BEYOND THE STANDARD MODEL SEARCHES AT THE LHC

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This report presents recent results from studies of Beyond the Standard Model physics at the LHC. A focus is placed on heavy gauge bosons, electroweak symmetry breaking and left-right symmetry.

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1. Introduction
There are many questions left unanswered by the Standard Model (SM) of particle physics. Many of these revolve around the concept of symmetries. In this report, the focus is on recent studies of the prospects for Beyond the Standard Model searches at the Large Hadron Collider (LHC). Studies in the context of SUSY, Extra-Dimensions and Black Holes are reported elsewhere in these proceedings.

2. Heavy Gauge Bosons
The SM is an extremely successful gauge theory based on the symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. Local gauge invariance requires the existence of vector bosons mediating the strong and electroweak forces: the gluons, photon, W and Z bosons. Many extensions of the SM predict the existence of additional gauge bosons resulting from enlarged symmetry groups. For example, $E_6$-based theories predict the existence of additional $U(1)$ groups originating from the breaking of $E_6$ into subgroups, eventually breaking down to the SM group at low energy. New heavy gauge bosons are generically referred to as $W'$ and $Z'$ bosons. These are also predicted in theories with extra dimensions in the form of Kaluza-Klein excitations of the electroweak bosons or gravitons.

The ATLAS and CMS Collaborations have studied the potential for $Z'$ discovery in the $\ell^+\ell^-$ channel (either $e^+e^-$ or $\mu^+\mu^-$). Dileptons are selected from pairs of isolated electrons or muons to reduce background from fakes. Isolation criteria for muons typically rely on tracking only and do not include energy from the calorimeters since high-momentum muons tend to lose significant amounts of energy via bremsstrahlung inside the calorimeter. As an example, the reconstructed di-electron invariant mass distribution for a 3-TeV Sequential Standard Model (SSM) $Z'$ in CMS is shown in Fig. 1.

In the SSM, $Z'$ bosons couple to fermions with the same couplings as SM $Z$ bosons. A very clear peak is observed over a smooth background consisting primarily of dileptons.
from the Drell-Yan process \( q \bar{q} \rightarrow \gamma^* \rightarrow \ell^+\ell^- \). An integrated luminosity of 0.1–1 fb\(^{-1}\) is required for a 5 \( \sigma \) discovery at \( M_{Z'} = 1 \) TeV, depending on the assumed model (SSM, \( E_6 \) or Left-Right symmetric models). An ultimate reach of \( M_{Z'} \sim 5 \) TeV is expected after several years of data taking at design luminosity (100–500 fb\(^{-1}\)).

Discrimination between various \( Z' \) models can be achieved by exploiting the fact that these models have different couplings between the \( Z' \) and fermions. Discriminating observables are: (i) the total width, which exploits differences in overall coupling strengths, (ii) the forward-backward asymmetry between positive and negative leptons relative to the initial quark direction, which exploits differences in parity-violating couplings (left- vs. right-handed couplings to final state leptons), (iii) the rapidity of the \( Z' \), which exploits differences in the couplings to the initial state up and down quarks. The total width observable is most useful for \( e^+e^- \)-final states since the momentum resolution is an order of magnitude worse for muons than for electrons at these very high momenta. Most powerful are the total width and the forward-backward asymmetry.

\( W' \) decays have been studied by CMS\(^1\) in the \( W' \rightarrow \mu\nu \) channel by combining an isolated muon with large missing transverse energy in the event. The discovery potential is similar to that for the \( Z' \) with an ultimate reach near 6 TeV for 300 fb\(^{-1}\).

3. Electroweak Symmetry Breaking

One of the most important goals of the LHC is to elucidate the origin of Electroweak Symmetry Breaking (EWSB). Two possibilities need to be considered. Either EWSB is due to a light Higgs boson or the Higgs boson does not exist and EWSB originates from a new kind of strong interaction. In the Higgs boson scenario one needs to cancel quadratic divergences due to quantum loop corrections to the Higgs mass, to avoid the well-known fine-tuning problem. The leading candidate for such a cancelation is Supersymmetry but “Little Higgs” models have also been proposed as an alternative.

The Littlest Higgs model\(^3\) studied by ATLAS\(^4,5\) predicts the existence of new heavy gauge bosons (\( A_H, W_H \) and \( Z_H \)) and a heavy \( q = +2/3 \) quark (\( T \)) required to cancel quadratic divergences in the Higgs mass due to quantum loop corrections involving SM gauge bosons and top quarks. For masses above 700 GeV, single-\( T \) production via the \( W \)-exchange reaction \( qb \rightarrow q'T \) dominates. The most promising decay channels are \( T \rightarrow tZ \) (with \( t \rightarrow b\ell\nu \)) and \( T \rightarrow bW \) (with \( W \rightarrow \ell\nu \)), for which a discovery is expected up to \( M_T = 1 \) and 2 TeV, respectively, with 300 fb\(^{-1}\). Heavy gauge bosons \( A_H, W_H \) and \( Z_H \) can be discovered via their leptonic decay modes with discovery potential up to about 5 TeV, depending on the mixing parameter \( \cot\theta \) between the two \( SU(2) \) gauge triplets of the model. However, to discriminate against the many models predicting dilepton resonances, one needs to also observe decay processes that are typical of Little Higgs models: \( W_H \rightarrow WH, Z_H \rightarrow ZH \) and \( W_H \rightarrow t\bar{b} \). The latter process is particularly important if \( \cot\theta \sim 1 \) since the first two modes are suppressed in that case. A study of the process \( W_H \rightarrow t\bar{b} \) with \( t \rightarrow b\ell\nu \) shows a clear signal excess over background (dominated by \( t\bar{t} \) production), see Fig. 2. Discovery of this decay mode is expected up to masses of 3 TeV, depending on \( \cot\theta \).

Another source of EWSB arises from theories of dynamical EWSB occurring via new strong interactions. In these theories there is no need for a Higgs boson, which removes the fine-tuning problem. CMS studied dynamical EWSB in the context of Technicolor\(^1\). In particular, the process \( p\bar{p} \rightarrow WZ \), with subsequent decay to a fully-leptonic final state, has been investi-
gated. After selection of isolated electrons and muons, measurement of the transverse missing energy and the application of W and Z kinematical constraints, an excess of signal events is observed above the background from WZ, ZZ, Zb over and t¯t production, for the parameters assumed in their study.

Without a Higgs boson, the cross section for scattering of longitudinally-polarized W bosons diverges at high energy, unless new physics contributes to cancel this divergence. Such new physics might manifest itself in the form of diboson resonances at the LHC. With this motivation, ATLAS studied dynamical EWSB in the general context of the Chiral Lagrangian model. In particular, WZ scattering has been investigated in the scattering process q′1 q′2 → q1 q2 WZ with the following combination of leptonic and hadronic final states from the WZ decay: ℓν ℓℓ, jj ℓℓ and ℓν jj. Events are selected with two forward jets, central leptons or jets and missing energy (depending on the particular WZ final state). For WZ final states involving jets, the event is required not to contain additional central jets and none of the jets can be identified as b-jets. The main background originates from quark-quark scattering via gluon and γ/Z exchange with the emission of both a W and a Z boson from the outgoing quarks. Other background processes are t¯t and W+4 jets. Initial studies indicate promising sensitivity for diboson resonances in the ~1 TeV mass region in final states including jets, for 100 fb–1.

A specific experimental issue for this study is the merging of jets from the decay of high-pT W or Z bosons, which requires running jet reconstruction with significantly smaller cones (ΔR = 0.2 instead of 0.7). Further work is also needed to investigate the impact of pileup on the forward jet tagging.

4. Left-Right Symmetry

Extensions of the Standard Model have been proposed that explicitly include a left-right symmetry. Such extensions aim to explain the existence of pure left-handed charged weak interactions (at low energy) via a spontaneously broken parity. They also provide a natural explanation for light neutrinos by incorporating heavy right-handed neutrinos, thereby accommodating light left-handed neutrinos via the see-saw mechanism. The left-right symmetric model based on SU(2)L ⊗ SU(2)R ⊗ U(1)B−L features a triplet (Δ0, Δ+, Δ++) and two doublets of Higgs scalar fields, and predicts new gauge bosons (WR and ZR) and neutrinos (νR).

ATLAS studied7 the striking signal expected in quark-quark scattering with the emission of two W+ bosons fusing into a doubly-charged Δ++ Higgs which then decays into a pair of like-sign leptons. The selection requires the presence of two forward jets and two like-sign electrons, muons or taus. Main background sources originate from quark-quark scattering with emission of a W+ boson from each quark, as well as Wt production. The discovery for Δ++ produced in this mode reaches up to ~2 TeV for low enough WR masses, with 300 fb–1.

ATLAS also studied the pair production of ΔR,LΔR,L in q¯q annihilation via virtual γ/Z/ZR,L. In this case, a very clean four-
lepton signature is expected and the background is negligible. The doubly-charged Higgs boson discovery reach, defined as the observation of 10 signal events, is shown in Fig. 3.

CMS also studied the left-right symmetric model with a search for $W_R$ and $\nu_R$. These states are produced via $q\bar{q} \rightarrow W_R \rightarrow \ell\nu_R$ and $q\bar{q} \rightarrow Z_R \rightarrow \nu_R\bar{\nu_R}$, with $\nu_R \rightarrow \ell jj$. Events are selected with at least two isolated electrons and at least two jets. A clean $W_R$ signal is observed in the $eejj$ mass distribution for $M_{W_R} = 2000$ GeV and $M_{\nu_R} = 500$ GeV, see Fig. 4.

5. Summary and Outlook

ATLAS and CMS are gearing up for data taking at the energy frontier when the LHC begins operations at $\sqrt{s} = 14$ TeV in 2008. Both experiments have significant discovery potential in areas related to fundamental symmetries. In particular, the discovery reach is up to $\sim 5$-6 TeV for heavy gauge bosons, $\sim 2$ TeV for the heavy top quark in Little Higgs models, $\sim 600$ GeV for the $\rho_{TC}$ technihadron, $\sim 2$ TeV for doubly-charged Higgs bosons and $\sim 2.5$ TeV for heavy neutrinos.

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