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Minimal Z' models and the early LHC

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Summary. — We consider a class of minimal extensions of the Standard Model with an extra massive neutral gauge boson Z'. They include both family-universal models, where the extra $U(1)$ is associated with $(B-L)$, and non-universal models where the Z' is coupled to a non-trivial linear combination of B and the lepton flavours. We discuss the interplay between electroweak precision tests and direct searches at the Tevatron, to assess the discovery potential of the early LHC.

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1. – Introduction

Extra neutral gauge bosons, known in the literature as Z', appear in many proposals for Beyond-the-Standard Model (BSM) physics; for a review, see for instance [1]. Here we focus on *minimal* Z', previously studied in [2], which stand out both for their simplicity, and because they could arise in several BSM scenarios, such as, *e.g.*, Grand Unified Theories (GUTs) and string compactifications.

2. – Theory

Following [3], we consider a minimal extension of the SM gauge group that includes an additional Abelian factor, labeled $U(1)_X$, commuting with $SU(3)_c \times SU(2)_L \times U(1)_Y$. The fermion content of the SM is augmented by one right-handed neutrino per family. We require anomaly cancellation, as this allows us to write the Lagrangian of the model only in terms of renormalizable operators. If family-universality is imposed, then the anomaly cancellation conditions (ACC) yield a unique solution: $X = (B - L)$, where B and L are baryon and lepton number, respectively(1). However, if the requirement of family-

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(1) The most general solution to the ACC is $X = a\,Y + b\,(B-L)$, with a, b arbitrary coefficients. However, the hypercharge component can be absorbed in the kinetic mixing in the class of models we consider.

universality is relaxed, it can be shown that the following set of family-dependent charges satisfy the ACC: $X = \sum_{a=e,\,\mu,\,\tau}(\lambda_a/3)(B - 3L_a)$, where L_a are the lepton flavours. We will consider a specific example of such *non-universal* Z' in the following.

In the basis of mass eigenstates for vectors, and with canonical kinetic terms, the neutral-current Lagrangian reads $\mathcal{L}_{NC} = eJ^\mu_{em}A_\mu + g_Z(Z_\mu J^\mu_Z + Z'_\mu J^\mu_{Z'})$, where A_μ is the photon coupled to the em current, while $(Z_\mu,\, Z'_\mu)$ are the massive states, which couple to the currents $(J^\mu_Z,\, J^\mu_{Z'})$, respectively, obtained from $J^\mu_{Z^0} = \sum_f [T_{3L}(f) - \sin^2\theta_W\, Q(f)]\,\overline{f}\gamma^\mu f$ and $J^\mu_{Z'^0} = (1/g_Z)\sum_f [g_Y\, Y(f) + g_X\, X(f)]\,\overline{f}\gamma^\mu f$ via a rotation of the $Z - Z'$ mixing angle θ'. The latter is given by $\tan\theta' = -(g_Y/g_Z)\, M^2_{Z^0}/(M^2_{Z'} - M^2_{Z^0})$. Thus, under our minimal assumptions, only three parameters beyond the SM ones are sufficient to describe the Z' phenomenology: the physical mass of the extra vector, $M_{Z'}$, and the two coupling constants (g_Y, g_X) which appear in the definition of $J^\mu_{Z'^0}$. In the following discussion, we normalize these couplings to the SM Z^0 coupling, namely $\widetilde{g}_{Y,X} = g_{Y,X}/g_Z$.

3. – Bounds from present data

The measurements providing constraints on minimal Z' can be divided into two classes: electroweak precision tests (EWPT) and direct searches at the Tevatron.

3·1. *Electroweak precision tests.* – Measurements performed at LEP1 and at low energy mainly constrain Z-Z' mixing, whereas data collected at LEP2 constrain effective four-fermion operators. To compute the bounds from EWPT on minimal Z', we integrate out the heavy vector and use the effective Lagrangian thus obtained to perform a global fit to the data. The results are shown in fig. 1, for the universal "χ model", corresponding to a particular direction in the $(\widetilde{g}_Y, \widetilde{g}_{BL})$ plane often considered in the literature.

3·2. *Tevatron direct searches.* – The CDF and D0 Collaborations have derived, from the non-observation of discrepancies with the SM expectations, upper limits on $\sigma(p\overline{p} \to Z') \times Br(Z' \to \ell^+\ell^-)$ $(\ell = e, \mu)$ [4]. To extract bounds on minimal Z', we compute the same quantity at NLO in QCD, and compare it with the limits published by the experimental collaborations. The summary of bounds from EWPT and from the Tevatron is shown in fig. 1 for the χ model. We see that bounds from EWPT have a linear behaviour in coupling *vs.* mass, because all the effects due to the Z' in the low-energy effective Lagrangian depend on the ratio $g_{Z'}/M_{Z'}$, whereas bounds from the Tevatron become negligible above a certain kinematic limit, which is of the order of 1 TeV. Thus for low masses the Tevatron data give the strongest limits, while above a certain value of $M_{Z'}$ (which is of the order of 500 GeV for the χ model) bounds from EWPT are stronger.

4. – Early LHC reach

In 2010/2011 the LHC will run at a centre-of-mass energy of 7 TeV, collecting up to $1\,\text{fb}^{-1}$ of integrated luminosity L [5]. Therefore, it is interesting to ask whether there are any minimal Z' which are both allowed by the present constraints and accessible for discovery in such early phase. To answer this question, we have performed a NLO analysis analogously to the Tevatron case, requiring the Z' signal to be at least a 5σ fluctuation over the SM-Drell Yan background. The results are compared with present bounds in fig. 1, for the χ model. We see that for $L \sim 100\,\text{pb}^{-1}$ (the luminosity approximately

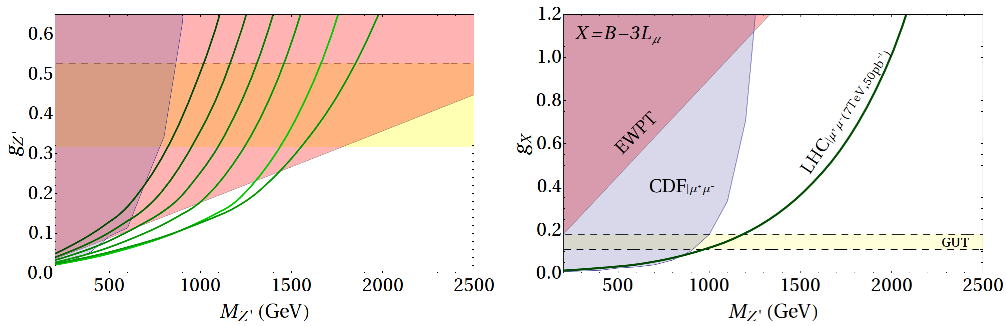

Fig. 1. – (Colour on-line) Left: comparison of bounds from EWPT (red), Tevatron (blue), and discovery reach of the early LHC (green curves, from left to right: 50, 100, 200, 400 and 1000 pb^{-1} at 7 TeV, and 400 pb^{-1} at 10 TeV) for the χ model. See [3] for the normalization of $g_{Z'}$. Right: present bounds and discovery prospects of the LHC at 7 TeV and 50 pb^{-1} for the *muonphilic* model with $\widetilde{g}_Y = 0$. The yellow bands correspond to the GUT-favoured regions, see [3] for details.

foreseen for 2010), no discovery is possible. On the other hand, for $L \sim 1\,\mathrm{fb}^{-1}$ some unexplored regions become accessible; however, Z's compatible with GUTs are still out of reach, and more energy and luminosity will be needed to test them.

4·1. *The muonphilic model.* – We have seen that universal models are strongly constrained by the present data. On the other hand, when we consider non-universal couplings to leptons, the bounds can be significantly altered. In particular, we can consider the case where $X = B - 3L_\mu$, which we called "muonphilic Z'". If kinetic mixing is negligible, *i.e.* $\widetilde{g}_Y \approx 0$, then the Z' has vanishing coupling to the electron. As a consequence, bounds from EWPT are strongly relaxed, the only surviving constraints coming from $(g-2)_\mu$ and ν-N scattering (NuTeV). On the other hand, the Tevatron reach is limited to $M_{Z'} \le 1$ TeV: therefore the LHC has access to a wide region of unexplored parameter space already with a very low luminosity at 7 TeV, as shown in fig. 1.

5. – Conclusions

We have discussed the present bounds and the early LHC reach on minimal Z' models, showing that the former cannot be neglected when assessing the latter. We have found that exploration of universal models, coupled to $(B - L)$, may need more energy and luminosity than those foreseen for 2010/2011. On the other hand, we have presented a non-universal model, the *muonphilic* Z', which is weakly constrained by present data and could be discovered at the LHC with very limited integrated luminosity.

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