EXPERIMENTAL RESULTS ON SEARCHES
BEYOND THE STANDARD MODEL

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Recent results for direct searches for physics beyond the Standard Model are reviewed. The results include Tevatron II data up to 1.2 fb$^{-1}$ and HERA results up to 350 pb$^{-1}$. Searches for Supersymmetry, for compositeness and for large extra dimensions are presented. The excess of events with an isolated lepton and high missing transverse momentum at HERA is discussed.

1. Introduction

We know from the corrections to the Higgs mass that new physics could be at a scale of 1 or few TeV. It would be possible then to see effects beyond the Standard Model (SM) at present colliders, and of course in future at the LHC. In this report, recent results from direct searches at HERA (up to 350 pb$^{-1}$ of integrated luminosity) and Tevatron (up to 1.2 fb$^{-1}$) are reviewed. A review of the present theoretical ideas and phenomenological models beyond the SM can be found in 1.

Searches for supersymmetry (SUSY) scenarios are reviewed in Sec. 2; searches for compositeness models (like leptoquarks and finite quark radius at HERA) are described in Sec. 3. Models based on large extra-dimensions and Randall-Sundrum gravitons are discussed in Sec. 4, which also describes searches for new heavy gauge bosons. Finally Sec. 5 describes a special signature studied at HERA, with isolated electrons or muons accompanied by large missing transverse momentum. Many more results can be found in the parallel session contributions at this conference. Searches for Higgs and minimal supersymmetric Standard Model (MSSM) Higgs at Tevatron and LHC are reported in other plenary contributions 2.

2. Search for Supersymmetry

Supersymmetry is one of the most attractive model for new physics, as it provides a solution to the hierarchy problem, provides unification of the three interactions at the GUT scale and a possible candidate for the dark matter (the light supersymmetric particle, LSP). For every particle, it predicts a partner (sparticle) with spin differing by one half. As we know that the selectron mass is different from the electron mass, Supersymmetry is a broken symmetry and various scenarios have been proposed. One popular scenario is the gravity mediated SUSY breaking scenario mSUGRA, where the > 100 parameters in SUSY are reduced to only five parameters that can completely describe the phenomenology: the common scalar mass at the GUT scale ($m_0$), the common gaugino mass ($m_{1/2}$), the common trilinear soft trilinear SUSY breaking parameter ($A_0$), the ratio of the Higgs vacuum expectation values to the electroweak scale ($\tan\beta$) and the sign of the Higgsino mass term (sign $\mu = \pm 1$).

Particles are assigned an $R$-parity $R_P = (-1)^{B+L+S}$, where sparticle have $R_P = -1$, while partner have $R_P = +1$, where $R_P$ is a multiplicative new quantum number. In models where $R_P$ is conserved, sparticles are produced in pairs and at the end of the chain decay in the LSP (in many models the lightest neutralino,$\tilde{\chi}_1^0$), which is weakly interacting and escapes de-
tection. This leads to a distinct signature of large missing transverse momentum, for instance at the Tevatron. Always at the Tevatron the cross sections are small, i.e. only \(< 100\) hundred events are expected for 1 fb\(^{-1}\) for various sparticles with masses under 400 GeV, but not impossible. The Standard Model background must however be modelled and understood very well, this will be especially true at the LHC.

### 2.1. Search for chargino and neutralino at the Tevatron

The charginos (\(\tilde{\chi}_{1,2}^{\pm}\)), which are the superpartners of the states coming from the mixing of the \(W^\pm\) and \(H^\pm\), and the neutralinos (\(\tilde{\chi}_{0}^{0,1,2,3,4}\)), which are the superpartners that come from the mixing of the neutral Higgses and SU(2)\(\times\)U(1) bosons, are best searched at Tevatron in associated production. The golden signature comes from the MSSM channel \(gg \rightarrow W^* \rightarrow \tilde{\chi}_{1}^{\pm}\chi_{2}^{0} \rightarrow ll\nu\tilde{\chi}_{1}^{0}\tilde{\chi}_{1}^{0}\). The final state has therefore three leptons and missing transverse energy (MET) coming from the neutrino and lightest neutralino, which is assumed to be the LSP. The cross section is small but the process is basically background free. Both CDF and D0 found no evidence in this signature, setting limits on the lightest chargino, as shown in Fig. 1 for the D0 experiment. A mass up to 140 GeV\(^{-1}\) on the \(\tilde{\chi}_{1}^{\pm}\) mass is excluded, extending the previous limit by LEP which was 103 GeV.

### 2.2. Search for RPC squarks at Tevatron

The inclusive production of squarks and gluinos is one of the most promising discovery channels for SUSY at the Tevatron, due to the large cross section. In \(RP\) conserving (RPC) scenarios, the cascade decays of the produced squark and gluino give a final state with quark, gluons and the LSP (the \(\tilde{\chi}_{1}^{0}\)), with a distinct topology with multijets and missing \(E_T\). D0 and CDF have searched\(^{[2]}\) for this signal optimizing the analyses for the three cases in which the mass of the squark is greater, equal or smaller than the mass of the gluino. As no particular excess is observed, limits are set in the two-dimensional plane \(M(\tilde{q}), M(\tilde{g})\) in the context of the mSUGRA model. The result is shown in Fig. 2 where it can be seen that limits are set for \(M(\tilde{q}) > 325\) GeV and...
\( M(\tilde{g}) > 241 \text{ GeV (D0)} \) or \( M(\tilde{q}, g) > 387 \text{ GeV (CDF)} \) in the case of equal masses. At LHC, squarks and gluinos can be discovered with a significance of 5-\( \sigma \) with 1 fb\(^{-1}\) up to a mass of 1.5 TeV.

In the case of the third generation squarks, there could be a large mixing between the right-handed and left-handed weak eigenstates, leading to a light mass eigenstate \((\tilde{t}_1, \tilde{b}_1)\). In \( R_P \)-conserving models, sbottom and stop are produced in pairs via \( q\bar{q} \) annihilation or gluon-gluon fusion and the cross-section has little dependence on the SUSY parameters other than the sbottom and stop mass, respectively. The produced sbottom or stop decay then in a quark and the LSP, \( p\bar{p} \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow e\bar{\chi}_1^0\bar{\chi}_1^0 \) and \( p\bar{p} \rightarrow \tilde{b}_1\tilde{b}_1 \rightarrow b\bar{\chi}_1^0\bar{\chi}_1^0 \). The topology is two acoplanar charm- or b-jets with high missing \( E_T \), and the main background is \( W/Z+\text{jets} \) production. In the case of the stop search, 8 events were observed by D0 at \( MET > 150 \text{ GeV} \) with an expectation of 3 events from the SM. However the missing \( E_T \) distribution of these events is larger than expected for a stop signal. A detailed investigation of these events did not reveal any anomaly.

In both searches \( \tilde{b} \), then, no clear anomaly above the background expectations was observed. Limits on the sbottom mass up to 200 GeV were set as shown in Fig. 3 depending on the neutralino mass, extending considerably the Run I limit, which was approximately 150 GeV, and the limits from LEP. The exclusion area for the stop is also shown in Fig. 3 for the stop mass versus the neutralino mass. The stop is excluded up to 131 GeV, in an exclusion area complementary to LEP results.

### 2.3. Search for events with photons and GMSB signatures

In Run I, CDF observed \( \tilde{b} \) a spectacular event with two \( e \), two \( \gamma \) and a missing \( E_T \) of 55 GeV, to be compared to a SM expectation of \( 10^{-6} \) events. A possible explanation of this event was \( pp \rightarrow \tilde{e}\tilde{e} \rightarrow e\chi_2^0\chi_2^0 \), with \( \chi_2^0 \rightarrow \gamma\chi_1^0 \). In addition 16 events with a lepton+photon+missing \( E_T \) were observed for an expectation of 7.6 ± 0.7. This has motivated a search \( \tilde{b} \) for events with leptons, photons and missing energy also in Run II and the analysis was repeated with the data taken recently, based on 929 pb\(^{-1}\). In total 163 events, with an expectation of 148.1 ± 13.0 were observed with the topology lepton+photon+\( MET \). No excess was also observed in events with either two muons or two electrons and a photon: the missing \( E_T \) distribution for these events, shown in figure \( \tilde{b} \) is always < 30 GeV and no event with...
two photons was observed.

![Graph](image)

**Fig. 4.** Missing \( E_T \) distribution for events with two muons or two electrons and a photon in the CDF Run II data (929 pb\(^{-1}\)).

The observation of the CDF Run I event has also motivated D0 to perform a general search for events with multiphoton and missing \( E_T \), a topology which is expected in gauge mediated SUSY breaking scenarios (GMSB), where the gravitino is the LSP, the neutralino is the next LSP, and decays in a gravitino and a photon. The missing transverse energy spectrum for events with two central high transverse energy photons (\( |\eta_\gamma| < 1.1 \) and \( E_{T\gamma} > 25 \) GeV), is shown in Fig. 4. For missing transverse energy greater than 45 GeV, there are 4 events observed, with an expectation of 2.1 ± 0.7 events expected from QCD processes and \( W\gamma, W+\text{jet} \) processes. The process is then used to set a limit on the GMSB scale \( \Lambda \), which also gives the scale of the gaugino masses: \( \Lambda > 88.5 \) TeV, \( M(\tilde{\chi}_1^\pm) > 120 \) GeV and \( M(\tilde{\chi}_1^0) > 220 \) GeV.

### 2.4. Search for RPV stop at HERA

Sparticles can only be produced singly at HERA, via \( R \)-parity violating (RPV) reactions. As the stop is not yet well constrained at the Tevatron, it can be produced at HERA in the s-channel from the positron beam and a \( d \)-valence quark in the proton. The cross-section is proportional to the square of the \( \lambda_{131} \) \( R \)-parity violating coupling. The stop can be detected as a narrow resonance, either decaying to \( e^\pm d \) (electron-jet), like a leptoquark; or via the gauge decay \( \tilde{t} \rightarrow b\tilde{\chi}_1^\pm \) and subsequent decays, giving topologies with multijet and neutrino, or multijet and positron in the final state. These three channels were recently investigated by ZEUS in the HERA I data observing no deviation from the SM expectation of deep inelastic scattering (DIS) events. The limit set on the stop mass, for a coupling similar to the electromagnetic strength of \( \lambda_{131} = 0.3 \), is around 260 GeV. In the region of MSSM space where \( M_2 \) and \( \mu \) are small, and therefore the gauge decays dominate over the leptoquark-type decay, the HERA limits are the most stringent to date.

### 2.5. Search for stopped gluino in split-SUSY models

Recently a new variant of SUSY, called split-Supersymmetry, has been proposed, in which scalars are heavy, possibly at the GUT scale, compared to the SUSY fermions. Due to the high mass of the scalar particles, gluino decays are suppressed and the gluinos become bound states of the gluino and quarks or gluons. These colourless \( R \)-hadrons live long enough to reach the calorimeter and, in case they are charged, they can lose all their momentum via ionization and come at rest in.
the calorimeters (so called ‘stopped gluinos’). These stopped gluinos then decay in a gluon (giving a jet) and a neutralino (the LSP, giving missing transverse energy).

D0 has performed a search \[11\] for these $R$-hadrons: assuming that the stopped gluino has a long enough lifetime (at least 10 $\mu$s), its decay would occur in a bunch-crossing later than the one when it was produced. The signature is then a largely empty event with a high-$p_T$ jet and large missing $E_T$. The background is mainly cosmic muons and beam-halo muons. The observed spectrum of monojets for empty events is in good agreement with the expected background. The D0 analysis excluded gluino masses up to $\approx 270$ GeV, for a light neutralino, as shown in Fig. 6.

3. Search for Compositeness

3.1. Search for leptoquarks

Leptoquarks (LQs) are colour triplet bosons which appear naturally in various unifying theories beyond the SM. At HERA, LQs can be singly produced from the fusion of the initial state electron/positron beam with a quark from the incoming proton. For masses below the centre of mass energy of 318 GeV they are produced as narrow resonances in the $s$-channel, for higher masses they are exchanged in the $u$-channel and contribute to the DIS cross-section.

H1 has presented a new analysis \[12\] on searches for $F = 2$ leptoquarks - where the fermion number $F$ is defined from the baryonic and leptonic numbers as $F = |3B + L|$ - profiting from the recent large sample of $e^- p$ collisions of the 2005 data, where there is most sensitivity to this type of leptoquarks. The signature is a narrow resonance in the invariant mass of the electron and jet or neutrino and jet final-state system. The lepton decay distribution in the center-of-mass frame of the hard subprocess can be used to distinguish the signal from the DIS charged current (CC) and neutral current (NC) background. As no evidence above the DIS background was found, H1 set limits on the LQ mass as a function of the Yukawa coupling $\lambda$ of the LQ to the electron and quark. The limit is shown for instance for the LQ $S_{0,L}$ (leptoquarks with $F=2$ have been classified in 7 different types by Büchmuller-Rückl-Wyler according to spin, isospin, chirality, hypercharge) in Fig. 7. H1 excludes, for a coupling of electromagnetic strength, leptoquark...
masses in the range of 276-304 GeV. The plot shows also the nice complementarity in this search between the colliders. At high masses the most stringent constraint comes from the indirect limits of L3 from the $e^+e^-\rightarrow q\bar{q}$ cross-section. At low masses, the LQ mass is constrained below 234 GeV at all values of the coupling by the pair production in the D0 Run I+II data.

### 3.2. Search for finite quark radius at HERA

The high $Q^2$ region, where $Q^2$ is the virtuality of the exchanged boson, is the most interesting kinematic region to look for new physics at HERA, especially for new interactions between electrons and quarks. If the scale of these new interactions is above the center of mass energy ($\sqrt{s} \approx 318$ GeV), the SM cross section can be modified via virtual effects. A finite charge radius for the quark would modify the $d\sigma/dQ^2$ with a form factor type term of the form $(1 - R^2_q/6Q^2)^2$, where $R_q$ is the root-mean-square radius of the electroweak charge of the quark. Figure 8 shows the new preliminary results from ZEUS, using the combined HERAI+HERAII dataset. As good agreement is shown between the data distribution and the SM prediction, limits on the quark radius of $R_q < 0.67 \times 10^{-16}$ cm are set. This constraint is the most stringent to date.

### 4. Search for LED, Z’ and W’

#### 4.1. Search for Large Extra Dimensions and Randall-Sundrum gravitons

Models based on Large Extra Dimensions (LED), such as the model of Arkani-Hamed, Dimopolous and Dvali (ADD) offer a suitable framework to solve the hierarchy problem. In these models gravity is allowed to propagate in the 4+n dimensional bulk of space-time, while the remainder of the SM fields are confined to the 3+1 dimensional world-volume of the brane configuration. The extra $n$ dimensions are compactified with a radius $R$ and the scale $M_D$ of gravity is related to the Planck scale by the relation $M_D^2 \sim R^n M_S^{n+1}$. If the size of the extra-dimensions is of the order of $\approx 10 \mu$m, $M_D$ could be as small as the size of the weak scale (of the order of 1 TeV) and its effect could be visible at present colliders.

At HERA, after summing the effects of gravitons excitations in the extra-dimensions, the graviton contribution could be visible as a contact interaction contributing to the $q\bar{q} \rightarrow q\bar{q}$ scattering. The effect could therefore be visible in the DIS neutral current cross-section, introducing terms of the form $g_G = \lambda M_S^4$ to the SM lagrangian, where $M_S$ is an ultraviolet cutoff scale, of the order of $M_D$, and $\lambda = \pm 1$. The ZEUS experiment has presented new results based on the same sample of data as used in Fig. 8.

As the cross-section shows good agreement with the SM prediction versus $Q^2$, limits on the scale $M_S > 0.88$ TeV, $\lambda = +1$ and $M_S > 0.86$ TeV, $\lambda = -1$ were derived.

At Tevatron (or LHC), gravitons can be produced directly in processes like $q\bar{q} \rightarrow gG$, $qg \rightarrow qG$, $gg \rightarrow gG$ and escape unde-
ected in the bulk of extra-dimensions, leaving a signature of a single energetic jet and large missing transverse energy. CDF has looked for this monojet signature in 1.1 fb$^{-1}$ of data. Spectacular events like monojets with a transverse energy of 384 GeV and missing $E_T$ of 390 GeV are found. However the number of candidate events is in agreement with the expectation of the SM background, which is expected mainly from $Z + jets$ production, with the $Z$ decaying in $\nu\bar{\nu}$. CDF set therefore limits on the scale $M_D$ as a function of the number of extra-dimensions $n$, which are shown in Fig. 9. For $n = 2, 3$, the most stringent limit on the scale (up to 1.6 TeV) is set by the LEP combined result, derived from searches for events with single photon and missing energy. For $n \geq 4$, CDF sets the most stringent limit, up to $M_D \approx 1$ TeV.

The zeroth KK mode remains massless and couples with the SM fields with gravitational strength, while the excited modes couple with a strength which depends on the curvature parameter $k$ and the scale $M_{Pl} = M_{Pl}/\sqrt{8\pi} (k/M_{Pl})$, which is expected to be between 0.01 and 0.1) and decay as narrow resonances in fermion-antifermion or diboson pairs. Both CDF and D0 have performed a search for the first excited mode of the KK graviton, looking for narrow resonances in $ee, \mu\mu$ in the dielectron and diphoton spectra. Both the diphoton and the dilepton spectra are in agreement with the SM expectations. The derived limits on the graviton mass as a function of the coupling $k/M_{Pl}$ are shown in Fig. 10. For $k/M_{Pl} = 0.1$ limits on the first excited mode of the graviton up to 875 (865) GeV for CDF (D0) are set. For $k/M_{Pl} = 0.01$, the limit on the RS graviton mass is around 230 GeV.

In the Randall-Sundrum (RS) model, gravity propagates in one extra-dimension, which is highly curved (‘warped’). The RS relationship between the weak and the Planck scales is given by $M_W = e^{-2kR} M_{Pl}$. In the model gravitons appear as Kaluza-Klein (KK) tower of massive excitations and can be resonantly produced in $pp$ collisions.

![Fig. 9. Limits on the scale of the compactified large extra dimensions as a function of the number of extra-dimensions. The CDF results from Run II data (1.1 fb$^{-1}$) are compared to limits from D0 in Run I and from LEP. The LEP limits are extracted in a search for events with single photon and missing energy.](image)

![Fig. 10. Limits at 95% C.L. on the mass of the first excited state of the graviton in the Randall-Sundrum model, as a function of the dimensionless coupling $k/M_{Pl}$ of the model. The results from CDF correspond to a combined limit in a search in $\gamma\gamma$ final states with $\approx 1.1$ fb$^{-1}$ and in $e^+e^-$ final states with $\approx 0.8$ fb$^{-1}$. The D0 results are from a combined limit from $\gamma\gamma$ and $e^+e^-$ final states with 1.1 fb$^{-1}$.](image)
4.2. Search for $Z'$ and $W'$ at Tevatron

Many extensions of the Standard Model predict new heavy objects decaying to electron pairs, like new heavy bosons $Z'$. The generic search for resonances decaying into $e^+e^-$ just described in the previous section can also then be applied to searches\cite{20} for spin-1 objects, like the $Z'$. The dielectron mass spectrum in the CDF data is shown in the range from 50 to 500 GeV in Fig. 11. The search for new narrow resonances is done up to $>\simeq 900$ GeV, but there are no events observed outside the scale of the plot, with the highest mass candidate having a mass of 491 GeV. The spectrum is perfectly reproduced by the SM contributions, mainly Drell-Yan production. Assuming that the $Z'$ couples to the electrons in the same way as the Standard Model electroweak $Z$ boson, CDF set a limit on the $Z'$ mass of 850 GeV. At the LHC, a new heavy boson $Z'$ with a mass of 1 TeV could be discovered in the decays in $ee,\mu\mu$ with the first 0.1 fb$^{-1}$ accumulated.

![Di-Electron Invariant Mass Spectrum](image)

Fig. 11. Invariant mass of electron pairs in the CDF Run II data, compared to the SM expectation.

The D0 Collaboration\cite{21} has searched instead for new heavy charged gauge bosons, $W'$. The new $W'$ is supposed to have the same couplings to the fermions as that of the SM $W$ and to have a width scaling with its mass. The new decay channel $W' \rightarrow WZ$ is assumed to be suppressed and new heavy leptons are assumed to be too heavy to be produced by a $W'$. With these assumptions, the search is performed in the $W' \rightarrow e\nu$ channel. Events with a central electron with transverse energy of at least 30 GeV and large missing transverse energy are selected. The transverse mass spectrum of the sample is shown in Fig. 12 in the range up to 800 GeV. The spectra is well described by the various SM backgrounds, the main contribution being events from the Standard Model $W$ production, $W \rightarrow e\nu X$. For a transverse mass above 150 GeV, 630 events are observed for an expectation of 623. D0 set therefore limits on the $W'$ production, excluding its mass up to 965 GeV.

![Transverse Mass $m_T$](image)

Fig. 12. Transverse mass in the electron channel in the D0 Run II data, compared to the SM expectation. The possible signal from a $W'$ of mass of 500 GeV is also shown.

5. Isolated lepton events at HERA

Since 1994, the H1 Collaboration at HERA has observed particular events, characterized by a high $p_T$ lepton (electron/positron or muon), an hadronic system $X$ with high transverse energy $P_T^X$ and high missing transverse momentum. One of these events is shown in Fig. 13. These events are expected in the SM from $W$-production, where
the $W$ is radiated from the incoming quark and decays in an electron or muon and neutrino, giving the topology mentioned above. The $P_X^T$ distribution for the H1 1994-2006 data is shown in Fig. 14, which shows in general agreement between the data and the SM prediction, which is dominated by $W$-production. However it can also be seen that at high $P_X^T$ there is a clear excess of observed events.

The number of events at high $P_X^T > 25$ GeV, observed and expected by H1, is reported in Table 1 separated in the $e^+p$ and in the $e^-p$ datasets. It is clearly observed that the excess is in the positron-proton collisions: in total H1 observes in $e^+p$ 15 events with an expectation of $4.6 \pm 0.8$, which is a $3.4 \, \sigma$ excess. The effect is reduced to $2.6 \, \sigma$ taking into account also the ZEUS events 23, where a good agreement with the SM is observed in both channels, $e$ or $\mu$, and in both datasets (see table). If the rate of these events would remain constant in H1, a $4.5 \, \sigma$ effect could be reached with additional 100 pb$^{-1}$ of $e^+p$ data. HERA has just restarted to collide positron and protons and plans to continue until March 2007 in order to collect the required amount of data. The last months of HERA data-taking, until June 2007, will instead be devoted to a low energy run to measure the longitudinal structure function.

In view of the discrepancy between the two experiments, recently 24 the H1 and ZEUS Collaborations have compared their efficiencies for a benchmark process for this type of topology, the $W \to e\nu, \mu\nu$ processes. An example is shown in Fig. 15 where the acceptances for ZEUS and H1 are shown as a function of the polar angle of the final state electron (for the muon channel, it is very similar). The main differences in the two analyses is actually in the range of this polar angle: as it can be seen it is restricted in ZEUS, compared to H1. However, in the region where they overlap, the two efficiencies are very similar. In addition most of the interesting events in H1, shown by the arrows in the plot, lie in the region of common acceptance. The ZEUS experiment plans to increase the efficiency also in the forward region, where most of the decay products of the $W$ lie, as shown by the dotted curve, and where new physics is expected.
6. Summary

No convincing sign of new physics was reported at this conference. Tevatron did not confirm special events found in Run I: they have just started the second part of their Run II program (Run IIb) and approximately 4 ÷ 8 pb⁻¹ are expected until 2009. HERA has just started the last part of the HERA II run and expects to collect > 100 pb⁻¹ of e+ p collisions until the end of HERA data-taking, which will be end of June 2007. This amount of integrated luminosity should be sufficient to give a definite answer on the isolated leptons events observed by H1. Finally we are all waiting eagerly for the start of LHC.

Acknowledgments

I would like to thank the organizers for the invitation to give this talk and the Tevatron, HERA, LHC and LEP colleagues who helped me in the preparation. Special thanks go to Emmanuel Perez and Cristinel Diaconu (H1), Beate Heinemann (CDF) and Jean-Francois Grivaz (D0) for providing me the information from their experiments and for their precious comments.

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