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Exotic (non-SUSY) Searches at the LHC

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New studies on exotic (non-SUSY) searches beyond the Standard Model are reviewed, which include contact interactions using jet p_T spectrum, leptoquark production, signals for new gauge bosons and extra dimensions, monojet events expected in ADD extra dimension scenarios, 4th generation quarks, and heavy stable charged particles [1]. Emphasis is given to the potential for early discoveries at the LHC, e.g., within the first year of physics data taking.

1 Introduction

Despite its amazing agreement with experimental data, there are theoretical indications and experimental evidence suggesting that the SM is only a low energy effective theory of a more fundamental theory. There are many intriguing questions we could ask ourselves about the SM. Are the quarks or leptons fundamental particles? Is the SM gauge symmetry a subset of an extended gauge symmetry? What is the nature of the electro-weak symmetry breaking (EWSB)? Almost every aspect of the SM has been extended to shed light on what could be the beyond-the-SM (BSM) theory. The extension of the SM gauge symmetry group has led the grand unification theory (GUT) of the electro, weak, and strong forces [2]. Several other GUT-inspired extensions were also discussed in the literature [3] [4]. So far the Higgs boson predicted in the SM has not been found experimentally. In addition to its existence, the Higgs mass suffers quadratic divergence due to the radiative corrections at one-loop level, the *hierarchy problem*. A possible solution to this problem is the Supersymmetry (SUSY). Other alternatives were also proposed, such as the little Higgs Model [5], Extra Dimensions [6] [7], Technicolor and extended Technicolor Models [8]. Many of these phenomenological models predict possible new physics at a TeV scale, which could be extensively explored at the LHC [9][a]. Both ATLAS [10] and CMS [11] have a 4π general-purpose hadron-collider detector, which is suitable for high-p_T physics studies at the LHC.

2 New Gauge Bosons

Experimentally the most studied Z' bosons are the ones predicted in the Sequential Standard Model (SSM), the Left-Right Symmetry Model (LRSM), and the E6 Model (Z'_χ, Z'_ψ, Z'_η) [4]. Direct searches for these gauge bosons at Tevatron set limits on the Z' mass from several hundreds GeV up to about 1 TeV [12] [13] [14]. Indirect constraints from electro-weak global analysis have also been undertaken by the LEP experiments [15]. The experimental signature of Z' bosons is a narrow resonance on top of the Drell-Yan mass spectrum. Both ATLAS [16] and CMS [17] [18] studied experimental sensitivities for the above models in both $Z' \to e^+e^-$ and $Z' \to \mu^+\mu^-$ decay channels. The overall trigger efficiency for signal events are over 90% for both CMS and ATLAS. The major background is the irreducible Drell-Yan

[a]Note that all studies discussed in this paper assume a 14 TeV center-of-mass energy.

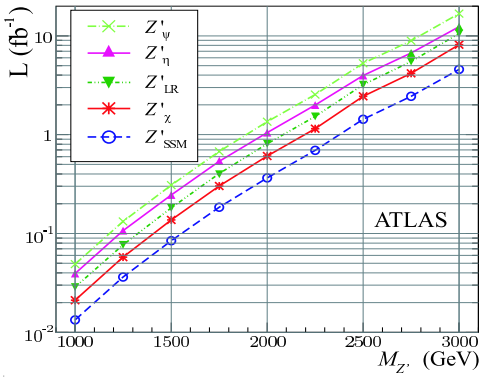

Figure 1: The required luminosity for 5σ discovery as a function of the Z' mass.

production. Others, such as QCD multijet events, W/Z+jets, SM diboson production, and $t\bar{t}$ also contribute. Figure 1 shows the required luminosity needed for a 5σ discovery of Z' $\rightarrow e^+e^-$ as a function of Z' mass. With less than 100 pb^{-1} of integrated luminosity, sensitivity beyond the Tevatron experiments could be achieved. The Z' $\rightarrow \mu^+\mu^-$ channel has very similar sensitivity. The CMS studies resulted in similar sensitivities as well.

Both ATLAS and CMS also studied experimental sensitivities to search for a W' bosons in the so-called extended SM model [19]. The leptonic final states, $W' \rightarrow \mu\nu$ and $W' \rightarrow e\nu$, were used in the study. The neutrino in the final state escapes detection and can only be inferred by the Missing Transverse Energy (MET). The experimental signature is a high-p_T lepton accompanied by large MET. The major background is QCD multijet events, W/Z+jets, and $t\bar{t}$ production. Both ATLAS [20] and CMS [21] studies obtained similar sensitivities. With about 100 pb^{-1} of luminosity, discovery is possible up to the W' mass of about 2.2 TeV. Current best experimental limit on the W' boson is $m_{W'} > 1$ TeV at 95% C.L. from the D0 experiment [22].

3 Extra Dimensions and Black Holes

The Arkani-Hamed, Dimopoulos, Dvali (ADD) model was suggested to solve the hierarchy problem between the electro-weak scale and the Planck scale by introducing a number δ of Extra Dimensions (ED) [6]. In the simplest scenario all the EDs are compactified over a torus and have the same radius R. The fundamental scale M_D is related to the M_{planck}, $M^2_{planck} = 8\pi M_D^{\delta+2} R^{\delta}$. If the scale M_D is of the order of TeV, light Kaluza-Klein gravitons can be directly produced at LHC, $q\bar{q} \rightarrow gG$, $gg \rightarrow gG$. Gravitons interact weakly with ordinary matter, therefore they escape detection and can only be inferred from the MET. The most stringent limits on the scale M_D range from 0.83 TeV up to 1.6 TeV at 95% C.L, depending on the number of EDs [23] [24]. CMS conducted a search for EDs with jet + MET final states. With 100 pb^{-1}, 3σ evidence could be achieved for M_D of 3.58 TeV (2.62 TeV) for $\delta = 2(4)$. In the absence of EDs, one could push the current experimental limits on the M_D for $\delta = 2$ or 4 by a factor of three higher [25].

If the scale M_D is low enough, Black Holes (BHs) could be produced at LHC [26]. BHs decay to all SM particles and have event signature of high multiplicity and spherical event shape. ATLAS conducted a search for BHs. In this study, the classical BH cross-section at parton level is given by $\hat{\sigma}_{qq' \rightarrow BH} = \pi r_h^2$, where r_h is the so-called horizon radius [27]. The production cross section for a BH with mass range between 5-14 TeV is at the order of 10 pb. The scaler summation of the p_T of each object in the event was used to distinguish the BH events from SM processes. A BH with mass > 5 TeV threshold could be discovered with only a few pb^{-1} of integrated luminosity [28].

4 Alternatives to Electro-Weak Symmetry Breaking Mechanism

Strongly interacting theories, such as the Technicolor and the extended Technicolor, provide a dynamical solution to the EWSB. ATLAS performed a search for the techni-rho (ρ_{TC}) and techni-omega (ω_{TC}) proposed in Technicolor Strawman Model [29] via the dimuon final states. This process has the same final states as the Z' decays and similar analysis techniques were used. The study showed that with less than 5 fb^{-1} of integrated luminosity, the ρ_{TC} and ω_{TC} with mass up to 1 TeV can be discovered [16]. The current best limits on these technifermions were given by the CDF collaboration [30].

In the absence of a light Higgs boson, the mechanism of EWSB will be best studied in the processes of vector boson scattering (VBS). Several models predicted the presence of new vector or scalar boson resonances at TeV scale [31]. The Chiral Lagrangian model with Pade unitarisation provides a framework to study the VBS at high mass. ATLAS has performed a search for these vector and scalar WW, WZ, or ZZ resonances via lepton+2jet+MET, or dilepton+dijet, or dilepton+MET final states. The discovery of resonances in VBS at high mass will take a few tens of fb^{-1} [32].

5 4th-generation, Excited Quarks, and Lepto-Quarks

A 4th-generation of massive fermions with the same quantum numbers as the known SM fermions has been actively searched for in high-energy experiments. The direct searches for the 4th-generation t' set the limit $m_{t'} > 311$ GeV at 95% C.L. by the CDF experiment [33]. The experimental sensitivity to search for a b' has studied by the CMS experiment. In this study, it was assumed that the mass of the b' is above the threshold of $b' \to tW$ decay, therefore the dominated process is $pp \to b'\bar{b'} \to t\bar{t}W^+W^-$. With 100 pb^{-1} of luminosity, more than 5σ significance can be achieved for a b' of mass 300 GeV. With the same luminosity, in the absence of b' signal events we can set the mass limit of the b' up to 450 GeV at 95% C.L., as shown in Fig. 2 [34].

In addition to searches for 4th-generation, CMS also conducted an analysis to search for excited quarks. In quark compositeness quarks can be excited to higher energy state by absorbing gluons and subsequently decay into quark-gluon final state, $qg \to q^* \to qg$. The dijet invariant mass spectrum were used to extract the possible signal. Figure 2 shows the fractional difference of different excited quarks from the purely QCD predictions of dijet mass spectrum. With less than 10 pb^{-1} of luminosity, a 2 TeV excited quark could be discovered [35]. The current limit on the excited quark is > 0.87 TeV at 95% C.L. from the D0 experiment [36].

Leptoquarks (LQ) are hypothetical particles motived to explain the apparent symmetries between leptons and quarks [37]. The LQs carry both quark and lepton quantum numbers. There are experimental limits favoring three generation of LQs, therefore each LQ decays to a lepton and a quark from the same generation. At LHC, LQs can be produced either strongly or in association with a lepton via the LQ-quark-lepton coupling. The pair production cross section of LQs at LHC, $pp \to LQ\ LQ$, is about 2 pb for a LQ with mass of 400 GeV [38]. ATLAS studied the experimental sensitivities for the first and second generation LQs in the dilepton + dijet final state. With less than 100 pb^{-1} of luminosity, both 1st and 2nd generation scalar LQ pair production could be discovered, provided that the mass of the LQs is smaller than 500 GeV [39]. Experimental limits on the LQs are about 200-300 GeV at 95% C.L., depending on the branching fraction of the $LQ \to lq$ decay [40].

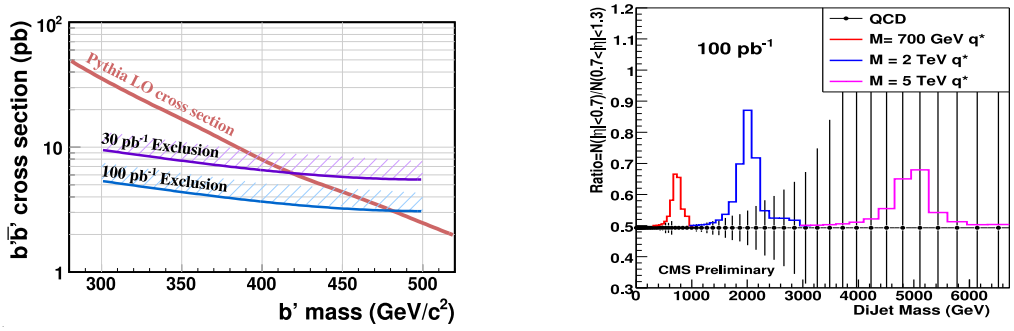

Figure 2: Left: the exclusion limits at the 95% C.L. on the $pp \to b'\bar{b}'$ production. Right: dijet resonance production compared to that in QCD.

6 Contact Interactions

New physics like quark compositeness or new interaction at a high scale (Λ) can be modeled as a contact interaction at much lower dijet mass or jet p_T. Such interactions can manifest as a large rate of jet production in the high-p_T region. CMS studied the sensitivity to contact interactions using the leading jet p_T spectrum [35]. The study showed that with less than 10 pb^{-1} of luminosity, CMS has access to Λ above the current experiment limit $\Lambda > 2.7$ TeV at 95% C.L. from the D0 experiment [41].

7 Heavy Stable Charged Particles

Heavy Stable Charged Particles (HSCPs) are predicted in many BSM physics models. Such particles can be distinguished from SM particles by exploiting their unique signature: a low velocity, β, associated with a high momentum of order of a few hundreds GeV. CMS studied the physics potential of searching for HSCPs using stau in Gauge Mediated Supersymmetric Breaking, KK-states in ED, gluino in split-SUSY, and supersymmetric top as benchmarks. The dE/dx in the CMS tracking system and the timing information in the CMS Barrel muon system were both used to reconstruct the β^{-1}. The study showed that HSCPs can be discovered with early data for different models and in different mass regions. The Stable gluino search with 1 fb^{-1} is sensitive to gluino masses above 1 TeV and the GMSB scenarios with stable stau can be discovered with a few pb^{-1} [42].

8 Summary

In summary, there is a very rich and exciting exotic physics program at LHC probing many fundamental aspects of the nature. With as little as 100 pb^{-1} of integrated luminosity at 14 TeV we could largely extend current experimental limits in searches for new gauge symmetry groups (W'/Z' bosons), Extra Dimensions, 4th generations, excited quarks, lepto-quarks, etc. Nature could come up with a surprise and new physics at TeV scale could be discovered with early LHC data.

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