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OTHER PARTICLE SEARCHES AT THE TEVATRON

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The CDF and DØ collider experiments at Fermilab have searched for evidence of physics extending beyond the scope of the Standard Model of particles and interactions. We report on the results of searches for heavy extra gauge bosons, extra dimensions and composite electrons in 200 pb^{-1}(per experiment) of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. No evidence of a new signal has been found, therefore limits on model parameters have been derived.

1 Introduction

The Standard Model of particles and interactions (SM) is by far the most successful theory describing high-energy physics data. It's predictions have been verified to great accuracy, but many fundamental questions still remain unanswered. Among them are the mechanism of electroweak symmetry breaking, why the gravitational interaction seems to be so weak in comparison to the other fundamental interactions and whether the fundamental interactions unify into one underlying physical interaction. Several models such as Large Extra Dimensions (LED), Grand Unified Theories (GUT), Supersymmetry (SUSY) and Technicolor (TC) have been proposed to address such questions. These models extend beyond the scope of the Standard Model and predict new signatures that can be detected at current high-energy colliders such as the Tevatron[a]. Searches for new phenomena though face some experimental challenges. The production cross sections tend to be very small (in the range of 1 pb) whereas the deep inelastic $p\bar{p}$ cross section is of the order of 10^{10} pb. It is often hard to distinguish new phenomena signal from known SM background processes. Jet based strategies are overwhelmed by SM processes, so we employ lepton based signatures, even though the rates are often suppressed. The results shown at this conference are based on 200 pb^{-1} per experiment of Run II delivered in 2002 and 2003.

[a] $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV located in the vicinity of Chicago in the USA. It expects to deliver $\approx$ 8000 pb^{-1} of Run II data until the end of 2009. The Tevatron hosts two collider experiments: The Collider Detector at Fermilab (CDF) [1] and the DØ Experiment [2].

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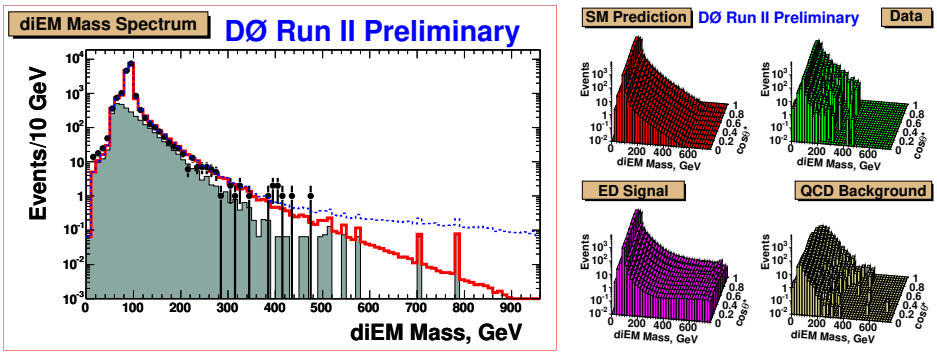

Figure 1. Left: The di-em mass distribution at DØ . Points are data, light filled histogram is QCD background, solid line is a fit to total background. Dashed line is an example of ED signal. Right: di-em mass vs. cos(scattering angle) distributions for SM background (top left), data (top right), ED signal plus background (bottom left) and QCD background (bottom right).

2 Search for Extra Dimensions

Various models of string theory suggest the existence of additional, finite size (R), spatial dimensions to the ones we sense in our everyday lives. If extra dimensions of large size exist, they could play an important role explaining why in our 3+1 dimensions the gravitational interaction is so much weaker than the other fundamental interactions.

2.1 ADD Model for Large Extra Dimensions

In the ADD [3] model, the Standard Model's chiral fermions and gauge bosons are confined to a 3-dimensional membrane. At the same time, gravity is allowed to propagate in all 3+n spatial dimensions. Fundamentally, gravity is as strong as the other gauge interactions ($M_{PL}(3+\mathrm{n}) \approx 1$ TeV$/c^2$), but this is apparent only for a 3+n dimensional observer. For a 3 dimensional observer, gravity is volume suppressed ($M_{PL}(\mathrm{3D}) \approx 10^{16}$ TeV$/c^2$) and its strength depends on the n-th power of the compactification radius R. While tabletop gravity experiments and astrophysical observations started to produce tight limits on the size of R and the number n, for n ≥ 3 colliders are the only sensitive probe. There are two main ways of probing large extra dimensions at colliders: 1) To look at the effects of virtual graviton exchange in fermion or boson pair production, 2) To look for the production of a real graviton recoiling against a gauge boson or a quark. In both of these cases, the strength of the effect depends on $M_{PL}(3+\mathrm{n})$ allowing to test R and n or set limits on $M_{PL}(3+\mathrm{n})$.

The first type of search for LED mentioned above focuses on the very high mass Drell-Yan region (due to heavy KK modes of the graviton). The expected signal has very energetic electrons and photons, therefore the very efficient ($> 99\%$) high-p_{T} single electron, dielectron or diphoton triggers were applied at DØ . Events with central-central or central-forward, isolated, $E_{\mathrm{T}} > 25$ GeV e's and γ's were selected. No tracking requirement has been made to treat the dielectron sample the same

way as the diphoton one. Drell-Yan and dijet QCD (with EM-like jets) are the main background sources. They were normalized by fitting to the low di-em mass spectrum where no LED signal is expected. Figure 1 shows the di-em invariant mass spectrum of DØ . CDF explored its dielectron sample, with similar selection as DØ , except a track requirement for electrons. Figure 3 shows CDF's dielectron invariant mass distribution.

Since no signal excess above expected background has been observed, DØ extracts limits by using a 2-D fit to the dilepton invariant mass and scattering angle distributions while CDF fits the dielectron invariant mass distribution. Both CDF and DØ set limits on $M_{PL}(3+\mathrm{n})$. Three formalisms were considered, GRW [4], HLZ [5] and Hewett [6]. Within the GRW formalism, CDF sets an upper limit $M_{PL}(3+\mathrm{n}) > 1.11$ TeV/c^2 . DØ produced a slightly higher limit[b] $M_{PL}(3+\mathrm{n}) > 1.36$ TeV/c^2 and when combined with data from 1992-1995 (called Run I), DØ finds $M_{PL}(3+\mathrm{n}) > 1.43$ TeV/c^2 . In the HLZ formalism, CDF's upper limit on $M_{PL}(3+\mathrm{n})$ were: 1.11, 1.17, 0.99, 0.89, 0.83 and 0.79 TeV/c^2 for n= 2 ... 7 respectively. DØ 's limits based on combined data with Run I in the HLZ formalism were: 1.67, 1.7, 1.43, 1.29, 1.20 and 1.14 TeV/c^2 for n as above. In the Hewett formalism, CDF sets 0.99 and 0.96 TeV/c^2 limit for $\lambda = +1$ and -1 respectively, while DØ sets 1.22 and 1.10 TeV/c^2 .

DØ also used 100 pb^{-1} of isolated, $p_{\mathrm{T}} > 15$ GeV/c dimuon data to search for LED. They set $M_{PL}(3+\mathrm{n}) > 0.88$ TeV/c^2 limit in he GRW formalism, 0.75, 1.05, 0.88, 0.80, 0.74 and 0.70 TeV/c^2 in the HLZ formalism for n = 2 ... 7 and 0.79 TeV/c^2 in the Hewett formalism for positive λ.

The second type search for LED, where a real graviton is produced in the collisions, escapes into the bulk, and leaves behind a monojet was carried out at DØ using 85 pb^{-1} of jet data. Events with one central jet of $E_{\mathrm{T}} > 150$ GeV and $\not\!\!E_{\mathrm{T}} > 150$ GeV separated by at least 30° in ϕ were selected. (Leptons were vetoed and the second jet's E_{T} was required to be < 50 GeV in order to reduce background.) The main (and irreducible background) comes from $Z \to \nu\nu$ + 1 or 2 jets. They observe 63 events while expecting 100 but with 60% uncertainty which mostly comes from large jet energy scale uncertainties. DØ sets an upper limit of $M_{PL}(3+\mathrm{n})$ being ≈ 700 GeV/c^2 across the range of extra dimensions of 4 to 7.

2.2 Randall-Sundrum Model

In the Randal-Sundrum (RS) Model [7], one extra dimension which is compactified to radius R is assumed. The weakness of the 3D gravity is explained by an exponential suppression which depends on the effective Planck scale $M_{PL}(eff)$, radius R and on a scale factor k of the order of the M_{PL}(3D). At colliders, the RS scenario can be probed by looking at the effect graviton exchange has on dilepton production, which depends on the ratio $k/M_{PL}(eff)$.

CDF has searched its high-p_{T} dimuon and dielectron samples to search for RS extra dimension. The dielectron sample is the same as in case of LED described in the previous paragraph. The dimuon sample consists of events with two isolated, $p_{\mathrm{T}} > 20$ GeV/c muons. Comparison of data with expected background is shown

[b] In case of DØ , the MC simulation has been scaled up by 30% to estimate NLO cross sections.

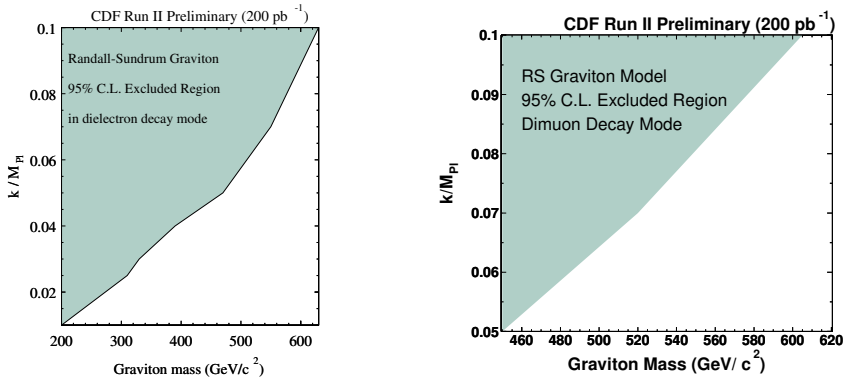

Figure 2. CDF's 95% C.L. excluded region in ee and $\mu\mu$ Randall-Sundrum model,

in Figure 3. Since no excess of data above expected SM background has been observed, CDF employs a likelihood fit to the invariant dilepton mass distributions and excludes regions up to ≈ 600 GeV/c^2 in graviton mass for $k/M_{PL}(eff) = 0.1$ as shown in Figure 2.

2.3 TeV^{-1} *Extra Dimensions*

In this model [8] matter resides on a high dimensional p-brane with chiral fermions confined to the ordinary 3 spatial dimensions but allowing gauge bosons to propagate in the extra (compactified) dimensions. This gives rise to Kaluza-Klein (KK) towers of the gauge bosons whose direct production or virtual effects would alter the dilepton production at high-energy colliders. (Gravity in the bulk is not of direct concern in this model.) The mass and the effect of the KK states depend on the number of extra spatial dimensions and on the compactification radius R $\approx 1/M_C$. (M_C is the compactification scale.) DØ performed a dedicated search in its 200 pb^{-1} of high-$p_{\rm T}$ dielectron sample (same sample as used in the ADD LED di-em search but electrons were not isolated and were required to have associated tracks.) By similar technique as in ADD LED search, DØ sets an upper limit of $M_C > 1.12$ TeV/c^2 .

3 Heavy Gauge Boson Search

Extra U(1) gauge bosons, Z', are predicted by many extensions of the SM, such as the SO(10) [9] or E_6 (Z_I, Z_ψ, Z_χ, X_η) [10] based Grand Unification Theory. As a reference "model" for experimental comparisons, it is often useful to consider a Z' boson whose coupling to fermions is Standard Model like. Experimentally, it is possible then to search for excess production of dilepton pairs at large invariant masses caused by exchange of real or virtual Z'. The main background events are coming from Drell-Yan events and QCD processes, such as misidentified jets.

CDF utilized the same high-$p_{\rm T}$ dielectron and dimuon data sets as used in the RS LED search (Figure 3). DØ obtained Z' search results on its high-$p_{\rm T}$ dielectron

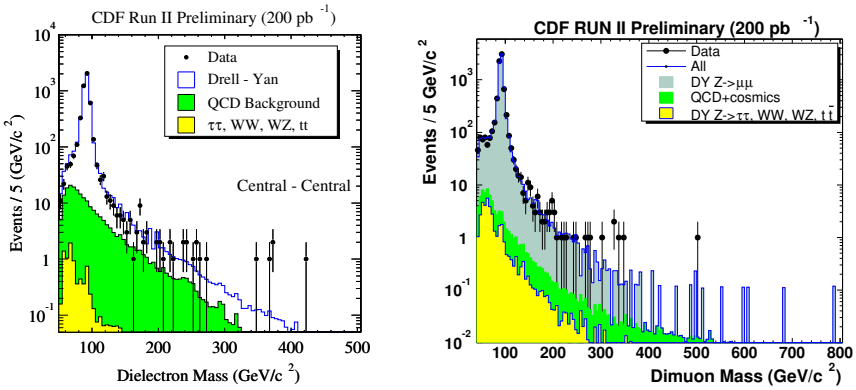

Figure 3. CDF's dielectron and dimuon invariant mass distributions.

sample as used in the TeV^{-1} ED search. No deviations from the SM predictions have been observed by neither experiments, therefore 95% C.L. upper limits on Z' masses were set. In the ee channel CDF sets a limit of 750, 570, 610, 625 and 650 GeV/c^2 for Z' with SM-like couplings, Z_I, Z_χ, Z_ψ, X_η respectively. In the ee channel DØ obtained similar results of 780, 575, 640, 650 and 680 GeV in the same order as above. In the $\mu\mu$ channel CDF obtained upper limits 735, 530, 600, 635 and 580 GeV/c^2 in the same order as above.

4 Search for Excited Electrons

One indication of a need for a theory going beyond the SM would be a discovery of excited leptons or quarks. At hadron colliders excited electrons, e^*, could be produced through contact interactions [11] or gauge mediated interactions [11]. CDF has searched 200 pb^{-1} for excited electron-electron pair production with e^* decaying to an electron and photon. The signature would therefore be events with eeγ with an M(eγ) resonance. Events with two electrons and a photon with $E_T > 25$ GeV were selected. No access of events above the SM background of Zγ, Z+jets, WZ, QCD multijets and $\gamma\gamma$+jets has been observed. Upper limits are set at 95% C.L. in the parameter space of M(e^*)/Λ vs M(e^*) [11] in case of the contact interaction model and of f/λ vs M(e^*) [11] in case of the gauge mediated interaction model. Figure 4 shows the excluded region for the two models.

5 Summary

Tevatron's CDF and DØ collaborations analyzed their first 200 $\mathrm{pb}^{-1}$of high-p_T diem and dimuon samples obtained from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. No deviation of data from Standard Model predictions have been observed, and strong limits were set in terms of parameters of proposed extra dimensions, heavy gauge bosons and excited electron models.

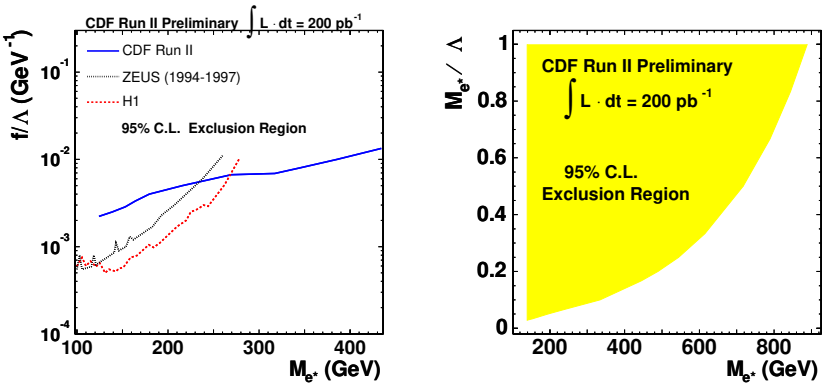

Figure 4. CDF 95% CL excluded region in the mass parameter versus f/λ for the gauge mediated model or versus M_{e*}/Λ for the contact interaction model.

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