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Search for Large Extra Dimensions in the Dimuon Channel with 250 pb^{-1} of Run II Data

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We report preliminary results on a search for large spatial extra dimensions in the dimuon channel using $250 \pm 16\text{pb}^{-1}$ of data collected by the DØ Experiment at the Fermilab Tevatron in 2002-2004 (Run II). We set a new lower 95% confidence level (CL) limit on the fundamental Planck scale of 1.1 TeV (in the GRW convention), which is the most stringent limit on Large Extra Dimensions in this channel to date.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

That we live in a three-dimensional space may seem to be a well-known fact; however it lacks rigorous experimental proof. Recent advances in string theory suggest that there might exist hidden dimensions in space of a finite size R beyond the three we sense daily. More recently, in 1998, an attractive realization of the above idea has been proposed by Arkani-Hamed, Dimopoulos, and Dvali [1] (ADD). In their formulation, the 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. At the same time, gravity is allowed to propagate in the n extra spatial dimensions, which explains its apparent weakness. Fundamentally, gravity is as strong as other gauge forces, but this becomes apparent only for a $(3+n)$-dimnesional observer. The apparent Planck scale of $M_{\rm Pl} = 1/\sqrt{G_N} \sim 10^{19}$ TeV $\gg M_{\rm EW} \sim 1$ 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 (ED).

While tabletop gravity experiments and astrophysical constraints have begun to produce tight limits on the fundamental Planck scale for the case of 2 extra dimensions, for any $n \geq 3$ they are easily eluded, which leaves high-energy colliders as the only sensitive probe for $n \geq 3$. Current best lower limits on the fundamental Planck scale for $n \geq 3$ come from LEP and the Tevatron Run I; they are ≈ 1 TeV. Limits from HERA are some 20% less restrictive.

The two main ways of probing large extra dimensions 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. Both types of studies were performed at LEP and at the Tevatron, with DØ having pioneered search for large extra dimensions at hadron colliders by analyzing dielectron and diphoton final states [2] and more recently from the complementary monojet channel [3].

For the current Run II DØ dielectron and diphoton large extra dimension results see Ref. [4].

II. METHOD

In this paper, we present results in the dimuon channel, obtained using ~ 250 pb^{-1} of data collected by DØ in Run II in 2002–2004. The effects of ED are parameterized via a single variable $\eta_G = \mathcal{F}/M_S^4$, where $\mathcal{F}$ is a dimensionless parameter of order unity, reflecting the dependence of virtual $G_{\rm KK}$ exchange on the number of extra dimensions. Different formalisms use different definitions for $\mathcal{F}$:

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

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

$$\mathcal{F} = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, \text{ (Hewett [7]).} \tag{3}$$

In both the GRW and HLZ models, the sign of interference between the SM and the effects of large ED is positive. In Hewett's more empirical model, neither the sign of the interference, nor the magnitude of the amplitude is fixed. The unknown effects of gravity are parameterized via a parameter λ of order one, which can be either positive or negative. We will use $\lambda = \pm 1$ to translate the limits on η_G into the limits on M_S in Hewett's formalism. Note that only within the HLZ formalism does $\mathcal{F}$ depend explicitly on n. The parameter η_G has dimensions of TeV^{-4} with M_S in units of TeV, and describes the strength of gravity in the presence of LED. While the physics meaning of scale M_S is an ultraviolet cutoff of a divergent sum over the winding modes of graviton in extra dimensions (Kaluza-Klein graviton tower), it is expected to be closely related to the fundamental Planck scale, as the latter gives a natural cutoff to this sum.

In this analysis we follow the prescription of Ref. [9] (also followed in the Run I DØ publication [2]) and analyze the dilepton data in the plane of two variables that completely determine the leading order (LO) $2 \to 2$ scattering: the invariant mass of the dilepton pair, and the cosine of the scattering angle in the center-of-mass (c.o.m.) frame, $\cos(\theta^*)$. This choice of variables yields optimum sensitivity to the contributions from extra dimensions [9]. The cross section in the presence of large ED is given by [5–7]:

$$\frac{d^2\sigma}{dM\,d\cos(\theta^*)} = f_{\rm SM} + f_{\rm int}\eta_G + f_{\rm KK}\eta_G^2, \tag{4}$$

where $f_{\rm SM}$, $f_{\rm int}$, and $f_{\rm KK}$ are functions of $(M, \cos(\theta^*))$ and denote the SM, interference, and $G_{\rm KK}$ terms.

III. MONTE CARLO GENERATOR

We model the SM background and the effects of ED via the parton-level LO Monte Carlo (MC) generator of Ref. [9], augmented with a parametric simulation of the DØ detector. The simulation takes into account the acceptance, efficiencies, and resolution of the detector, initial state radiation, and the effect of different parton distributions. We used leading order CTEQ5L [10] parton distributions to estimate the nominal prediction. The parameters of the detector model are tuned using $Z(ee)$ and $Z(\mu\mu)$ data as well as full MC simulation.

The MC includes SM contributions (Z/γ^*), Kaluza-Klein graviton exchange diagrams, and their interference in dilepton production. Since the parton-level generator involves only the $2 \rightarrow 2$ hard-scattering process, we model next-to-leading order (NLO) effects by adding a transverse momentum to the dimuon system, based on the measured transverse momentum spectrum of $Z(ee)$ events.

In the presence of the NLO corrections, the scattering angle θ^* is defined in the dimuon helicity frame, i.e., relative to the direction of the boost of the dimuon system. Since the parton-level cross section is calculated at LO, we account for NLO effects in the SM background by scaling the cross sections by a constant K-factor of 1.3 [11]. While NLO corrections to the Kaluza-Klein diagrams have not yet been calculated, we use the same constant K-factor for the signal. This choice is reasonable, since the ED diagrams are very similar to those of the SM production.

The K-factor for graviton exchange is expected to grow with invariant mass, similar to that for Z/γ^* exchange [11]; consequently, our assumption tends to underestimate both the ED contribution at high invariant mass (i.e., the signal) and the contribution from the SM (i.e., background) and thus is conservative in terms of sensitivity to the effects of extra dimensions.

We use Bayesian likelihood fitting technique to extract the information on the most likely value of the parameter η_G. The fit uses Monte Carlo templates for double-differential SM cross section, the interference term, and the direct extra dimensional term, and gives an unbiased way of extracting the best estimate of the parameter η_G, as well as to set upper limits on its value. The fit takes into account systematic errors on the signal acceptance and efficiency, K-factor, choice of parton distribution functions, choice of p_T smearing in the MC and background estimate.

IV. DATA SELECTION

The data used for this analysis were recorded between 2002 and 2004, in the Run II of the Fermilab Tevatron. All the data have been reconstructed with the most modern version of the DØ reconstruction program. This data corresponds to a total integrated luminosity of ≈ 250 pb^{-1} and was collected via a suite of single muon and dimuon triggers, which run unprescaled at all instantaneous luminosities. Given that the analysis is concerned only with high-p_T muons, the trigger is $99 \pm 1\%$ efficient for the signal.

We require at least two muons in the event, with p_T above 15 GeV, which pass data and track quality cuts, have high invariant mass and pass cosmic ray vetoes and isolation selections. Furthermore, due to the fact that our dominate background stems from Drell-Yan events where one of the muons is badly measured, yielding a very high artificial momentum, we apply a fix which corrects this badly measured muon. This fix sets both of the muon's transverse momenta equal to a weighted average based on both muons original p_T measurements and errors. In the case of a Drell-Yan event which has one badly measured (very high p_T) muon its transverse momentum is set to a value near the original p_T of the other muon in the event. This is because the error for such a high p_T track is very large and therefore does not contribute much in the calculation of the weighted average. For an event where both muons transverse momenta and errors are similar the new p_T value they are set to will not be very different from the original values.

After the p_T rescaling, we recompute the four-momenta and re-apply the invariant mass selection to form our final data set. This procedure is also applied to the fast MC which generates our background and signal.

This selection leaves us with a sample of 16,796 events, as documented in Table I.

Selection	Number of events passing cut
Starting sample	115,009
Bad run removal	108,574
Duplicate events removed	105,863
Track quality cuts	65,163
Dimuon invariant mass > 50 GeV	40,744
Cosmic veto	25,811
Isolation requirements	17,193
After p_T fixed re-apply mass cut	16,796

TABLE I: Event selection.

V. BACKGROUNDS

The SM backgrounds from Drell-Yan and Z boson production are already included in the output of the fast Monte Carlo used to simulate signal. We determine the normalization for this background by fitting the low-mass region of the dimuon mass spectrum to the sum of the Drell-Yan background, with the integrated luminosity being the free parameter of the fit. Since the effects of large extra dimensions are negligible at low invariant dimuon masses, this technique is not biased by a possible presence of the signal in our data.

The cuts made to remove cosmic ray events are chosen such that the level of dimuon events originating from this process are negligible. Similarly the isolation criteria used in this analysis eliminates all but a negligible level of dimuon events that originate from $b\bar{b}$ production.

All other physics backgrounds that result in a dimuon final state are negligible.

VI. COMPARISON BETWEEN THE DATA AND BACKGROUND

The comparison between the data sample of 16,796 events and predicted background is illustrated in Figure 1.

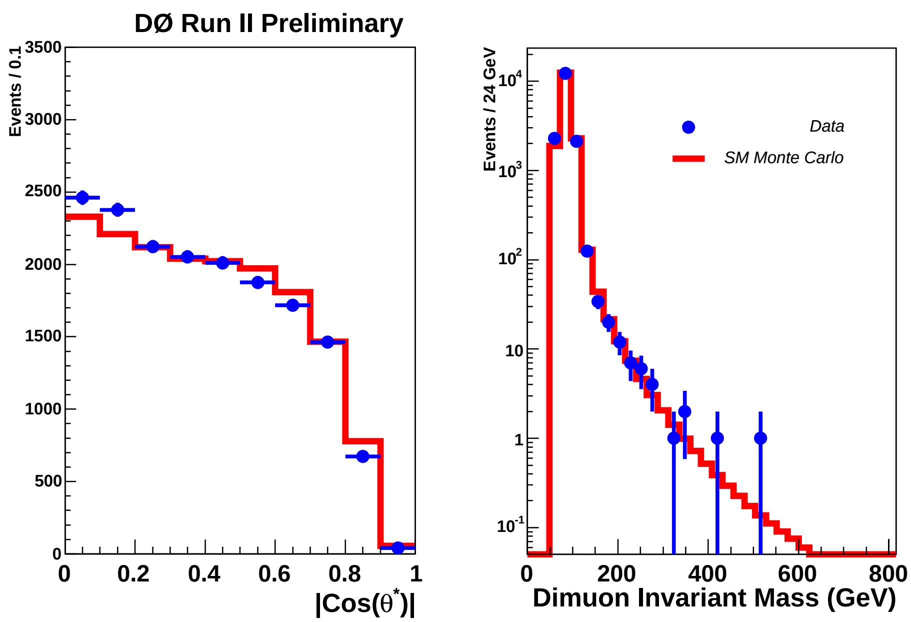

FIG. 1: Comparison between data (points) and SM background (histogram) for $|\cos(\theta^*)|$ and $M_{\mu\mu}$ distributions.

Because this analysis is concerned with very high mass events and to help quantify the agreement between the data and the background in the mass spectrum, we calculate the prediction for the background above certain mass cutoff and compare it with the data for a number of mass cutoffs. The results are summarized in Table II.

Minimum $M_{\mu\mu}$	Expected background	Number of candidates
120 GeV	221.0	213
150 GeV	84.9	73
180 GeV	43.6	43
210 GeV	24.8	24
240 GeV	15.1	15
270 GeV	9.6	9
300 GeV	6.4	5
330 GeV	4.4	5
360 GeV	3.2	2
390 GeV	2.3	2
420 GeV	1.7	1
450 GeV	1.3	1
480 GeV	1.0	1
510 GeV	0.83	1
540 GeV	0.67	0

TABLE II: Comparison between the data and expected background for events above certain dimuon mass cutoffs. The middle column shows the number of predicted background events. While the last column shows the number of candidate events seen.

Furthermore, to help show the agreement between data and SM background in the high mass regime for $\cos(\theta^*)$, Figure 2 shows data and background comparisons for events with invariant mass greater than 120 GeV.

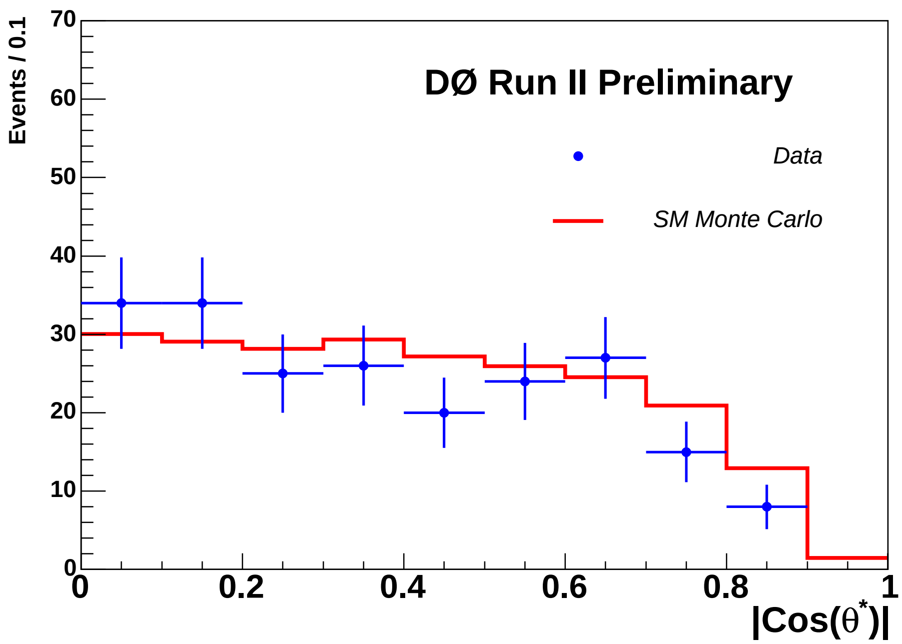

FIG. 2: Comparison between data (points) and SM background (histogram) for $|\cos(\theta^*)|$ distribution for events with $M_{\mu\mu} >$ 120 GeV.

As the data agrees with the SM predictions, we proceed with setting limits on large extra dimensions.

VII. LIMITS ON LARGE EXTRA DIMENSIONS

When setting limits on extra dimensions, we assign systematic uncertainties of 13% on signal and on background estimates, as documented in Table VII. The uncertainty on the signal is dominated by the uncertainty on the shape of the NLO corrections (i.e., energy dependence of the K-factor, 10%), choice of parton distribution functions (5%), possible residual p_T dependence on the efficiency (5%), choice of p_T smearing in the fast MC (4%), and the fast MC to data normalization (1%). The normalization used in this analysis is referred to as the effective luminosity and is the factor that scales the NLO Z-peak cross section to the data in the mass region less than 120 GeV. By using the effective luminosity we reduce the systematic error on the MC to data normalization, which otherwise would be larger if the errors from the luminosity, efficiencies and so on, were calculated independently and added in quadrature.

Source of systematics	Uncertainty
K-factor	10%
Choice of p.d.f.	5%
p_T dependence on efficiency	5%
Choice of fast MC p_T smearing	4%
Fast MC to data normalization	1%
Total	13%

TABLE III: Sources of systematic uncertainty on the calculated differential cross section.

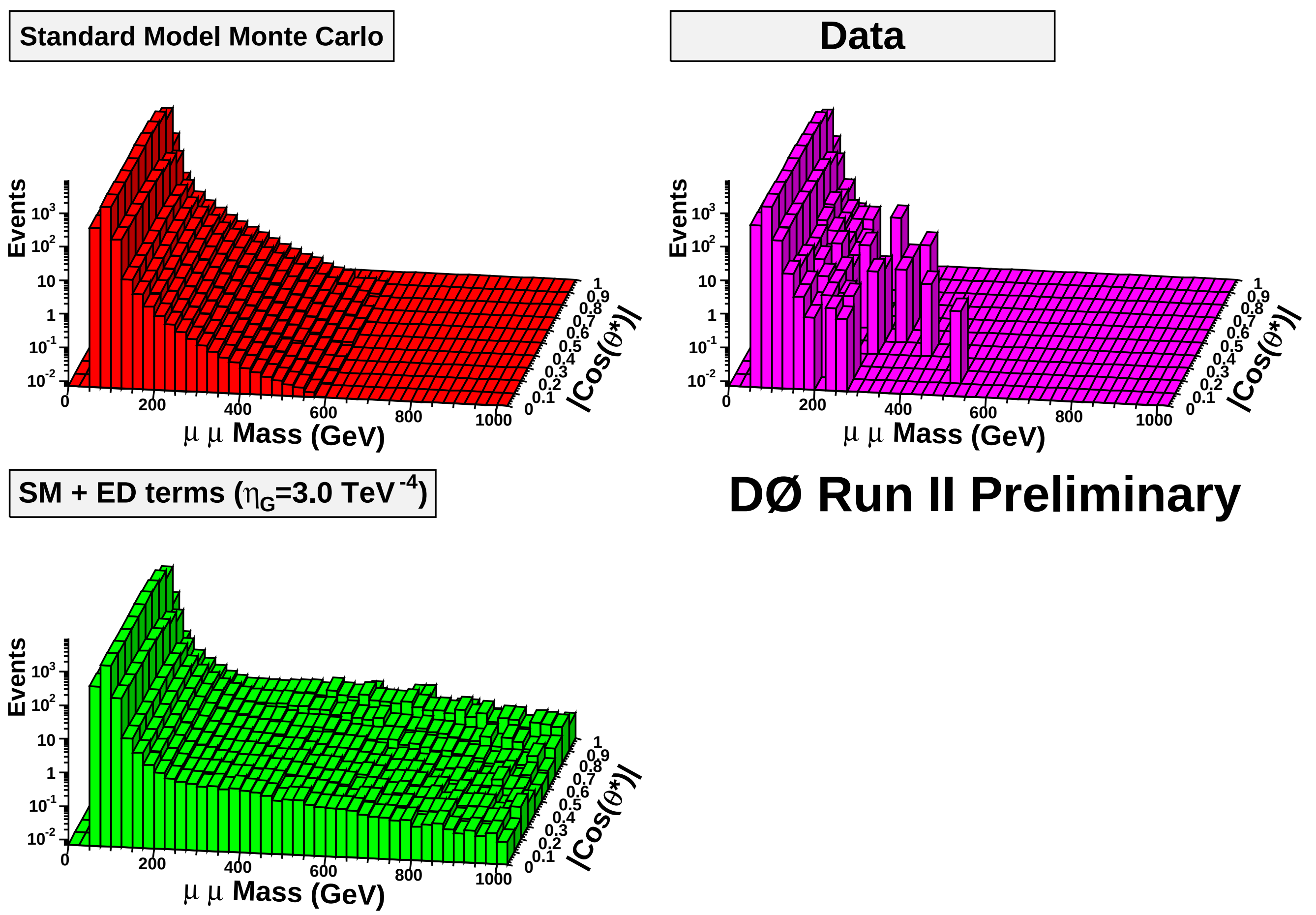

FIG. 3: Distributions in $M_{\mu\mu}$ vs. $|\cos(\theta^*)|$ for data and the MC templates. The lower left plot shows SM plus contributions from ED with η_G=3 TeV^{-4}.

We then proceed with extracting the best estimate for parameter η_G by fitting the two-dimensional distributions to the sum of the SM, interference, and the direct gravity templates, as seen in Figure 3. The size of the 2D-grid used in the main analysis in $M \times \cos(\theta^*)$ is 20×10. The results are stable w.r.t. the granularity of the grid. The best estimate on the parameter η_G from the fits are:

$$\eta_G \;=\; 0.00 \begin{array}{l} +0.33 \\ -0.00 \end{array} \text{TeV}^{-4}; \tag{5}$$

i.e. consistent with zero (no gravity contribution), as expected. The 95% upper CL limit on η_G, calculated in both a

Bayesian and purely frequentist Poisson likelihood method, are determined to be:

$$\eta_G^{95\%} = \begin{cases} 0.71\ \mathrm{TeV}^{-4} & \text{Likelihood} \\ 0.72\ \mathrm{TeV}^{-4} & \text{Bayesian} \end{cases}$$

The obtained limits agree well with the expected sensitivity as illustrated in Figure 4

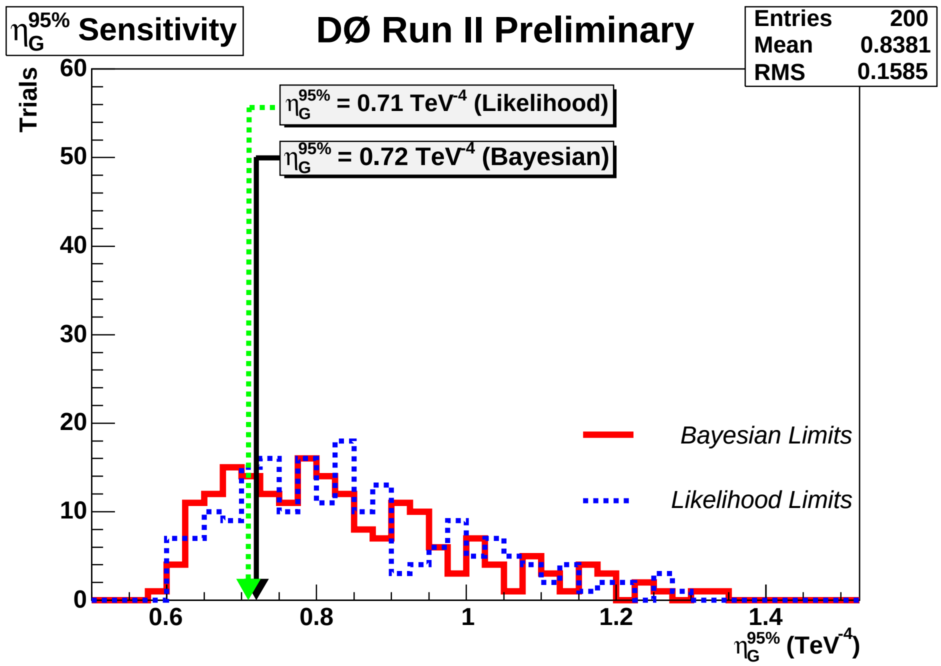

FIG. 4: Expected 95% CL upper limit on the parameter η_G from an ensemble of MC experiments, together with the actual limits obtained in this analysis. The dashed histogram represents the Likelihood distribution, while the solid histogram is the Bayesian distribution. Arrows with labels indicate Bayesian and Likelihood limits, found from the data.

We also obtain limits for negative sign of the interference term, possible in Hewett's convention. The procedure is the same, and the corresponding results are:

$$\eta_G = -0.11 \ \pm 0.41\ \mathrm{TeV}^{-4}; \tag{6}$$

$$\eta_G^{95\%} = -0.77\ \mathrm{TeV}^{-4}\ \text{Bayesian}. \tag{7}$$

We translate the Bayesian limits on η_G into limits on the fundamental Planck scale, M_S. The results are summarized in Table IV. For the HLZ formalism, $n = 2$, we used average value of M^2 at the Tevatron, which is $(0.64\ \mathrm{TeV})^2$ [9]. These limits are the tightest limits on large extra dimensions from a single measurement in this channel.

GRW [5]	HLZ [6]						Hewett [7]
	n=2	n=3	n=4	n=5	n=6	n=7	$\lambda = +1/-1$
1.09	1.00	1.29	1.09	0.98	0.91	0.86	0.97/0.95

TABLE IV: Lower limits at 95% CL on the fundamental Planck scale, M_S, in TeV.

VIII. CONCLUSIONS

We performed search for large extra spatial dimensions using $\sim 250\ \mathrm{pb}^{-1}$ of data collected by the DØ experiment in Run II of the Fermilab Tevatron. The lower 95% CL limit on the fundamental Planck scale was set to be 1.1 TeV in the GRW convention. This is now the world's most stringent limit in the dimuon channel for large extra spatial dimensions.

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