THE FATE OF THE LEPTOPHOBIC $Z'$

Michelangelo L. MANGANO, Guido ALTARELLI
CERN, TH Division, Geneva, Switzerland

Nicola Di Bartolomeo
SISSA, Trieste, Italy

Ferruccio FERUGLIO
Dipartimento di Fisica dell'Università and INFN, Padova, Italy

Raoul GATTO
Département de Physique Théorique, Univ. de Genève, Geneva, Switzerland

Abstract
We review the main features of the leptophobic-$Z'$ phenomenology, commenting on the prospects of these models after the recent experimental results on $R_c$, $R_b$ and after the recent theoretical analyses of jet production at the Tevatron.

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\(^b\)Presenting author. On leave of absence from INFN, Pisa, Italy.
1 Introduction

The possible existence of a new gauge interaction, mediated by a neutral, massive vector boson \((Z')\) and very weakly coupled to leptons, has stimulated a large number of studies over the past year. Although the presence of additional \(U(1)\) groups is a recurrent feature of models beyond the SM, the particular class of theories that we will be interested in here originated from the attempts to explain a very specific set of anomalies present in recent experimental data from LEP and from the Tevatron:

1. a \(-2.5\sigma\) discrepancy between the measured and expected value of \(R_c\) (the fraction of hadronic \(Z\) decays into charm-quark pairs),

2. a \(3.5\sigma\) discrepancy between the measured and expected value of \(R_b\) (the fraction of hadronic \(Z\) decays into bottom-quark pairs), and

3. a large discrepancy between the measured and expected rate of high-\(E_T\) jets produced at the Tevatron \(p\bar{p}\) collider.

The total disappearance of the first effect, the existence of a new precise measurement of \(R_b\) which indicates a sharp decrease of the relative anomaly and the reduced significance of the high-\(E_T\) jet anomaly due to a better estimate of the gluon-density systematics, remove completely the need to invoke such a departure from the SM. Or, to say the least, make it much less appealing than before. In this presentation I will nevertheless dutifully comply to the request of the session organizers, and present a short review of the main features of the leptophobic \(Z'\) models and of their possible phenomenological applications.

2 The origin

What made the proposal of a leptophobic \(Z'\) appealing was the coincidence of several, independent, facts. The large size of \(\delta R_b\), for example, made explanations in terms of virtual effects, such as supersymmetry, unlikely. The anomaly in \(R_c\) would also not easily be understood in a supersymmetric model, requiring additional features not present in the standard SUSY realizations. Among possible new tree-level phenomena, the existence of an extra \(U(1)\), weakly coupled to leptons but sufficiently coupled to quarks so as to affect the relative rate of \(Z\) decays to different quark flavours, seemed a natural explanation to the \(R_c\) and \(R_b\) anomalies. Such a model, however, would have required a fine tuning of the \(Z'\) couplings to different quark flavours, in order to explain the precise agreement between the measured total \(Z\) hadronic width (\(\Gamma_h\)) and its SM value. Such a fine tuning would have spoiled the elegance of the model. A third feature of the data allowed an elegant solution to the fine-tuning problem: the 1995 values of \(R_b\) and \(R_c\) led in fact to the remarkable numerical coincidence that \(3\delta R_b + 2\delta R_c = -0.0047 \pm 0.0134\), i.e. a number compatible with zero. This can be naturally accommodated by assuming a family-independent coupling of the \(Z'\) to up- and down-type quarks. This reduces the number of independent couplings to quarks from 9 to 3, and makes it easier to enforce the stability of \(\Gamma_h\). It is this feature that in my view made the models of ref. particularly appealing. A failure of the relation among the \(R_c\) and the \(R_b\) anomalies would make this class of models less interesting. Using the latest data, one now gets \(3\delta R_b + 2\delta R_c = 0.0047 \pm 0.0057\), a number still compatible with 0 at the 1-\(\sigma\) level. The current experimental situation, in which the world averaged \(R_b\) is a couple of \(\sigma\) away from the SM and the \(R_c\) anomaly has vanished, would however be explained in a more theoretically-rewarding way by invoking a supersymmetric interpretation.

3 The models and their constraints

A leptophobic \(Z'\) model with the features sketched above is defined by at least 5 parameters: \(M_{Z'}\), the \(Z-Z'\) mixing angle \(\xi\), the coupling to \(L\)-handed quarks \((x)\) and the couplings to \(u\) and \(d\)-handed quarks \((y_{u,d})\). To obtain a consistent model one should also provide a Higgs sector and complete the set of fermions in order to achieve anomaly cancellation. In addition to this, but not mandatory, one might want to consider high-energy embeddings of \(\text{SM} \times U(1)'\) into GUT or string models. The minimal required Higgs sector can be determined by calculating the \(U(1)'\)
charges of the doublet Higgs fields involved in the couplings to the known fermions. It is easy to see the these charges are $x - y_u$, $x - y_d$ and 0 for $u$-quark, $d$-quark and lepton mass terms respectively. Only one Higgs doublet is therefore necessary if $x = y_u = y_d$ (plus a field to break the $U(1)'$ symmetry), two are needed if either $x = y_u$ or $x = y_d$ or $x - y_u = x - y_d \neq 0$, and three Higgs doublets are necessary otherwise. The phenomenology of this extended Higgs sector, by itself, could lead to interesting phenomena and additional features observable at the Tevatron.

The main constraints on the values of the 5 parameters of the models come from precision EW data. The $Z'$ contribution to a generic EW observable $\mathcal{O}$ can be parametrized as follows:

\[
\delta \mathcal{O} = A_\mathcal{O} \delta \rho_M + B_\mathcal{O} (x, y_u, y_d) \xi ,
\]

where

\[
\delta \rho_M = \left[ \left( \frac{M_{Z'}}{M_Z} \right)^2 - 1 \right] \sin^2 \xi
\]

\[
M_{Z'} \sim M_Z \left( \frac{M_Z \xi}{M_Z} \right)^2 .
\]

Typical examples are:

- the total $Z$ hadronic width:

\[
\delta \Gamma_h \sim \xi \left( 0.52 x + 0.28 y_u - 0.21 y_d \right) ,
\]

(2)

which sets a strong correlation among the values of the three couplings because of the per mille accuracy of the agreement between data and SM;

- the weak charge of the Cesium nucleus:

\[
\delta Q_W \sim \xi \left[ 1 - \left( \frac{M_Z}{M_{Z'}} \right)^2 \right] \times (798 x + 376 y_u + 422 y_d) ,
\]

(3)

(experimentally equal to 1.8) which for $M_{Z'} \gg M_Z$ sets an independent correlation among $x$, $y_u$ and $y_d$ because of the large coefficients;

- the $Z \rightarrow b\bar{b}$ partial hadronic width ($R_b$):

\[
\delta R_b \sim \xi \left( -3.2 x + 0.7 y_u + 0.3 y_d \right) .
\]

(4)

Fits performed using pre-Warsaw data, \textit{i.e.} data incorporating the spring results, give (for

\[ M_{Z'} = 1 \text{ TeV}, \ M_H = 300 \text{ GeV and } \alpha_s = 0.118 \):

\[ \xi = (2.8^{+0.9}_{-1.3}) \times 10^{-3} \quad x = -1.4^{+0.6}_{-1.4} \]

\[ y_u = 3.3^{+2.9}_{-1.3} \quad y_d = 1.8^{+2.0}_{-1.0} \]

Fits performed using the Warsaw data give (for $M_{Z'} = 1 \text{ TeV}, \ M_H = 300 \text{ GeV and } \alpha_s = 0.118$):

\[ \xi = (2.2^{+0.9}_{-5.3}) \times 10^{-3} \quad x = -0.49 \pm 0.6 \]

\[ y_u = 2.0 \pm 1.4 \quad y_d = 2.1 \pm 1.7 \]

Notice that, neglecting correlations in the error matrix, all couplings and mixing are now individually compatible with 0 to within 1.5 $\sigma$.

4 \ Z' \ phenomenology \ at \ the \ Tevatron

As already mentioned, one of the appealing features of the leptophobic $Z'$ is its possible connection with the high-$E_T$ jet rate anomaly at the Tevatron. Several other possible implications for the Tevatron physics have been considered in the literature: the enhancement of the top-quark cross section $\left[ \mathcal{E}_T \right]$; the associated production of a light $Z'$ and EW gauge bosons $\left[ \mathcal{E}_T \right]$; the associated production of $W/Z$ with neutral and charged Higgs bosons $\left[ \mathcal{E}_T \right]$; the decay of the $Z'$ into exotic fermions $\left[ \mathcal{E}_T \right]$; the impact of $Z'$-exchange on dijet angular correlations $\left[ \mathcal{E}_T \right]$. We present here the impact

\[ \text{Figure 1: Solid: dijet cross section at the Tevatron from the production of a } Z', \text{ integrated over the mass and rapidity ranges indicated in the plot. Dashes: } 95\% \text{CL Limits on the production cross section of a resonance decaying into jet pairs, as a function of the resonance mass, from CDF data.} \]

\[ M_{Z'} = 1 \text{ TeV}, \ M_H = 300 \text{ GeV and } \alpha_s = 0.118 \]:

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\[ y_u = 2.0 \pm 1.4 \quad y_d = 2.1 \pm 1.7 \]
on some observables which cover the $Z'\,$ mass range $130 < M_{Z'} (\text{GeV}) < 1200$. We used the central values of the fit results presented in the previous section for both the pre-Warsaw and post-Warsaw experimental data. Fig. 1 shows the dijet invariant mass spectrum, in the range $150$–$1000$ GeV, compared to CDF limits on a resonance of mass $M$ and approximate width $\Gamma \sim 0.1M$. The latest $R_{b,c}$ results reduce the window in which a $Z'$ can be excluded from the $280$–$560$ GeV range to the $320$–$500$ GeV range. The reduction in excluded range is not dramatic as one might expect, due to decreased width of the $Z'$, which partly compensates the loss in total production rate by making the signal more peaked. Above $600$ GeV the $Z'$ becomes very wide. Only a small fraction of its rate can be found in a mass region of $\pm 0.1M_{Z'}$, so that no limit can be obtained from bump searches in this region. Coverage down to lower mass values can be obtained from the old UA2 analysis, in which the $90\%$CL excluded range is reduced to a window between $200$ and $250$ GeV. The effect of a $Z'$ on the top production cross section, compared to the SM expectation, is shown in fig. 2. This effect used to set the strongest constraints on a $Z'$ with mass in the region between $300$ and $1000$ GeV. Now one can exclude the region $350$–$600$ GeV, similar to the window excluded by the CDF searches in the $m_{jj}$ spectrum.

The effect of the $Z'$ on the dijet mass spectrum at the Tevatron, compared to current CDF data, is shown in fig. 3 for $1$ TeV $Z'$. As already pointed out in ref. 7, the central values of the typical pre-Warsaw fit would give too large a jet rate in the region around $1000$ GeV, unless the $Z'$ mass were larger than $1.2$ TeV. The reduction in couplings due to the latest fit improves a bit the situation, but again less than naively expected, due to the reduced width which reduces the dijet mass smearing. One could nevertheless argue that the current fits produce a reasonable agreement with the high-mass behaviour of the data. If one neglected the indications that the uncertainty in the gluon density could reduce the jet anomaly, one should accept this as the only remaining evidence for the possible existence of a leptophobic $Z'$.

Figure 2: Same as fig. 1, from UA2 data at the $90\%$CL.

Figure 3: Contribution of the $Z'$ to the total $t\bar{t}$ cross section at the Tevatron (solid), compared to the SM expectation (dashes).

Figure 4: The standard comparison between data and QCD (or $Z'$ vs QCD) for the dijet mass spectrum, on a linear scale. We show results for a $1$ TeV $Z'$, with the set or pre- and post-Warsaw fitted couplings.
5 Conclusions

The new measurements of $R_{c,b}$ seriously undermine the phenomenological motivations for the class of leptophobic $Z'$ models recently considered in the literature. Due to the weakening of the fitted couplings (which are now consistent with 0 at the 1.5-σ level) the mass regions in which a $Z'$ would have given a signal in hadronic collisions are significantly reduced. A $Z'$ in the range below 200 GeV and above 600 GeV would have easily escaped detection so far. The high-$E_T$ jet anomaly at CDF remains as the only set of data supporting, but not necessarily mandating, the existence of a $Z'$.

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