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Beyond the Standard Model Searches

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We present a review of the experimental searches for physics beyond the Standard Model, presented at ICHEP 2010.

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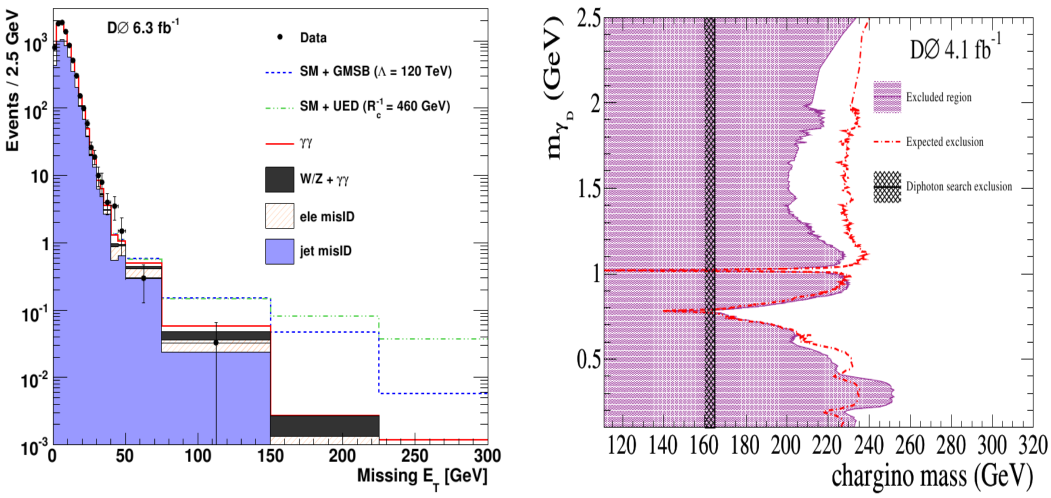
1. Introduction

Remarkable success of the standard model (SM) makes one wonder how a model, known to be incomplete, could describe so well all known data on particle interactions. On the other hand, this knowledge gives a very strong motivation to searches for physics beyond the standard model (BSM). We know it should exist and finding it is just a matter of time. In this writeup we briefly summarize status of the experimental searches for BSM physics presented at the conference.

2. Searches for the Supersymmetry

One of the most promising and explored extensions of the SM is the supersymmetry (SUSY) [1]. Minimal supersymmetric extention, the MSSM, includes partners of all the SM particles and two Higgs doublets. To avoid contradictions with the experimental limits on the proton lifetime, "standard" SUSY assumes R-parity conservation.

Phenomenology of a particular SUSY model depends on the SUSY breaking mechanism. In models with gauge-mediated symmetry breaking (GMSB) the lightest stable particle (LSP) is a gravitino $\tilde{G}$, with $M_{\tilde{G}}$ being in a KeV range. If the next lightest SUSY particle is a neutralino $\tilde{\chi}_1^0$, the gaugino pair production can cascade to $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}$ leading to a final state with two photons and large $\not{E}_T$. D0 collaboration performed a search for GMSB SUSY in this final state [2]. Fig. 1(a) shows distribution in $\not{E}_T$ for $\gamma\gamma$ candidate events observed in 6.3 $fb^{-1}$of data. The data distribution in $\not{E}_T$ agrees well with the predicted background and, assuming zero $\tilde{\chi}_1^0$ lifetime, results in a 95% CL limit on the $\tilde{\chi}_1{}^0$ mass $M(\tilde{\chi}_1{}^0) > 175$ GeV/c^2



(a) Distribution in $\not{E}_T$ for $\gamma\gamma\not{E}_T$ events from [2]. (b) Limits on the gaugino mass versus m_{γ_D} from [8]

Figure 1:

Due to mixing in the squark sector, the 3rd generation bottom squark, $\tilde{b}$, could be light enough to have mass within the reach of the current collider experiments. Strong pair production of b-squarks, $p\bar{p} \rightarrow \tilde{b}\bar{\tilde{b}}$, followed by the squark decays $\tilde{b} \rightarrow b\tilde{\chi}_1{}^0$ into the LSP neutralino and the bottom quark would produce final states wth two b-jets and large $\not{E}_T$. D0 experiment searched for the $\tilde{b}$

production in this final state and, assuming B($\tilde{b} \to b\tilde{\chi}_1{}^0$) = 100% and $M_{\tilde{\chi}_1{}^0} = 0$ set a lower limit on the $\tilde{b}$ mass $M_{\tilde{b}} > 247$ GeV$/c^2$[3].

2.1 Hidden Valley Models

"Hidden valley" models [4] represent a special class of SUSY-inspired models, where unlike in the "standard" SUSY, the hidden sector particles have low masses. These models attracted significant interest in conjunction with several recent cosmic ray experiments [5, 6], which results could be attributed to the annihilation of the dark matter particles into a pair of new light gauge bosons, the dark photons [7]. The dark photons could decay into the SM fermions via mixing with photons. D0 collaboration performed a search for the dark photons γ_D, assuming they are produced in decays of the SUSY gauginos and decay into a e^+e^- or $\mu^+\mu^-$ pair [8]. No signal corresponding to the dark photon production has been observed. Limits on the gaugino mass plotted versus the dark photon mass m_{γ_D} are shown in Fig. 1(b).

3. Non-SUSY searches

In this section we review searches for new physics motivated by the theoretical models based on symmetries different from SUSY.

3.1 Heavy Gauge Bosons

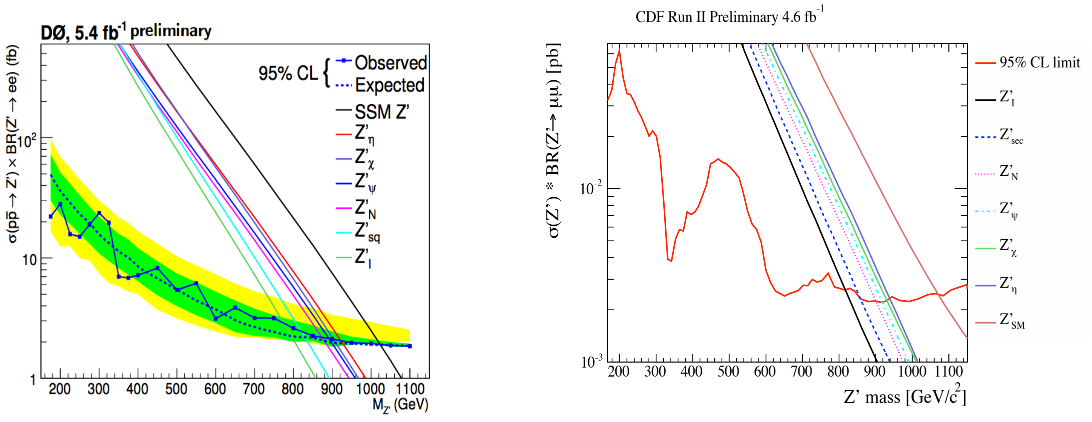
Extending the SM symmetries with an additional U(1) group results in a new particle state with the quantum numbers of the Z boson, the Z' boson (for an excellent review see [9]). Over the last decade, heavy Z' bosons have been extensively searched for experimentally. The most stringent limits come from the searches for $Z' \to l^+l^-$ decays by the Tevatron experiments, CDF and D0 [10, 11]. Results of these searches are shown in Fig.2. Z' boson couplings to the SM particles depend on the choice of a theoretical model, which makes experimental limits on the Z' boson mass also model-dependent. The best limit on the mass of a sequential Z' boson with SM-like couplings to leptons and quarks, is $M_{Z'} > 1071$ GeV$/c^2$[10].

The CDF collaboration has also searched for the Z' boson decays into a $t\bar{t}$ pair, predicted by the topcolor models[12]. Assuming narrow Z', $\Gamma_{Z'} = 0.012 M_{Z'}$, the search excluded Z' masses $M_{Z'} < 900$ GeV$/c^2$ [13] .

States with the quantum numbers of the W boson, W' bosons, arise in models with additional $SU(2)_L \times SU(2)_R$ symmetries [14]. Search for a heavy W' in the $W' \to WZ \to 3l + \nu$ decay mode, performed by the D0 collaboration, at 95% CL excludes W' masses in the range of [188 GeV$/c^2$, 520 GeV$/c^2$] [15].

3.2 Heavy Quarks

Although measurement of the Z boson width limits number of the lepton generations with light neutrinos to three [16], the 4-th generation of fermions is not theoretically ruled out. If the mass splitting between the 4-th generation quarks, t' and b', is small such that $M_{t'} - M_{b'} < M_W$, the branching ratio $B(t' \to Wq) = 100\%$. Searches for the pair-produced heavy t' quarks in $W^+W^-q\bar{q}$



(a) D0 limits on $\sigma(p\bar{p} \to Z' \to ee)$ from [11] (b) CDF limits on $\sigma(p\bar{p} \to Z' \to \mu\mu)$ from [10]

Figure 2: Results of $Z' \to l^+l^-$ searches

channel have been carried out at the Tevatron. The current best limit on the t' mass, $M_{t'} > 335$ GeV/c^2 at 95% CL, has been set by the CDF collaboration [17].

For a 4-th generation b' quark which is lighter than the t', the dominant decay mode would be $b' \to Wt$. Pair production of the b' quarks in $p\bar{p}$ collisions, $p\bar{p} \to b'\bar{b}' \to WWWWb\bar{b}$, would result in the final states with four W bosons. A search for such final states by the CDF collaboration results in a 95% CL limit on the b' quark mass $M_{b'} > 385$ GeV/c^2[18].

3.3 Extra Dimensions

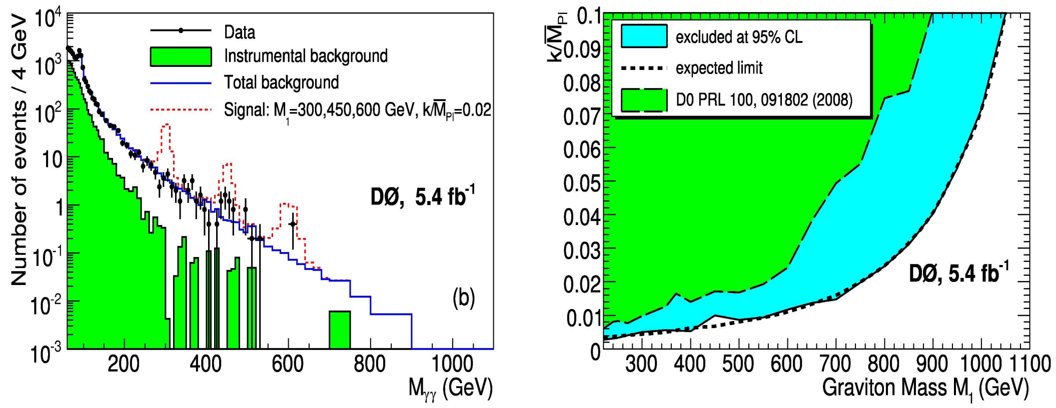
Models with extra space dimensions [19, 20] provide alternative to SUSY mechanism of solving the hierarchy problem. Models of warped extra dimensions [20] predict Kaluzza-Klein (KK) excitations of the graviton, G^*, with masses at TeV scale and coupled to the SM particles. The lowest KK states would manifest themselves as narrow peaks in the invariant mass distributions of their decay products. The dominant decay modes of the Randall-Sundrun (RS) graviton are $G^* \to \gamma\gamma$ and $G^* \to l^+l^-$. Fig. 3 shows results of the RS graviton search in $G^* \to e^+e^-$ and $G^* \to \gamma\gamma$ final states performed in [21] by the D0 collaboration using 5.4 fb^{-1} of data. Combined analysis of the invariant mass spectra $M_{e^+e^-}$ and $M_{\gamma\gamma}$ at 95% CL excludes graviton mass $M_{G^*} < 1050$ GeV/c^2, assuming universal coupling to the matter $k/\bar{M}_{Pl} = 0.1$

3.4 Search for the Proton Decay

Finite proton lifetime is a distinct feature of the grand unified theories [26]. Super-Kamiokande collaboration searched for nucleon decays using full set of data corresponding the total exposure of 173 kton·year [27]. Lower 90%CL limits on the proton lifetime are $1.0 \cdot 10^{34}$ years in the $p \to e^+\pi^0$ mode, and $3.3 \cdot 10^{33}$ years in the $p \to \bar{\nu}K^+$ mode. A limit of 10^{34} years for a single decay mode has been reached for the first time.

4. Searches at HERA

Although HERA accelerator has stopped running in 2007, ZEUS and H1 collaborations con-

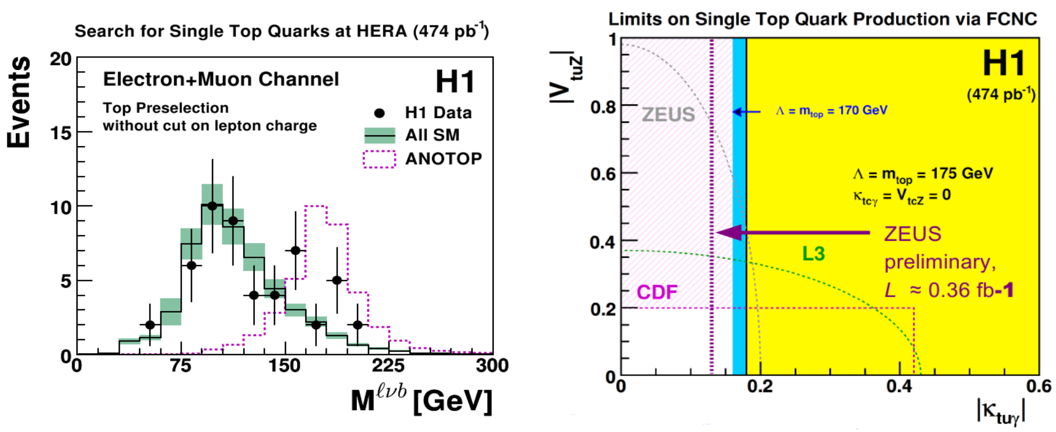


(a) Distribution in the diphoton invariant mass, $M_{\gamma\gamma}$

(b) G^* mass exclusion region as a function of the graviton coupling $k/\bar{M}_{Pl}$

Figure 3: Results of the RS graviton search by the D0 collabortion [21]

tinue to analyse the collected data. In many cases searches at HERA are complementary to the searches at the Tevatron. Using 474 $pb^{-1}$of ep collision data, H1 experiment searched for anomalous single production of the top quark which could occur via flavor changing neutral currents (FCNC) [29]. Observed agreement between the data and the expected contributions of the SM processes (see Fig. 4(a)) translates into a 95% CL limit on the single top production cross section in ep collisions of $\sigma(ep \to etX) < 0.25$ pb at $\sqrt{s} = 318$ GeV and on anomalous FCNC top quark coupling $K_{tu\gamma} < 0.18$, shown in Fig. 4(b).



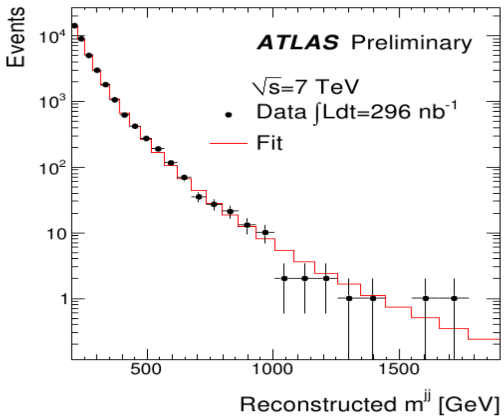
(a) Distribution in the reconstructed invariant mass of a top candidate

(b) Limits on the anomalous top quark couplings

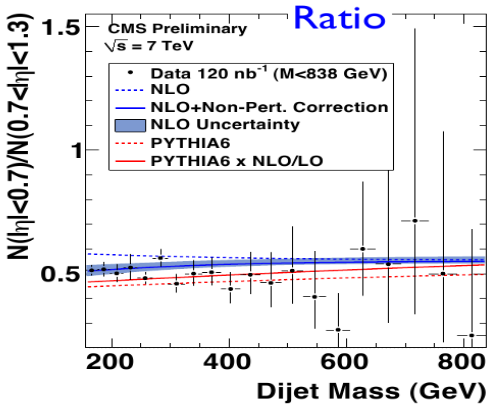
Figure 4: Results of the search for single top production by the H1 Collaboration [29].

5. First Searches at LHC

First searches at LHC explore channels where increase in the $\sqrt{s}$ provides sensitivity to new physics even with very small datasets. Using first 296 nb^{-1} of data collected at $\sqrt{s} = 7$ TeV, ATLAS collaboration searched for narrow resonances decaying into dijets [22]. Shown in Fig. 5(a) distribution in the dijet invariant mass M_{jj} doesn't have statistically significant deviations from the predicted background. Interpretation of the results in the framework of the excited quark model [23] allows to exclude excited quarks with masses in the range [400 GeV/c^2, 1290 GeV/c^2]. This preliminary result improves the best published limit on the excited quark mass $M_{Q^*} > 870$ GeV/c^2 by the CDF experiment [24].



(a) M_{jj} spectrum by the ATLAS experiment [22]



(b) dijet centrality ratio vs M_{jj} by the CMS experiment [25]

Figure 5: Dijet searches at LHC

Angular distributions of the produced jets are also a sensitive probe of new physics: compared to QCD production, new heavy particles decaying into two jets are expected to produce jets with more central rapidity distributions. To search for this effect, CMS collaboration defined so-called jet centrality ratio, $N_{|\eta|<0.7}/N_{0.7<|\eta|<1.3}$. $N_{|\eta|<0.7}$ is a number of dijet events in which both jets are central and have pseudorapidity $|\eta| < 0.7$, and $N_{0.7<|\eta|<1.3}$ is a number of events in which both jets have pseudorapidity $0.7 < |\eta| < 1.3$. Distribution in the jet centrality ratio observed by the CMS collaboration in 120 nb^{-1} of data [25] is shown in Fig. 5(b) as a function of M_{jj}. CMS result at 95% CL excludes contact interactions with scale $\Lambda < 1.9$ TeV.

Heavy long-lived or stable charged particles arise in multiple extentions of the SM [30]. One of the most popular scenarios is a hadronization of a stable gluino into a massive charged R-hadron. If lifetime of such hadron is large enough, it could leave the detector behaving like a muon with anomalously large ionisation in the tracking system. CMS search for anomalously ionising particles resulting from the gluino hadronisation sets a 95% CL lower limit on the gluino mass $M_{\tilde{g}} > 284$ GeV/c^2[31].

6. Summary

So far, we continue to improve our knowledge of physics beyond the standard model only by setting better, more stringent, limits on the new processes, further and further expanding region of the phase space where new physics doesn't exist. Experimental data, inconsistent with the standard model, are yet to be found.

Most of the current limits on new physics are currently set by the Tevatron experiments. However, the year of 2010 is marked by the LHC startup. LHC experiments have demonstrated impressive readiness for physics. They are producing first physics results, and collider searches for new physics have moved to a competely new energy frontier of $\sqrt{s} = 7$ TeV.

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