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Prospects for Exotic Physics at the LHC

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Abstract: The sensitivity of the ATLAS experiment to extra dimensions, excited quarks and leptons, new gauge bosons, charged heavy leptons, lepton flavour violation and strong symmetry breaking is discussed. Finally, a brief summary of the extended potential of an upgraded LHC will be presented.

Keywords: extra dimensions, excited quarks, new gauge bosons, heavy leptons.

1. Introduction

The LHC will offer a large range of physics opportunities due to the high energy, $\sqrt{s} = 14\ TeV$, and luminosity, $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$. The ATLAS physics programme is well documented in [1, 2]. Searches beyond the Standard Model are among the important goals of the ATLAS experiment. Details will not be discussed in this document, but a few representative processes will be discussed and a large list of references will be included.

Signatures involving jets or photons in conjunction with missing transverse energy are considered as a signal for theories of large extra dimensions. The determination of the parameters, number of extra dimensions and scale of the new physics, is discussed. Models of warped extra dimensions lead to heavy narrow spin-2 resonances. The possible observation of these resonances in leptonic final states is also discussed and determination of the spin is shown to be possible. Excited quarks and leptons should be observable in different channels, if they exist, up to masses of about 7 TeV. New gauge bosons can be discovered up to masses of 6 TeV. In the context of left-right symmetric models, the existence of right-handed W and heavy Majorana neutrinos can be assessed up to a few TeV and charged heavy leptons can be discovered up to masses of 1.1 TeV. Resonances in the WZ channel, either from the presence of a W', or as predicted in technicolor-like scenarios, can be observed at the TeV scale. A summary of the potential of an upgraded LHC will be discussed.

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2. Extra dimensions

2.1 Large extra dimensions

If the compactification scale (R) of the additional dimensions is large enough, the fundamental scale of gravity (Planck scale) is reduced to a scale M_D close to M_W [3], thus solving the hierarchy problem between these energy scales. Because $G_N = 8\pi R^\delta\ M_D^{-(2+\delta)}$, if $M_D \sim 1\ TeV$ then $R \sim 10^{(32/\delta)-16}$ mm. If the number of extra dimensions $\delta \geq 2$, R is smaller than $\sim$ 1 mm, where gravitational interactions have not been probed. At LHC, for these large dimensions, the Kaluza-Klein states of the graviton form a continuum tower, and the direct emission of G leads to a signal $(gg \to gG,\ qg \to qG,\ q\bar{q} \to gG,\ q\bar{q} \to \gamma G)$ observable as an excess of events of jets and missing E_T over background $(jet + Z(\to \nu\nu),\ (jet + W(\to \tau\nu),\ (jet + W(\to \mu\nu),\ (jet + W(\to e\nu))$, [4]. A signal will be observable if the scale is below 9 TeV, for $\delta = 2$, or 6 TeV if $\delta = 4$.

From the E_{Tcut}^{jet} dependence of the integrated cross section $\sigma(pp \to jet + G)$ one cannot determine both δ and M_D because the curves for $\delta = 2$ and $M_D = 6\ TeV$ are very similar to those for $\delta = 3$ and $M_D = 5\ TeV$, [4], but if one could compare results at different energies, one could discriminate between $\delta = 2$ and $\delta = 3$ since the ratio $\frac{\sigma(pp\to jet+G)_{\sqrt{s}=10\ TeV}}{\sigma(pp\to jet+G)_{\sqrt{s}=14\ TeV}}$ is almost independent of M_D, Figure 1.

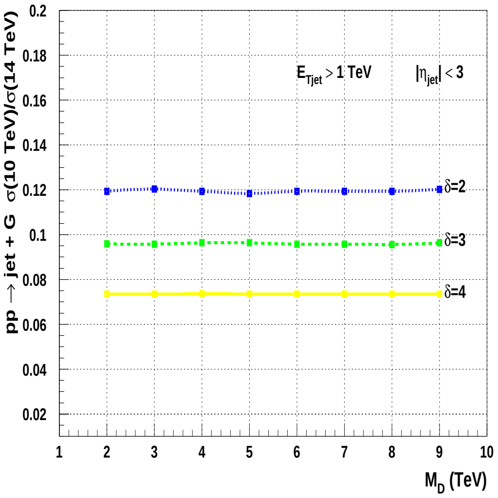

Figure 1: The M_D dependence of the ratio between the signal $(pp \to jet + G)$ cross section at $\sqrt{s} = 10\ TeV$ and $\sqrt{s} = 14\ TeV$ for different values of δ.

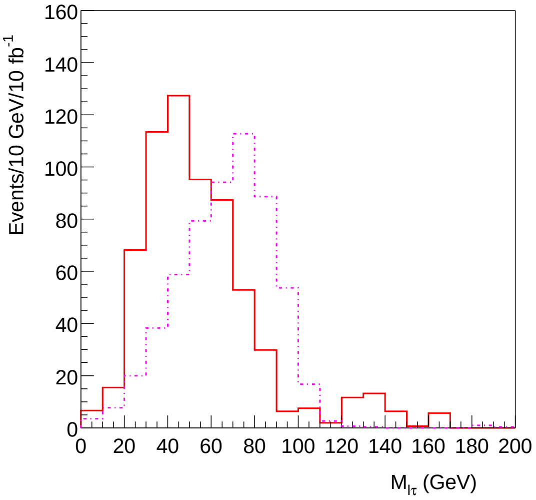

Figure 2: Mass distribution for $l^\pm\tau^\mp - l^\pm\tau^\pm$ (solid) and $\mu^\pm\tau^\mp$ from LFV decays with BR=10% (dot dashed).

2.2 Virtual graviton effects

The presence of the virtual graviton in Drell-Yan processes leads to a considerable excess in the production of dilepton and diphoton events. The maximal reach in the string scale M_S in di-lepton and di-γ production channels, was 6.6 and 6.32 TeV respectively, for low luminosity and 7.9 TeV, for both channels, at high luminosity [5].

2.3 Narrow graviton resonances

Models with small extra dimensions, such as the Randall and Sundrum model [6], lead to well-space Kaluza-Klein states of the graviton up to 2.1 TeV [7]. They can be detected as narrow resonances in di-fermion and di-boson channels. The decay mode $G \to e^+e^-$ gives a good signal of narrow graviton resonances up to 2.1 TeV [7], if the Randall and Sundrum scenario is used. The angular distribution of the lepton pair favours a spin-2 hypothesis at 90% confidence for graviton masses up to 1720 GeV. The precision of the measurement of the mass and cross section will allow the determination of the model parameters.

3. Lepton-flavour violation

Strong mixing between the μ and τ family, is suggested by the atmospheric neutrino oscillation experiments [8]. In a supersymmetric model, lepton flavour violation (LFV) can be introduced, at one loop level, by adding a right-handed Majorana neutrino coupling with the lepton left doublet and Higgs, as well as a flavour-changing component in the left sector. Considering a SUGRA scenario (point 5) [9], LFV will be measured by the decay $\chi_2^0 \to \tilde{\tau}\mu \to \chi_1^0\mu\tau$, leading to an excess of $\chi_1^0\mu\tau$ over $\chi_1^0 e\tau$. Using the technique of sign subtraction $(N(l^\pm\tau^\mp) - (N(l^\pm\tau^\pm)$ and flavour subtraction $(N(\mu^\pm\tau^\mp) - (N(e^\pm\tau^\mp))$, the signal can be derived over the SM background (Figure 2) [10] with a limit, for this particular case of SUGRA parameters, corresponding to $BR(\tau \to \mu\gamma) < 10^{-9}$.

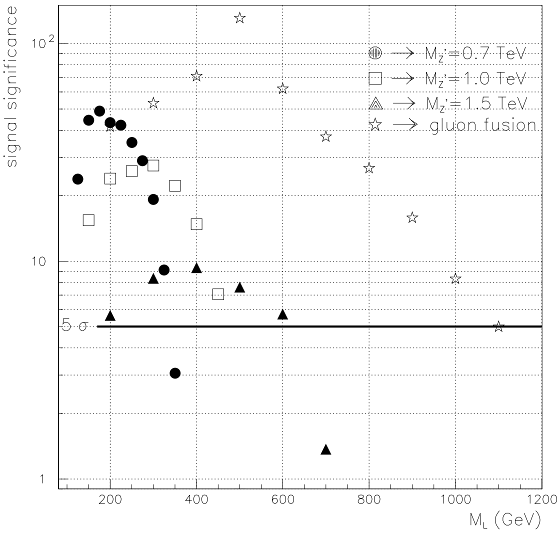

Figure 3: ATLAS sensivity for charged heavy leptons pair production by Drell-Yan and gluon fusion mechanisms.

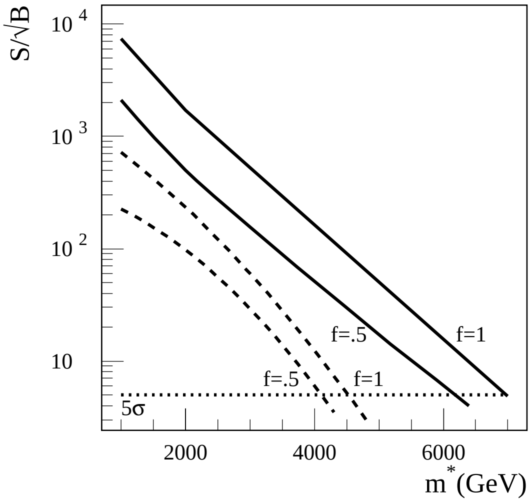

Figure 4: Excited quark signal significance for $(q^* \to qW)$ channel (solid line) and $(q^* \to qZ)$ channel (dashed lines).

4. Charged heavy leptons

Heavy leptons arise in several theories beyond the SM and experimental lower limits on M_L

are around 0.7 TeV. The sensitivity of ATLAS to charged heavy lepton pair production by Drell-Yan mechanisms and gluon - gluon fusion, for the $L^{\pm} \rightarrow e^{\pm} Z^{0} \rightarrow e^{\pm} - dijet$ channel, is presented in Figure 3 [11]. Backgrounds considered were $t\bar{t}$, ZZ, WZ, $W^{+}W^{-}$, ZQQ. After three years of low luminosity (30 fb^{-1}) data taking, ATLAS can discover the charged heavy lepton pair ($L^{+}L^{-}$), produced by Drell-Yan mechanism, together with the new neutral gauge boson Z', for masses up to 0.6 and 1.5 TeV, respectively. The M_L observability limit is pushed up to 1.1 TeV if the charged heavy leptons are produced by gluon-gluon fusion. The study will be extended to single heavy lepton production, to high luminosity and Super LHC conditions and to different theories beyond the Standard Model: mirror fermions, vector fermions, superstring inspired E(6) models, etc.

5. Excited quarks and leptons

The excited quarks production at the LHC by the quark gluon fusion was studied for their subsequent decays to photon + jet [12], to quarks and gauge bosons and to quarks and gluons [13, 14]. For an integrated luminosity of 3×10^{5} pb^{-1} and different couplings f determined by the compositeness dynamics, the ($q^{*} \rightarrow qW$) channel allows the discovery of new excited quarks up to masses of 7 TeV, for the ($q^{*} \rightarrow qZ$) channel the upper mass limit is 4.5 TeV, 6.5 TeV for the ($q^{*} \rightarrow \gamma + jet$) channel and 6 TeV for the ($q^{*} \rightarrow gq$) channel, Figure 4. A discovery limit of 3.8 TeV for the mass of the excited lepton is obtained, if it is produced by $q\bar{q}$ fusion ($q\bar{q} \rightarrow e^{*}e$) and the highest branching ratio for $e^{*} \rightarrow eW$ is chosen.

6. New gauge bosons

In the theoretical framework of the left-right symmetric model, after three years of data taking at low luminosity (30 fb^{-1}), the $pp \rightarrow W_R \rightarrow eN_e \rightarrow eejj$ channel allows the discovery of the new charged gauge boson W'_R as well as the right-handed Majorana neutrinos N_e up to masses of 4.6 and 2.8 TeV, respectively. The mass limit is increased after three years of high luminosity (300 fb^{-1}) to 5.8 and 3.4 TeV, respectively [15]. Within the same theoretical model, N_e can be observed together with the new neutral gauge boson Z', if m_{N_e} and $m_{Z'}$ are smaller that 1.2 and 4.3 TeV, respectively [16].

7. Strong symmetry breaking

In case that strong dynamical scenarios must be invoked to explain electroweak symmetry breaking, the study of longitudinal gauge boson pair production at high mass becomes important. Within the Chiral Lagrangian model [17], but also in technicolor scenarios, it was shown [18] that after a three years of high luminosity the resonant process $W_L Z_L \rightarrow W_L Z_L$ can be probed at the LHC. Non-resonant processes of longitudinal gauge boson scattering have also been studied [19]. These processes will require a few years of high luminosity running, but also a good understanding of backgrounds. Some sensitivity to the unitarization model was found.

8. Super LHC

Ultimately, the LHC could be upgraded to a Super-LHC, with a luminosity increased by a factor 10 and with possible increased energy. With some detector upgrade, the physics reach can be considerably increased for many different processes [20] such as compositeness, triple gauge boson vertices, strong dynamics, extra dimensions, etc..

9. Conclusions

A review of some of the most important results obtained by the ATLAS Exotic Physics Group was briefly presented.

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