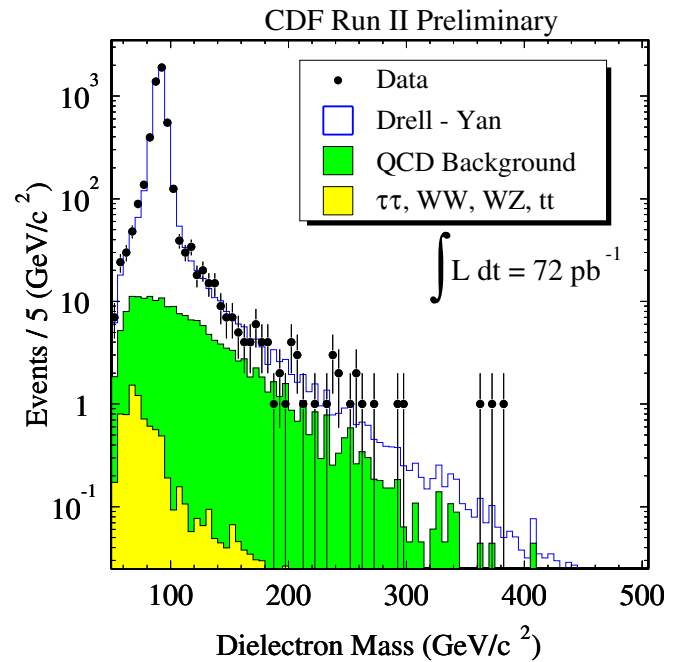
Fig. 3. Invariant mass distribution of electron pairs in CDF Run II data

3 Conclusion and outlook

To explain the large difference between the Planck scale and the electroweak scale, models have been proposed in which gravity propagates in more than four dimensions. The effects of these higher dimensional models were searched for at the Tevatron, and were not found, yet. Lower limits on the higher dimensional Planck scale were set, reaching over 1 TeV in current Tevatron Run II data. The combined di-photon and di-electron sample of DØ provides the most stringent limits on the ADD model. In the near future, more data from Run II at the Tevatron will become available, increasing the sensitivity to extra dimensions. After 2007, the experiments at the LHC will take over and explore and possibly discover extra dimensions up to multi-TeV scales.

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