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Detecting exotic heavy leptons at the Large Hadron Collider

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Abstract: New almost-degenerate charged and neutral heavy leptons are a feature of a number of theories of physics beyond the Standard Model. The prospects for detecting these at the Large Hadron Collider using a time-of-flight technique are considered, along with any cosmological or experimental constraints on their masses. Based on a discovery criterion of 10 detected exotic leptons we conclude that, with an integrated luminosity of $100\,\mathrm{fb}^{-1}$, it should be possible to detect such leptons provided their masses are less than 950 GeV. It should also be possible to use the angular distribution of the produced particles to distinguish these exotic leptons from supersymmetric scalar leptons, at a better than 90% confidence level, for masses up to 580 GeV.

Keywords: Beyond Standard Model, Supersymmetric Standard Model, Hadronic Colliders.

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Contents

1. Introduction

One of the most widely considered possibilities for new physics beyond the Standard Model (SM) is supersymmetry (SUSY) [1, 2]. Supersymmetry is theoretically attractive and is able to solve some of the problems faced when trying to understand how fundamental models at higher energy scales are consistent with what is seen by experiments at low energy scales. SUSY solves the so-called hierarchy problem and improves the unification of the three gauge couplings at a higher energy scale.

The simplest possible SUSY extension of the Standard Model is the Minimal Supersymmetric Standard Model (MSSM). The model has a second Higgs scalar doublet and for each SM particle there is an associated superpartner.

We know that supersymmetry is broken because we do not see associated superpartners with the same masses as the known particles. It has long been known that a viable way to break supersymmetry is in a hidden sector — the SUSY breaking in a particular model is then transmitted to the "outside world" by some means (usually gravitational or gauge interactions).

One scenario motivated by string theory is that of an intermediate scale [3]–[6]. This is a result of the realisation that, if a fundamental theory includes higher dimensional objects like D-branes, the fundamental scale is effectively a free parameter and does not have to be close to the Planck scale as previously thought. The fundamental scale could, in theory, be as low as experimental limits allow (i.e. 1 TeV).

In the type of model being considered here, gauge coupling unification is assumed to occur at an intermediate scale. “Intermediate” refers to an energy scale ($\sim 10^{11}$ GeV) which is the geometric mean of the weak and Planck energy scales. This choice is motivated by the scale of supersymmetry breaking in hidden sector, gravity mediated, scenarios. One of the strongest arguments supporting the intermediate string scale scenario is that of the axion decay constant [4]. The axion field is the Goldstone mode of a chiral symmetry introduced to the Standard Model to solve the strong Charge Parity problem (which gives an unnaturally small bound on one of the parameters) [7]. Astrophysical and cosmological bounds constrain the axion decay constant to be in the approximate energy range 10^9–10^{12} GeV. The intermediate scale is also consistent with some neutrino mass mechanisms, and is favoured by certain cosmological inflation models. High energy cosmic ray observations and certain non-thermal dark matter candidates are also supporting arguments for the intermediate energy scale.

Various intermediate scale models are motivated from different string models in references [3]–[6]. Some phenomenological constraints on intermediate scale models are provided by [8], and $g-2$ constraints have also been discussed [9, 10].

One of the ways of achieving this intermediate scale unification is to include new leptons as part of extra supermultiplets added to the MSSM. Although this choice is not unique, the extra leptons in [8] are three vector-like copies of left-handed SU(2) doublets (L', $\bar{L}'$) and two right-handed singlets (E',$\bar{E}'$).

By assumption there are no new Yukawa couplings for the model in [8]. This means that the lightest heavy lepton is stable and the others will decay into it. This is possible because the tree-level mass degeneracy of the charged and neutral leptons will be destroyed by electroweak symmetry breaking.

As in the MSSM, the renormalisation group equations can be used to determine the spectrum of supersymmetric particles which will have phenomenological implications for the Large Hadron Collider (LHC). However the characteristic feature of this model is the new leptons and so this work concentrates on the phenomenology due to the extra leptons themselves. More specifically we consider whether it will be possible to detect them at the LHC, and for what range of masses.

Previous limits on the masses of any new quasi-stable charged leptons have been determined by the energy available for particle production in lepton colliders. The gauge unification arguments in intermediate scale models mean that the extra leptons are expected to have masses in the TeV range. At the LHC enough energy should be available to produce and detect these exotic heavy charged leptons.

In this paper we first review the existing cosmological and experimental limits on heavy particles to ensure that the leptons incorporated in this intermediate scale model are not ruled out. In section 3 we describe the changes to the HERWIG Monte

Carlo event generator to take account of these new heavy leptons. Then we consider the detection of these leptons at the LHC using a "time-of-flight" technique. Heavy leptons will arrive at the detector significantly later than relativistic particles — in section 4 the prospects of using this time delay as a method of detection are studied for a range of masses. We also consider how to distinguish such leptons from scalar leptons on the basis of their different angular distributions. Our results are presented in section 5.

2. Cosmological and experimental constraints

The mass degeneracy of the charged and neutral leptons will be broken by radiative corrections. The electromagnetic self-energy correction for the charged lepton ensures that its mass will be greater than that of the neutral lepton [11]. This means that the charged lepton can decay to its neutral partner producing either a real or virtual W, depending on the mass difference. The neutral heavy lepton can be assumed to be totally stable (i.e. it has a lifetime orders of magnitude longer than that of the universe) because of the assumption that there are no new Yukawa couplings.

There are a number of cosmological and experimental limits on leptons (particularly charged leptons) as a function of both mass and lifetime:

- The relic abundance of the leptons (calculated from the self-annihilation cross section) must not "over-close" the universe i.e. provide more than the critical energy density ($\sim 10^{-5}$ GeV cm^{-3}) which is presumed to be accounted for by Dark Matter [12, 13].
- A stable, charged lepton must have a low enough relic abundance for it not to have been detected in searches for exotic heavy isotopes in ordinary matter (see e.g. [14]).
- The massive lepton and any decays it may have must not significantly affect nucleosynthesis or the synthesised elemental abundances [15, 16].
- If the lepton decays before the recombination era (at $\sim 10^{12}$ s) it must not distort the cosmic microwave background radiation [15].
- If the lepton has a longer lifetime it must not contradict the limits from gamma-ray and neutrino background observations [17, 18].
- The mass and lifetime of the new leptons must not be such that they would have been detected in a previous collider experiment [19].

Most of these limits are summarised in [20] and no constraints on charged leptons are found for lifetimes less than $\sim 10^6$ s, even for masses up to the TeV scale. The mass splitting between the neutral and charged leptons will be of order MeV [11] which means that the lifetime of the charged lepton will certainly be shorter than 10^6 s.

This means the only relevant limits on the mass of the heavy leptons being studied are the experimental ones, which rule out masses of less than 93.5 GeV [19].

3. Theoretical input to HERWIG

The general purpose Monte Carlo event generator HERWIG 6.3 includes subroutines for both neutral and charged Drell-Yan processes in a hadron collider [21, 22, 23]. As described in [22] the initial-state parton showers in Drell-Yan processes are matched to the exact $\mathcal{O}(\alpha_S)$ matrix-element result [24]. However the neutral Drell-Yan processes all use the approximation that the two fermions produced can be treated as massless. It is reasonable that this is a valid approximation for the SM quarks and leptons but this will not necessarily be the case for the proposed new heavy leptons discussed above which may have masses of order 1 TeV.

For this reason full Born-level expressions for the Drell-Yan cross sections were derived, taking into account the masses of the produced leptons. This was done for the neutral and charged current cases (in both cases the result was expressed in terms of vector and axial couplings to keep it as general as possible and allow for new couplings in the intermediate scale model).

The derived expressions for both differential and total cross sections for neutral current Drell-Yan processes ($q\bar{q} \to Z^0/\gamma \to L^-L^+$) are shown below. The notation is influenced by that already used in subroutines within HERWIG 6.3.

The differential cross section is given by

$$\frac{d\hat{\sigma}}{d\Omega}(q\bar{q} \to L^-L^+) = \frac{e^4}{48\pi^2}\frac{1}{\hat{s}^2}\frac{p_3}{E}\left[C_1\left(E_3E_4 + p_3^2\cos^2\theta^*\right) + C_2 m_3 m_4 + 2C_3 E p_3 \cos\theta^*\right], \tag{3.1}$$

where

$$\begin{aligned}
C_1 &= \frac{\left[\left(d_V^f\right)^2 + \left(d_A^f\right)^2\right]\left[(d_V^i)^2 + (d_A^i)^2\right]\hat{s}^2}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2} + \left(q^f\right)^2\left(q^i\right)^2 + \frac{2q^f q^i d_V^f d_V^i \hat{s}\,(\hat{s}-m_Z^2)}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2}, \\
C_2 &= \frac{\left[\left(d_V^f\right)^2 - \left(d_A^f\right)^2\right]\left[(d_V^i)^2 + (d_A^i)^2\right]\hat{s}^2}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2} + \left(q^f\right)^2\left(q^i\right)^2 + \frac{2q^f q^i d_V^f d_V^i \hat{s}\,(\hat{s}-m_Z^2)}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2}, \\
C_3 &= 2\left(\frac{2d_V^f d_A^f d_V^i d_A^i \hat{s}^2}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2} + \frac{q^f q^i d_A^f d_A^i \hat{s}\,(\hat{s}-m_Z^2)}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\right).
\end{aligned} \tag{3.2}$$

In these expressions q^i and q^f are the charges (in units of the electron charge) of the initial- and final-state particles respectively. The angle θ^* is the angle between the outgoing lepton (L^-) direction and the incoming quark direction in the centre-of-mass frame. E_3 and p_3 refer to the centre-of-mass energy and magnitude of momentum of the produced lepton. Similarly the subscript 4 refers to the produced anti-lepton. E is the energy of both the colliding quarks in the centre-of-mass frame (i.e. $\hat{s} = 4E^2$).

The couplings d_V and d_A are related to the normal vector and axial coupling constants to the Z^0 (c_V and c_A) by relations like

$$d_V = \frac{c_V g_Z}{2e} \,. \tag{3.3}$$

Equation (3.1) is a general expression which includes the Z^0/γ interference terms. The massless case is retrieved by setting $p_3 = E_3 = E_4 = E$ (as well as $m_3 = m_4 = 0$). The normal charged current Drell-Yan case ($q\bar{q}' \to W^\pm \to L^\pm L^0$) is given by setting $c_V = c_A = 1$ and replacing g_Z, m_Z, Γ_Z and $q^{i/f}$ by $g_W/\sqrt{2}$, m_W, Γ_W and 0 respectively.

Integration of eq. (3.1) gives the following equation for the cross section:

$$\hat{\sigma}(q\bar{q} \to L^- L^+) = \frac{e^4}{12\pi} \frac{1}{\hat{s}^2} \frac{p_3}{E} \left[C_1 \left(E_3 E_4 + \frac{p_3^2}{3} \right) + C_2 m_3 m_4 \right] . \tag{3.4}$$

In order to distinguish these heavy leptons from heavy supersymmetric partners of SM particles it would be necessary to consider the angular distribution of the produced particles. For the neutral current production of left/right-handed scalars the expression for the differential cross section would be

$$\frac{d\hat{\sigma}}{d\Omega}(q\bar{q} \to \tilde{l}_{L/R} \tilde{l}^*_{L/R}) = \frac{e^4}{96\pi^2} D \frac{1}{\hat{s}^2} \frac{p_3}{E} p_3^2 \sin^2\theta^* \,, \tag{3.5}$$

where

$$D = \frac{h_{L/R}^2 \left[\left(d_V^i\right)^2 + \left(d_A^i\right)^2 \right] \hat{s}^2}{\left(\hat{s} - m_Z^2\right)^2 + m_Z^2 \Gamma_Z^2} + \left(q^f\right)^2 \left(q^i\right)^2 + \frac{2 q^f q^i h_{L/R} d_V^i \hat{s} \left(\hat{s} - m_Z^2\right)}{\left(\hat{s} - m_Z^2\right)^2 + m_Z^2 \Gamma_Z^2} \,. \tag{3.6}$$

The couplings d_V and d_A are defined as above and $h_{L/R} = g_{L/R} g_Z / e$ where $g_{L/R}$ is the coupling to left/right-handed sleptons at the gauge boson-slepton-slepton vertex.

The $\sin^2\theta^*$ angular distribution contrasts with the asymmetric distribution for the heavy leptons as seen in eq. (3.1). This will be studied in section 5.3.

4. Implementation

4.1 Modifications to HERWIG 6.3

The above formulae were incorporated into a new subroutine added to HERWIG 6.3 together with new particle entries (for the heavy leptons) and new process codes (IPROCs) for the new processes.

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Increasing the mass of the new leptons allowed the variation of cross section with mass to be studied — the mass was varied over a range from of order the top quark mass to a maximum of order 1 TeV. The lifetimes of the charged leptons produced were set to 1 s so that the number of decays occurring inside the detector will be negligible.

The angular distribution of the produced leptons was studied over the same mass range to investigate the possibility of distinguishing heavy leptons from MSSM sleptons. The detection of long-lived sleptons at the LHC has been considered in ref. [25].

4.2 Time-of-flight technique

Our main aim was to consider the possible detection of charged heavy leptons at the LHC and for what mass ranges this might be practical. This work refers specifically to the technical specifications of the ATLAS detector [26, 27, 28]. However we believe similar results will be obtained for the CMS experiment [29].

The method used was a time-of-flight technique as discussed in ref. [30]. This method utilises the fact that, when compared to relativistic particles, there is a considerable time delay for heavy particles to reach the muon system. Heavy charged leptons like those being considered in this work will be detected in both the central tracker and the muon chambers, and from the measured momentum and time delay it is possible to reconstruct the mass.

Imperfections in the time and momentum resolutions will cause a spread of the mass peak. Uncertainty over which bunch crossing a particular detected particle comes from may also provide a background signal (from muons produced in Drell-Yan processes and also from heavy quark decays). Plots from [28] display the behaviour of the processes which are most likely to produce muons which might be mis-identified as heavy leptons. These are reproduced in figures 1 and 2.

The studies presented here do not attempt to model the background, which it is not thought will be significant (there is no "physics" background, only "detector" background as discussed above), and use a simple cut (as in [30]) on the range of time delays allowed.

The calculation of a reconstructed mass from the time delay Δt and momentum is straightforward. For a lepton hitting the radial part of the muon spectrometer, the time delay with respect to a relativistic ($\beta = v/c = 1$) particle is given by

$$\Delta t = \frac{r}{p_T}(E-p)\,, \tag{4.1}$$

where r is the radius of the outer layer of the muon system, p_T the transverse momentum, and E and p the total energy and momentum respectively. Substituting for E in the energy-momentum invariant $E^2 - p^2 = m^2$ gives the result

$$m^2 = p^2\left(\frac{1}{\beta^2}-1\right) = \frac{p_T\Delta t}{r}\left(2p + \frac{p_T\Delta t}{r}\right). \tag{4.2}$$

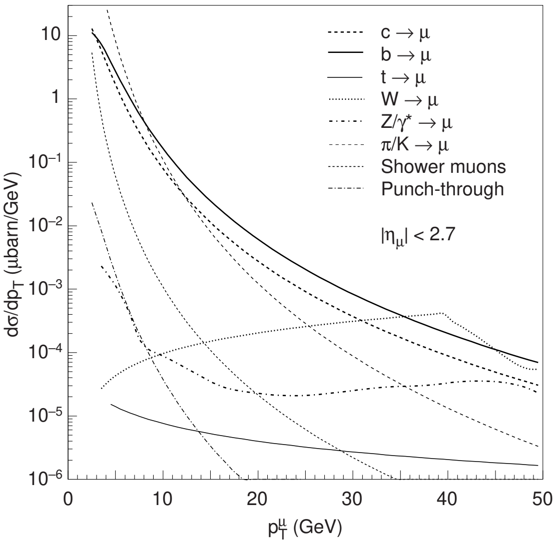

Figure 1: Transverse momentum dependence of the inclusive muon cross section integrated over $|\eta| < 2.7$. The horizontal scale is the transverse momentum at production. (Reproduced from [28]).

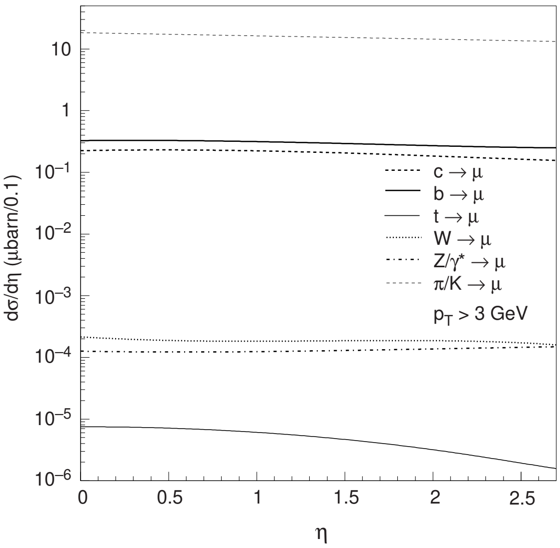

Figure 2: Rapidity-dependence of the inclusive muon cross sections, integrated over $3 < p_T < 50\,\text{GeV}$. (Reproduced from [28]).

It is also necessary to check for occasions when the lepton hits the endcap of the detector by considering the magnitude of $\frac{p_T}{p_z}$. The muon system is modelled approximately as a cylinder of radius 10 m and a half-length of 20 m [28]. A pseudo-rapidity cut requiring that $\eta < |2.7|$ was applied to take account of the region close to the beam where particles cannot be detected.

From the expression (4.2), the time delay and measured momentum for any particle detected in the muon system can be used to calculate the mass. As in [30] the time delay was smeared with a gaussian (although a width of 0.7 ns [28] rather than 1 ns was used) and a cut on the smeared time delay was applied such that $10\,\text{ns} < \Delta t < 50\,\text{ns}$. Increasing the lower limit on Δt would reduce the efficiency but improve the mass resolution by removing many of the high β leptons for which the time resolution contribution is large. The upper limit eliminates very slow particles which lose most of their energy in the calorimeter. An alternative upper limit of 25 ns, reflecting practical concerns, is discussed in section 5.2.

The most important contribution to the momentum uncertainty Δp is due to the measurement error on the sagitta (the deviation from a straight line of a charged particle in a magnetic field). Δp_{sag} was taken into account by using

$$\frac{\Delta p_{\text{sag}}}{p^2} = 1.1 \times 10^{-4}\,, \tag{4.3}$$

where p is the total momentum in GeV. The constant in eq. (4.3) was obtained from [26] as an average over the different parts of the ATLAS detector. This expression should be valid near the discovery limit for heavy leptons when multiple scattering is insignificant — the maximum time delay cut is found to remove most of the low β leptons for which multiple scattering would have more effect. However to allow investigations over a full mass range a multiple scattering term (Δp_{ms}) was also incorporated with

$$\Delta p_{ms} = 2 \times 10^{-2} \sqrt{p^2 + m^2} \,. \tag{4.4}$$

The constant depends on the material distribution in the spectrometer — the above value is given in [31] for the ATLAS muon detector.

The two errors in eqs. (4.3) and (4.4) were taken to be independent and hence combined in quadrature. A third possible contribution to momentum resolution — due to fluctuation in the energy loss in the calorimeter — is neglected as it is always dominated by one of the other terms.

Using the momentum and time resolution as described above we are able to satisfactorily reproduce the mass resolution as a function of β for 101 GeV particles as given in [26].

The efficiency of the muon detection system is approximated to be 85%, independent of the particle momentum [26].

5. Results

5.1 Backgrounds

Any "detector" background is greatly dependent on the details of the muon detection system. Such a background would come from muons either from the decay of heavy quarks or from Drell-Yan (both these processes have very high cross sections compared to that for heavy lepton production). If timing inadequacies do mean that some of these muons are mistakenly thought to have come from an earlier interaction i.e. they appear to have a large time delay, they could obscure the exotic lepton mass peak. For a background signal to look like a heavy lepton neutral current signal, however, two opposite charge muons would have to be mis-identified at the same time which makes it very unlikely that background could be significant.

To eliminate any possible background from heavy quark decays, a cut requiring the transverse momentum to be greater than 50 GeV was made to produce the plots in section 5.2. Figures 3 and 4 show that a p_T cut at 50 GeV should remove most of the muons from bottom quark decay without significantly reducing the exotic heavy lepton signal. It can be seen that as the mass of the exotic heavy lepton increases, the peak in the p_T spectrum becomes less well defined and shifts to higher values. Top quark decays can give rise to muons at high p_T but the small top cross section, combined with the improbability of mis-identifying two muons, should suffice to eliminate this source of background.

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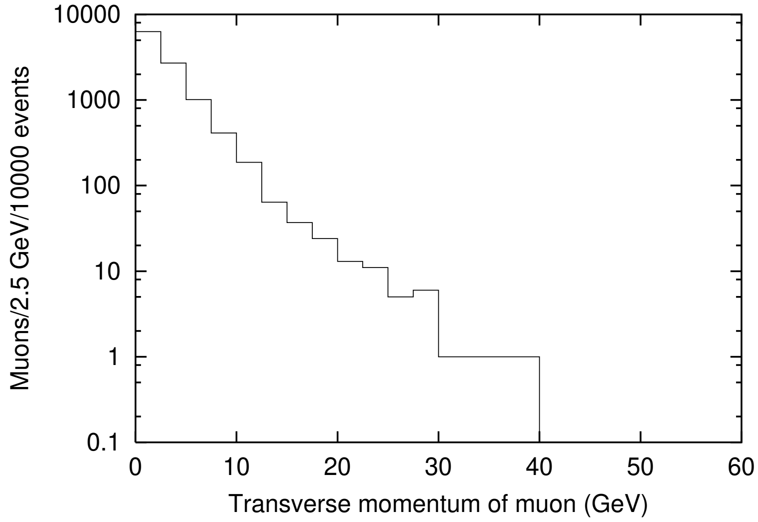

Figure 3: p_T spectrum for muons produced in b decays.

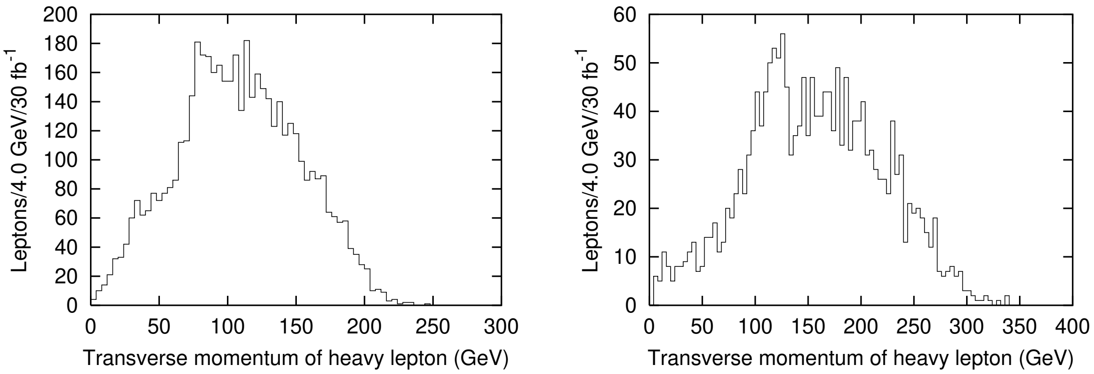

Figure 4: p_T spectra for 175 and 250 GeV heavy leptons from Drell-Yan processes.

5.2 Heavy lepton mass peaks

The results presented in this section show the reconstructed mass peaks for an integrated luminosity of 100 fb^{-1} after the cuts outlined above have been applied.

The possibility of detection at the LHC is found to be entirely cross section limited — the decrease of cross section with increasing lepton mass is shown in figure 5. The fraction of leptons passing the cuts actually slightly increases with mass due to the longer time delays.

Figure 6 for the neutral Drell-Yan process makes it clear that for masses up to about 1 TeV it should be possible to detect new charged heavy leptons at the LHC (particularly if a larger integrated luminosity can be obtained). A discovery criterion of 10 leptons (from 5 events) in the mass peak is found to give a mass limit of 950 GeV for the detection of such leptons using an integrated luminosity of 100 fb^{-1}.

To reduce possible backgrounds the plots are based on events from which both leptons produced passed the cuts imposed.

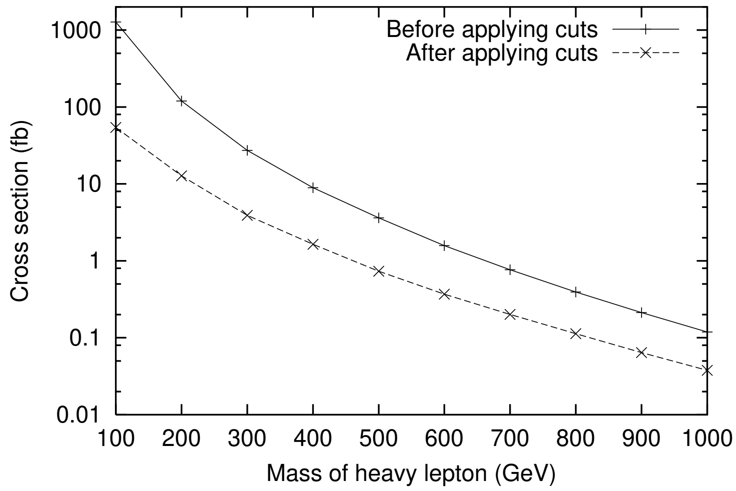

Figure 5: Cross section for Drell-Yan heavy lepton production as a function of the lepton mass.

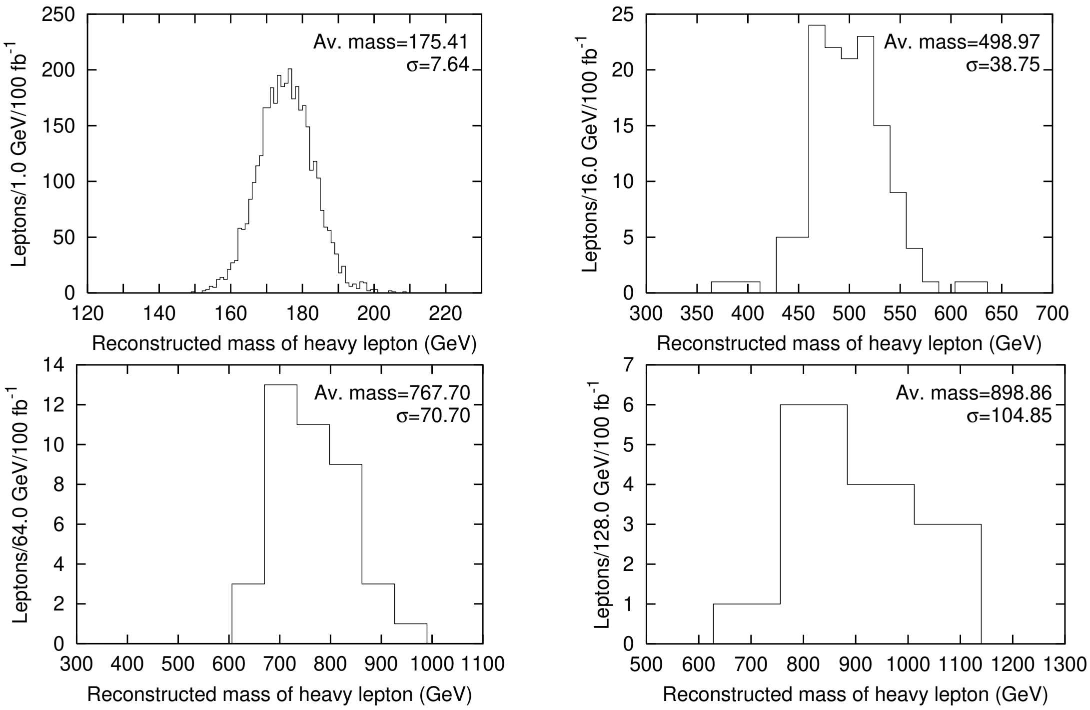

Figure 6: Reconstructed mass peaks for exotic leptons with masses of 175 GeV, 500 GeV, 750 GeV and 900 GeV.

We note that the long drift times in the muon chambers used by ATLAS allow the recording of events with time delays at arrival much greater than the 25 ns beam crossing interval of the LHC [28]. We have assumed a maximum time delay of 50 ns following [30]. However, to correctly associate the delayed track in the muon system with the event recorded in the other detector systems would require a specialised trigger, based, for example, on the presence of high p_T tracks in the inner detector, which would identify the true event time. Without this, the maximum delay time

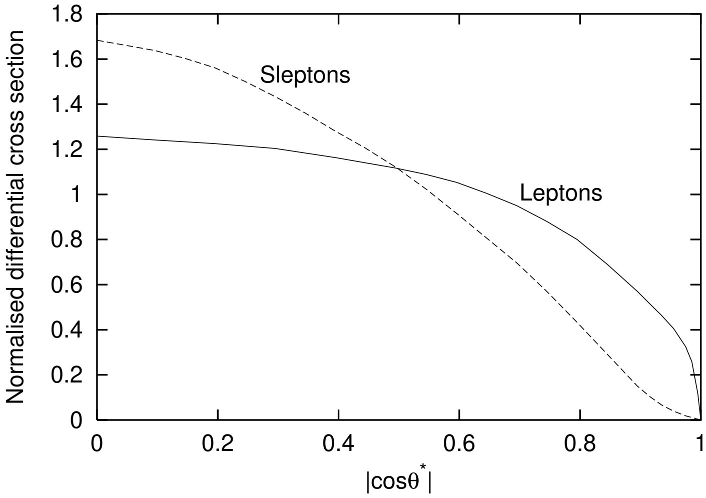

Figure 7: Angular distributions of detected pairs of 400 GeV particles. θ^* is the angle between the outgoing particle and incoming quark directions.

allowable would be 25 ns, and the discovery reach would be reduced to a lepton mass of 800 GeV. The statistical sample available for the angular distribution analysis in section 5.3 would also be reduced by a factor of about 2, depending on the lepton mass.

5.3 Distinguishing leptons from sleptons

As mentioned in section 3 it should be possible to distinguish these new heavy leptons from heavy scalar leptons by studying the angular distribution with which they are produced. The two different angular distributions in the centre-of-mass frame are shown in eqs. (3.1) and (3.5). The application of the cuts described in section 4.2 as well as the effects of the mass and momentum resolution mean that the observed angular distributions are somewhat different to these.

The forward-backward asymmetry for the exotic heavy leptons was not considered because of the difficulty in a *pp* collider of distinguishing the quark and anti-quark in the centre-of-mass frame. Hence only $|\cos\theta^*|$ was used when the angular distributions were compared. Figure 7 shows the angular distribution for both exotic leptons and sleptons of mass 400 GeV.

A chi-squared test was applied to find the probability that a scalar model describes the data. The model was the angular distribution of a large Monte Carlo sample of scalars, and the total number of detected scalar pairs was rescaled to the expected number of detected pairs of heavy leptons. An "average" data-set was obtained from a rescaled Monte Carlo sample of leptons, generated according to their angular distribution. Both these rescaled distributions had negligible theoretical errors compared to the (Poisson distributed) statistical errors on the model for $100\,\mathrm{fb}^{-1}$ of integrated luminosity.

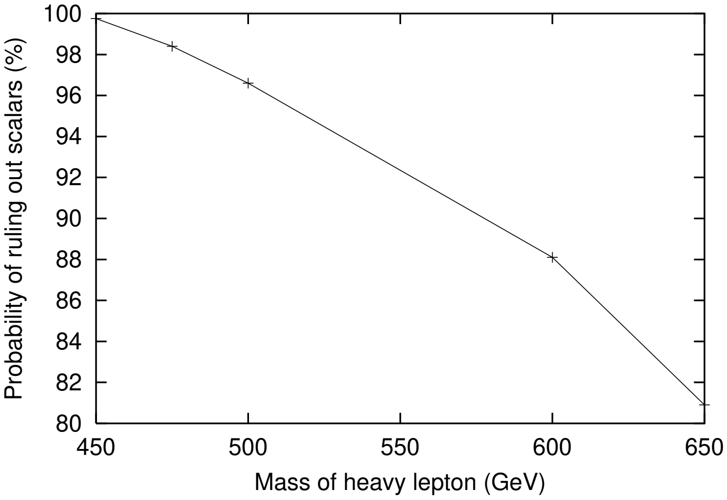

Figure 8: Probability at which it will be possible to rule out the scalar hypothesis by studying the angular distribution of the detected leptons.

Figure 8 shows that it will be possible to rule out scalar leptons at a confidence level of better than 90% up to a mass of 580 GeV. The angular distribution does not change significantly over the mass range of this plot — the decreasing probability of ruling out the scalar hypothesis as the mass increases is mainly because of the decreasing statistics.

6. Conclusions

This work was motivated by some of the new models of physics beyond the Standard Model in which the gauge couplings unify at an intermediate energy scale ($\sim 10^{11}$ GeV). Many of these intermediate scale models include additional leptons added to the Minimal Supersymmetric Standard Model and which are expected to have TeV scale masses.

We conclude that, assuming Standard Model couplings and a long enough lifetime, it should be possible to detect the charged heavy leptons in intermediate scale models up to masses of 950 GeV with 100 fb^{-1} of integrated luminosity. Background from mis-identified muons should be negligible and can be reduced by the application of a $p_T^{\min}$ cut at about 50 GeV. It will be difficult to use the angular distribution of the produced particles to distinguish them from scalar leptons for masses above 580 GeV because the falling cross section limits the available statistics.

The absence of a specialised trigger in the inner detector could reduce the discovery limit to 800 GeV and would reduce the statistics available for the angular distribution analysis.

No present cosmological or experimental limits were found to rule out additional exotic leptons at the masses considered in this work.

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