SEARCHES FOR NEW PHYSICS AT HIGH ENERGY COLLIDERS

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Recent searches for physics beyond the Standard Model at high energy colliders are presented. The main focus is on searches for supersymmetry, extra dimensions and new gauge bosons. In all search analyses the data are found to agree well with the Standard Model background expectation and no evidence for contributions from physics beyond the Standard Model is found. The data are thus used to place limits on new physics scenarios.

1 Introduction

The Standard Model of particle physics describes all data taken at high energy colliders up to now. However, there are strong theoretical reasons, particularly the hierarchy problem, to believe that new physics should exist at the TeV scale. Also, from cosmology data (particularly the WMAP data) it is known that 95% of the energy and matter in the Universe is not accounted for by SM particles.

There are many theoretical models that attempt to solve these problems by proposing new particles, e.g. Supersymmetry, Extra Dimensions, new gauge groups, compositeness (predicting e.g. leptoquarks, excited fermions) and Technicolor. In this report I will concentrate on Supersymmetry and searches for new high-mass gauge bosons and extra dimensions.

The TeV scale is currently probed by the CDF and DØ experiments at the Tevatron collider at Fermilab. Protons and antiprotons are accelerated to an energy of 980 GeV and brought to collisions at the two experiments at a centre-of-mass energy of $\sqrt{s} \approx 1.96$ TeV. So-called "Run 2" at the Tevatron started in 2001. Until summer 2004 an integrated luminosity of about 700 pb^{-1} has been delivered to the experiments and about 500 pb^{-1} of high quality data are used for physics analyses. In this report most results are based on about 200 pb^{-1} taken up to September 2003. This dataset is a factor two larger than Run 1.

The HERA electron-proton collider at DESY has also recently resumed operation after a 2-year break, starting "HERA Run 2". Electrons or positrons are accelerated to an energy of 27.6 GeV, and protons to an energy of 920 GeV resulting in a centre-of-mass energy of $\sqrt{s} \approx 320$ GeV. In 2004 an integrated luminosity of 90 pb^{-1}of data have been delivered to the H1 and ZEUS experiments and 45 pb^{-1}are used for physics analyses. At HERA Run 1 about 100 pb^{-1}of e^+p and 15 pb^{-1}of e^-p data were collected and analysed.

The LEP electron-positron collider at CERN has stopped operation in 2000. Most data are analysed and published but final combinations from the four experiments (ALEPH, DELPHI, L3 and OPAL) are still ongoing and in many areas of searches for new physics the LEP results provide still the most stringent constraints.

In this report I will focus on new results from the Tevatron and HERA experiments.

2 Searches for Supersymmetry

Supersymmetry (SUSY) models are among the most promising theories since they address the hierarchy problem and provide a natural dark matter candidate. For each SM particle there is a correspondent super-partner which carries the same quantum numbers apart from the spin: each fermion has a sfermion super-partner of spin 0 and each gauge bopson has a gaugino super-partner of spin 1/2. Since no super-partners have yet been observed it is known that SUSY must be a broken symmetry if it exists. The nature of the breaking mechanism largely determines the phenomenology of the models. Furthermore the phenomenology of the models depends strongly on whether R_p is conserved where $R_p = (-1)^{3(B-L)+2S}$ and B is the baryon number, L the lepton number and S the spin. If R_p is conserved the lightest gaugino, the neutralino (χ_1^0) is an excellent candidate for Dark Matter in the Universe.

In this report I will focus on two R_p conserving scenarios and discuss stop production in R_p-violating SUSY:

- in "mSUGRA" models SUSY is broken at the GUT scale (10^{16} GeV). There are five parameters that determine the masses and cross sections for the super-partners: a common scalar mass m_0, a common sfermion mass $m_{1/2}$, the ratio of the vacuum expectation values of the higgs fields $\tan\beta$, the trilinear coupling A_0 and the Higgsino mixing parameter μ. The lightest SUSY particle is the χ_1^0. LEP has set a lower mass limit on the neutralino mass: $m_{\chi_1^0} > 47$ GeV [1]. The characteristic signature of SUSY production is large imbalance in transverse momentum, $\not\!\!E_T$, due to the outgoing neutralino which is not detected. .

- an alternative SUSY scenario with different experimental signatures is the "Gauge Mediated Symmetry Breaking Model" (GMSB). In these models SUSY is broken at a lower scale, $\mathcal{O}(10)$ TeV, than in mSUGRA models. The lightest SUSY particle is the gravitino, $\tilde{G}$, with a mass of $\mathcal{O}(1)$ keV. In GMSB models the characteristic signature is also $\not\!\!E_T$ due to the outgoing $\tilde{G}$'s. A typical signature is a decay of the NLSP into a photon and a $\tilde{G}$ which is explored in this report.

- in models where R_p is not conserved the lightest SUSY particle is not stable and thus there is no natural candidate for dark matter. Furthermore, large values of the R_p-violating coupling parameters, λ_{ijk}, lead to proton decay inconsistent with experimental results. Therefore it is often assumed that just one out of 45 possible coupling constants is non-zero. The weakest constraints on the couplings exist for quarks and leptons of the 3rd generation. In R_p-conserving models there is no intrinsic $\not\!\!E_T$.

Note, that the SUSY models that are used throughout this report should be considered as "benchmark"-models. It is quite likely that none of these *minimal* models is realised exactly in nature and they are largely used just as guidance for the experimentalists and for the purpose of comparing between experiments.

2.1 Squarks and Gluinos

DØ have searched for generic squarks and gluinos by analysing 85 pb^{-1}of data with two jets with high transverse energy, E_t, and large $\not\!\!E_T$ [2]. The leading (subleading) jet is required to exceed $E_T^1 > 60$ GeV ($E_T^2 > 50$ GeV), the scalar sum of the transverse jet energies, H_T, is required to be > 275 GeV and $\not\!\!E_T > 175$ GeV. Further cuts are placed to reduce experimental and electroweak backgrounds. The dominant background after all cuts comes from $Z + 2$ jets$\rightarrow \nu\bar{\nu} + 2$jets production.

The $\not\!\!E_T$ distribution is shown in Figure 1 before the $\not\!\!E_T$ cut of 175 GeV for the data and the SM background. The data agree well with the estimated background. One spectacular event with $\not\!\!E_T = 380$ GeV is seen in the data. Also shown is the distribution of a signal which has been excluded by these data

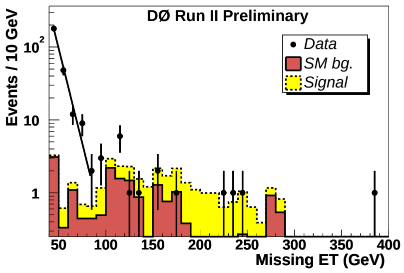

Figure 1. Missing E_t distribution for the search for gluino and squark production. Shown are the data (points) and the SM expectation (brown/dark histogram). The lighter (yellow) histogram shows an example signal ($m_{1/2}$ = 130 GeV/c^2) which is excluded by these data at 95% C.L.

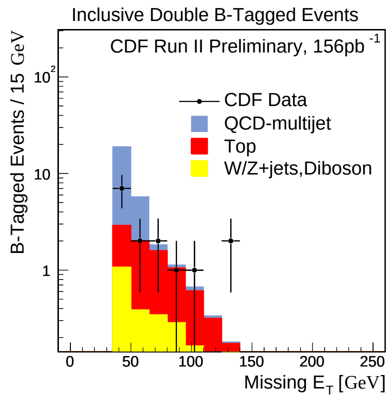

Figure 2. Missing E_t ditribution of the events selected in the $\tilde{g} \to \tilde{b}b$ analysis.

at 95% C.L.. The data are then used to constrain the masses of gluinos and squarks. The SUSY parameters were chosen to be $m_0 = 25$ GeV/c^2, $\tan\beta = 3$, $A_0 = 0$, $\mu < 0$. The lower limit on the gluino mass is $m(\tilde{g}) > 333$ GeV/c^2 and correspondingly $m(\tilde{q}) > 292$ GeV/c^2 or $m_{1/2} \geq 131$ GeV/c^2. This exceeds the previous best limit from CDF [3] by about 20 GeV in gluino mass.

At large values of $\tan\beta$ the third generation squarks (sbottom and stop) may be light. CDF has searched for gluino pair production [4] with subsequent decay of the gluino into sbottom and bottom quarks: $\tilde{g}\tilde{g} \to \tilde{b}b\tilde{b}b \to bb\chi_1^0 bb\chi_1^0$. The final state consists of 4 b-jets and large $\not\!\!E_T$. In the analysis either one or two b-jets and $\not\!\!E_T > 80$ GeV are required. b-jets are identified by reconstructing a secondary vertex displaced from the primary interaction point. The $\not\!\!E_T$ distribution of events with 2 b-tagged jets is shown in Figure 2.

The data are in good agreement with the SM background which is dominated by $t\bar{t}$ production. 21 events are observed with one b-tagged jet compared to an expectation of 16.4 ± 3.7, 4 events are observed with 2 b-tagged jets compared to 2.6 ± 0.7 expected. No triple-tagged event is seen in the data. The data are then used to place limits on the gluino and sbottom mass within mSUGRA for $m(\tilde{q}) = 500$ GeV, $m(\chi_1^0) = 60$ GeV and for the branching ratio $\mathcal{B}(\tilde{g} \to \tilde{b}b) = 100\%$. The exclusion plane $m(\tilde{b})$ versus $m(\tilde{g})$ is shown in Figure 3: gluinos are excluded up to masses of 280 GeV/c^2 and sbottom quarks up to $m(\tilde{b}) = 240$ GeV in this parameter space.

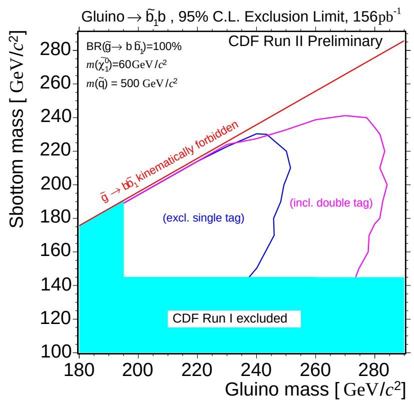

Figure 3. Sbottom versus Gluino Mass. Shown are the regions excluded by the $\tilde{g} \to \tilde{b}b$ analysis for single b-tag and double b-tagged events. They are compared with previous $m(\tilde{b})$ and $m(\tilde{g})$ limits from CDF.

The stop quark, $\tilde{t}$, is likely to be the lightest squark due to the large mass splitting in the top sector. CDF has searched for quasi-stable stop quarks in 53 pb^{-1}of Run 2 data. In this search the stop quark is assumed to have a large lifetime and will not decay inside the CDF detector. The stop quark is assumed to hadronise similar to a b-quark [5] and thus into a charged hadron with a probability of 56.2%. In this case it will act like a minimum-ionising particle and penetrate the CDF detector to the muon chambers. However, it can be distinguished from muons in the time-of-flight detector which measures the arrival time of particles with a resolution of 100 ps. E.g. a particle with $m = 100$ GeV/c^2 is expected to take $2 - 3$ ns longer to arrive at the TOF radius of 140 cm. In this analysis CDF therefore looks for heavy particles consistent with the signature of a high momentum muon but a late arrival time $\Delta t_{TOF} > 2.5$ ns.

In the search region 7 events are observed and 2.9 ± 0.7 expected. The data are used to constrain quasi-stable $\tilde{t}$ quarks to have a mass $m_{\tilde{t}} > 108$ GeV/c^2.

At HERA stop quarks can be singly produced ($e^+q \to \tilde{t}$) if R_p is violated and the coupling of the stop quark to the first generation quarks and leptons, λ'_{131}, is large. Thus both H1 and ZEUS have searched for stop production in the context of R_p violating SUSY models.

H1 has searched in a scenario where $m(\tilde{t}) > m(\tilde{b})$ and the stop either decays via $\tilde{t} \to e^+d$ or $\tilde{t} \to \tilde{b}W \to \bar{\nu_e}dW$. The 2nd signature is particularly interesting since it leads to events with large $\not{E}_T$, and isolated high P_t lepton and a high E_t jet, and H1 has observed an excess of events in this signature in their Run 1 data analysis whilst ZEUS find agreement with the SM prediction [8]. In 105 pb^{-1} of Run 1 e^+p and data H1 observed 10 events compared to a SM expectation of 2.9 ± 0.5 with $P_T^X > 25$ GeV/c^2 where P_T^X is the transverse momentum of the hadronic jet. H1 also analysed the first 45 pb^{-1}of Run 2 data and observes 3 events compared to 1.5 ± 0.2 expected. In 113 pb^{-1}of e^+p data ZEUS finds good agreement between the data and the SM for $P_T^X > 25$ GeV/c^2: 5 events are observed and 4.6 ± 0.8 are expected [7]. At low values of P_T^X both experiments find good agreement between the data and the SM expectation. More data from HERA Run II are required to evaluate whether the H1 excess at large P_T^X is a statistical fluctuation or is significant.

Assuming that the H1 excess is due to new physics, it may be a signature of stop quark production as described above $\tilde{t} \to \tilde{b}W \to \bar{\nu_e}dW$. H1 searched for this signature by requiring large $\not{E}_T$, a jet and a W boson decaying via $W \to e\nu$, $W \to \mu\nu$ or $W \to jj$ [9]. There is a slight excess of events in the muon channel (8 events observed and 2.7±0.5 events expected) but the other two channels agree well with the SM expectation. This excess in the muon channel is due to the same events as the excess discussed above. Assuming the presence of a stop quark of mass $m_{\tilde{t}}$ the observed event yields were used to determine an allowed range of the $\tilde{t}$ production cross section $\sigma_{\tilde{t}}$. This is shown in Figure 4 separately for the three channels. It can be seen that the muon data can be interpreted in this model but the other two channels do not support this hypothesis. The probability that the channels are consistent with each other was estimated to be 1%.

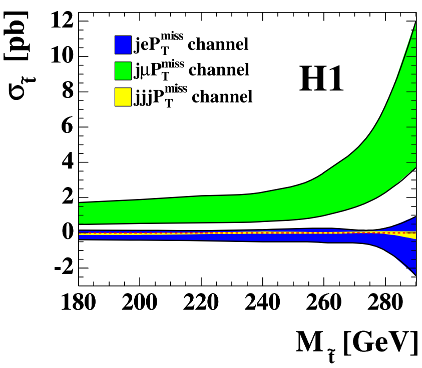

Figure 4. H1 Cross section measurement of $\tilde{t}$ quark production versus the mass, $m_{\tilde{t}}$, for the electron jeP_T^{miss}, muon $j\mu P_T^{miss}$ and jet $jjjP_T^{miss}$ analyses.

H1 thus place a limit on stop production in this model as function of λ'_{131} and $m_{\tilde{t}}$. This is shown in Figure 5. For a coupling strength equivalent to the electro-magnetic coupling $\lambda'_{131} = 0.3$ masses of up to 280 GeV/c^2 are excluded in this scenario.

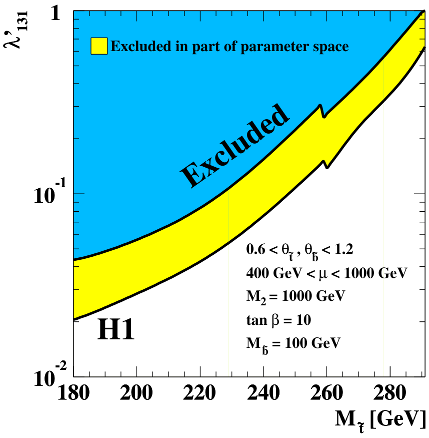

Figure 5. Exclusion region of λ'_{131} versus $m_{\tilde{t}}$. The dark area is excluded for all the paramter space scanned by H1 and the light shaded (yellow) area for part of that parameter space.

ZEUS have searched 66.5 pb^{-1}of e^+p data for $\tilde{t}$ quarks in a scenario where the $\tilde{t}$ quark is the lightest squark, in particular it is lighter than then $\tilde{b}$ and can thus not decay in the above decay channel. In this case the dominant decay mode is $\tilde{t} \to b\chi^+$ with subsequent decay of the χ^+ leading to a positron and multiple jets in the final state. The data are found to agree well with the SM background prediction and no evidence for stop production is found. ZEUS are thus able to place limits on stop production as function of λ'_{131} and $m_{\tilde{t}}$. This is shown in Figure 6. Up to masses of $m_{\tilde{t}} \approx 210$ GeV the ZEUS limit on λ'_{131} is stronger than indirect limits from Atomic Parity Violation constraints. For a coupling strength equivalent to the electro-magnetic coupling $\lambda'_{131} = 0.3$ masses of up to 230 GeV/c^2 are excluded.

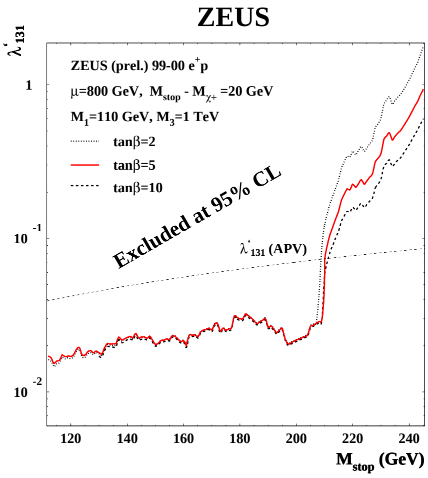

Figure 6. Exclusion region of λ'_{131} versus m_{stop} for three values of $\tan\beta$. Shown are also constraints from Atomic Parity Voliation experiments.

2.2 Charginos and Neutralinos

The results of three searches for neutralinos and charginos in the context of three models for SUSY are described: mSUGRA, GMSB and R-parity violation.

The analysis in the context of the mSUGRA model searches for chargino-neutralino pair production with subsequent cascade decays of the χ_2^0 and χ_1^+ into leptons. The final state then contains three leptons and large $\not{E}_T$ due to outgoing χ_1^0's and neutrinos.

The DØ experiment has analysed four final states: $ee + t$, $\mu\mu + t$, $e\mu + t$ and $\mu^\pm\mu^\pm$ [2]. Here e and μ denote identified electrons and muons, t is a track that is isolated w.r.t. other tracks. The inclusion of a track as 3rd lepton enhances the acceptance since it allows for τ-lepton decays. The $\mu^\pm\mu^\pm$ analysis searches for two muons of the same charge and requires no third lepton. The 1st and 2nd lepton are required to have $p_T > 11$ GeV, the third is required to have $p_T > 5$ GeV. The Standard Model background is further suppressed by requirements on the dilepton invariant mass, the difference in azimuthal angle $\Delta\phi_{ll}$, $\not{E}_T$ and several other variables.

In Table 1 the data are compared to the SM expectation in all these channels.

Table 1. Numbers of expected and observed events in the four tri-lepton analysis channels. The uncertainty on the background expectation includes both statistical and systematic errors.

	Expected	Observed
$ee + t$	0.7 ± 0.5	1
$\mu\mu + t$	1.8 ± 0.4	1
$e\mu + t$	0.3 ± 0.3	0
$\mu^\pm\mu^\pm$	0.1 ± 0.1	1

The data are thus combined and interpreted as an upper limit on the cross section times branching ratio $\sigma(\chi_2^0\chi_1^+) \times \mathcal{B}(3 \text{ leptons})$ shown in Figure 7. The upper limit at 95% C.L. is about 0.4 pb for a parameter choice of $\tan\beta \sim 3$, $A_0 \sim 0$, $\mu > 0$, $M(\chi_1^+) \sim M(\chi_2^0) \sim 2M(\chi_1^0) \sim M(\tilde{l})$. This corresponds to a lower limit on $M(\chi_1^+)$ of 97 GeV which is about 6 GeV lower than the direct model-independent limits obtained at LEP. With only 25% more data the LEP limits will be exceeded in certain regions of the parameter space.

If the next-to-lightest SUSY particle is the χ_1^0 it typically decays into a photon and a $\tilde{G}$ resulting in a signature of two photons and large $\not\!\!E_T$. Both CDF ($\mathcal{L} = 202$ pb^{-1}) [10] and DØ ($\mathcal{L} = 263$ pb^{-1}) [11] have searched for this signature. The DØ $\not\!\!E_T$ distribution is shown in Figure 8.

The results are summarised in table 2. In both experiments the data are consistent with the SM expectation. At high $\not\!\!E_T$ the main background results from $W\gamma \to e\nu\gamma$ events where the electron is misidentified as a photon due to track misreconstruction or hard Bremsstrahlung.

The data are used to set an upper limit on the cross section. This is then interpreted as a lower limit on the χ_1^0 (χ_1^+) mass of 93 GeV (167 GeV) by CDF and 108 GeV (195 GeV) by DØ at 95% C.L..

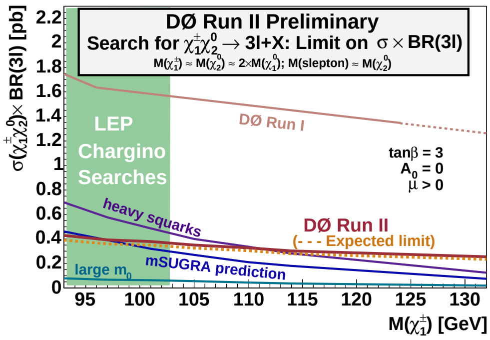

Figure 7. Cross section versus the mass of the lightest chargino χ_1^+. Shown is the experimental upper limit and several theoretical predictions. The line labelled "mSUGRA prediction" shows the theoretical prediction within mSUGRA for $\tan\beta \sim 3$, $A_0 \sim 0$, $\mu > 0$, $M(\chi_1^+) \sim M(\chi_2^0) \sim 2M(\chi_1^0) \sim M(\tilde{l})$. The line labelled "Heavy Squarks" shows the theoretical cross section for a model where the sfermion mass unification is relaxed and the squark masses have very high values. The line labelled "large m_0" is for the case that the sfermion mass scale is larger.

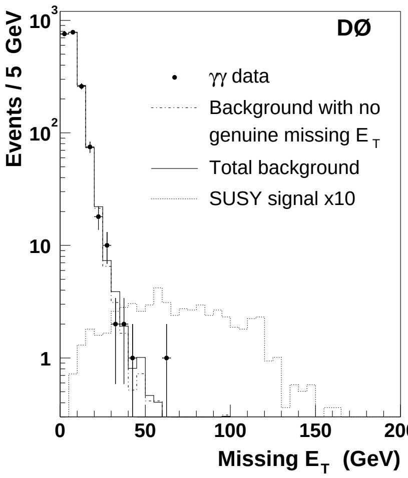

Figure 8. $\not\!\!E_T$ distribution for diphoton events. The data (points) are compared the the Standard Model expectation (solid histogram). A SUSY signal is also shown (dashed histogram).

Table 2. Numbers of expected and observed events in the GMSB search for 2 photons and large $\not\!\!E_T$. DØ require 2 photons with $E_T^\gamma > 20$ GeV and $\not\!\!E_T > 40$ GeV, CDF require 2 photons with $E_T^\gamma > 12$ GeV and $\not\!\!E_T > 45$ GeV. .

	Expected	Observed
CDF	0.3 ± 0.1	0
DØ	3.7 ± 0.6	2

2.3 $B_s \to \mu^+\mu^-$

The SM branching ratio of the B_s meson is only $\mathcal{B}(B_s \to \mu^+\mu^-) = 3.42 \pm 0.54 \times 10^{-9}$ [12]. In SUSY models the branching ratio can be significantly enhanced at high values of $\tan\beta$ [13]. CDF [14] and DØ [15] have searched for this decay in 171 pb^{-1}and 240 pb^{-1}of Run 2 data, respectively. Neither experiment finds any evidence for this decay. The results of the search are given in table 3.

Table 3. Numbers of expected and observed events in the $B_s \to \mu^+\mu^-$ search.

	Expected	Observed
CDF	1.1 ± 0.1	1
DØ	3.7 ± 1.1	4

The data are thus used to place an upper limit on $\mathcal{B}(B_s \to \mu^+\mu^-)$. CDF finds $\mathcal{B}(B_s \to \mu^+\mu^-) < 7.5 \times 10^{-7}$ and DØ finds $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-7}$ at 95% C.L.. Note, that this result is complementary to the tri-lepton searches since it constrains the SUSY parameter space at high $\tan\beta$ whilst the tri-lepton search is most sensitive at low $\tan\beta$.

3 New Gauge Bosons and Large Extra Dimensions

There are several models of physics beyond the SM that predict new particles at high mass, e.g. new gauge groups (Z') and Extra Dimension models. Here, the invariant mass distribution of dilepton and diphoton events is examined and used to constrain such models of new physics.

3.1 Di-lepton Searches

In the SM dilepton production arises predominantly from the Drell-Yan process which has a relatively small cross section for $m(l^+l^-) > 100$ GeV, i.e. when the mass is significantly larger than the Z boson. It is thus an ideal place to look for new physics, e.g. new gauge bosons (Z').

Both CDF and DØ have analysed the di-electron and di-muon mass spectra [16]. Figure 9 shows the CDF e^+e^- mass and the DØ $\mu^+\mu^-$ mass spectrum. Both are in good agreement with the SM background expectation and no evidence for any resonance production of a new particle is seen.

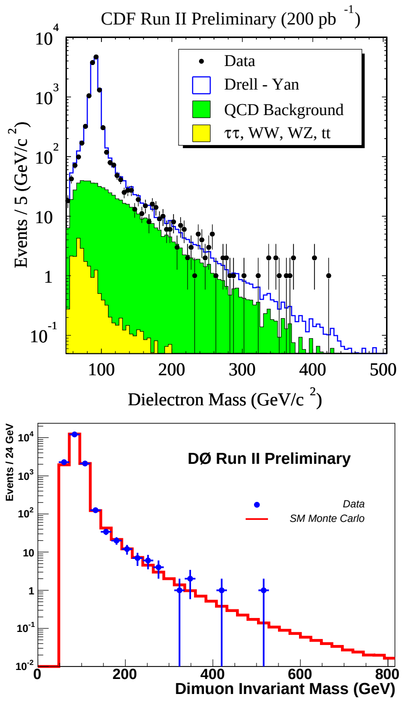

Figure 9. Invariant mass of di-electron (upper plot) and dimuon (lower plot) candidates.

Both experiment thus derive an upper limit on the cross section times the branching ratio into two leptons for $Z' \to l^+l^-$. The CDF 95% C.L. upper limit is shown in Fig-

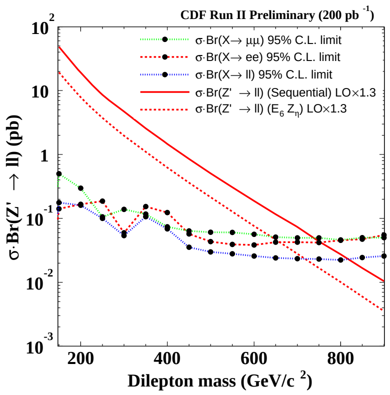

Figure 10. Upper limit on the cross section of $Z' \to l^+l^-$ production. Shown are the experimental limits on $\sigma\times$Br and the theoretical predictions for a Z' with SM couplings ("Sequential") and the E_6 Z_η model. Both prediuctions are increased by 30% as an approximate value for the NLO k-factor.

ure 10 for electrons and muons separately and combining both channels (assuming lepton universality). Also shown is the theoretical prediction of a Z' boson with SM couplings and in the E_6 Z_η model [17].

CDF have also searched for di-τ production at high mass. At hadron colliders the selection of τ's is significantly more difficult than that of electrons or muons due to the large background from hadronic jets. The data are compared to the SM expectation at $m_{visible} > 120$ GeV where $m_{visible}$ is the "visible" mass formed by the lepton, τ and $\not\!\!E_T$. The mass distribution is shown in Figure 11.

In the search region $m_{visible} > 120$ GeV 4 events are observed in good agreement with the SM expectation of 2.8 ± 0.5 events. The data are then used to set an upper limit on the production cross section times the branching ratio $\mathcal{B}(Z' \to \tau^+\tau^-)$ of about 2 *pb* at $m(Z') = 400$ GeV/c^2. For a Z' boson with SM couplings this corresponds to a lower mass limit of 394 GeV/c^2. Although this is not competitive with the dielectron and dimuon channels within this model this analysis is more sensitive to new particles which have an enhanced coupling to τ-leptons, e.g. Higgs bosons.

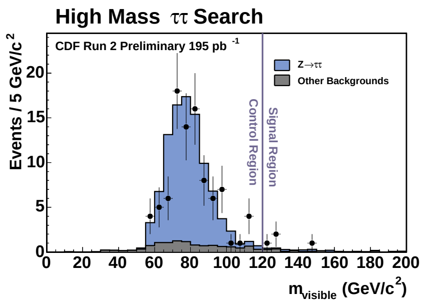

Figure 11. "Visible" mass of ditau events.

3.2 *Di-photon Searches*

The SM cross-section for diphoton production is even lower than that for dilepton production and is thus another excellent place to search for new physics. CDF perform an inclusive analysis of the diphoton mass distribution. The data mass distribution is shown in Figure 12 and compared with the SM expectation. The data agree well with the SM background, the highest mass event is found at $M(\gamma\gamma) = 404$ GeV.

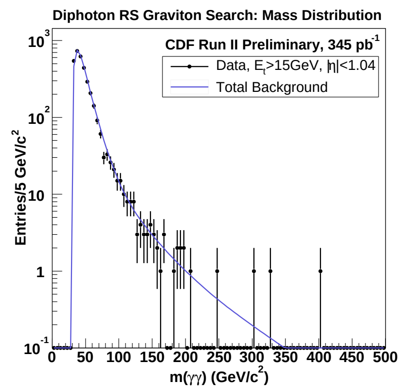

Figure 12. Diphoton mass distribution. The CDF data are compared to the SM background.

The DØ experiment analysed the dielectron and diphoton mass spectrum together in one analysis. This has the advantage of gaining in both electron and photon selection efficiency and thus improving the sensitivity to models which are predicted to result in both diphoton and dielectron final states. One such model is graviton production in Randall-Sundrum models [19]. These couple to both leptons and photons but the main sensitivity comes from diphoton production due to the two times larger coupling stength. In this model a single small highly curved extra dimension is postulated and the Planck mass is reduced to $\mathcal{O}(1)$ TeV to solve the hierarchy problem. The model is determined by two parameters: the coupling strength k/M_{Pl} and the mass of the first Kaluza-Klein mode $M(G)$. k/M_{Pl} also determines the width of the Kaluza-Klein mode. The search is restricted to $k/M_{Pl} < 0.1$ where the width is narrow.

Figure 13 shows the plane of k/M_{Pl} versus $M(G)$ and the shaded area represents the area excluded by the DØ analysis. At $k/M_{Pl} = 0.1$ DØ excludes Randall Sundrum gravitons up to massed of 785 GeV. The CDF diphoton analysis excludes masses up to 690 GeV.

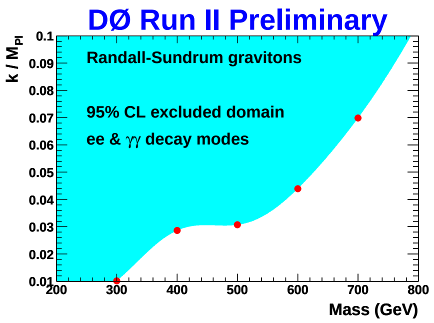

Figure 13. k/M_{Pl} versus Graviton mass. The shaded area is excluded by D0.

The LEP, Tevatron and HERA experiments have also performed searches for Large Extra Dimensions in the context of the "ADD model" [18]. In this model the hierarchy problem is solved by postulating extra spacial dimensions and allowing some of them to be "large", i.e. $\gg 1/M_{Pl}$. This lowers the Planck scale to a value M_D which may be near the TeV scale. The important parameter in this model is the "cut-off parameter" $M_S \approx M_D$: for scales larger than M_S the effective theory breaks down. There are two experimental signatures predicted by this model: 1) virtual graviton exchange enhances the production cross sections of leptons, quarks and gauge bosons at high invariant masses and 2) direct graviton emission results in a graviton which escapes detection and thus leads to large $\not\!\!E_T$

At LEP and at the Tevatron the signature resulting from virtual graviton exchange is an enhancement of diphoton and dielectron production at high masses and low values of $\cos\theta^*$ where θ^* is the opening angle of the two photons/leptons in the rest frame. The difference in angular distribution arises due to the spin-2 nature of the gravitons. At HERA the neutral current cross section $ep \rightarrow eq + X$ would be altered at the highest values of virtuality Q^2 of the exchanged boson due to the additonal contribution from graviton exchange. The resulting lower limits in the Hewett [20] convention are given in table 4.

Table 4. Lower limit on M_S for the Tevatron (DØ and CDF), the combined LEP and the HERA (H1 and ZEUS) experiments. Given are the final states used for the search. The results are presented for constructive ($\lambda = +1$) and destructive ($\lambda = -1$) interference.

Analysis	M_S (TeV/c^2)	
	$\lambda = +1$	$\lambda = -1$
DØ $e^+e^- + \gamma\gamma$	1.28	1.16
DØ $\mu^+\mu^-$	0.97	0.95
CDF e^+e^-	0.96	0.99
LEP e^+e^-	1.20	1.09
H1 e^+q	0.82	0.78
ZEUS e^+q	0.78	0.82

The most stringent limits on M_S are currently set by the DØ experiment.

4 Conclusions

I have presented a review of the experimental results on searches for new particles at the high energy colliders: LEP, HERA and Tevatron. At the Tevatron, up to now no significant deviations of the data from the SM have been observed. However, within the next few years the datasets are expected to increase by an order of magnitude leading to a substantial improvement in sensitivity. At HERA first analyses of Run 2 data have started and it will remain to be seen how the excess in the "isolated leptons" will evolve. The LEP experiments still provide the most stringent limits on new physics in many cases, particularly on SUSY, but the new data from the Tevatron are starting to improve upon those. With the continuously improving performance of the Tevatron and HERA many, hopefully exciting, results are expected to appear over the next few years.

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