LC-TH-2000-006

Z' indication from new APV data in Cesium and searches at linear colliders

R. Casalbuoni [a,b], S. De Curtis [b]
D. Dominici [a,b], R. Gatto [c] and S. Riemann [d]

a) Dipartimento di Fisica, Univ. di Firenze, I-50125 Firenze, Italia.
b) I.N.F.N., Sezione di Firenze, I-50125 Firenze, Italia.
c) Dépt. de Phys. Théorique, Univ. de Genève, CH-1211 Genève 4, Suisse.
d) DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany.

1 Introduction

In a recent paper [1] a new determination of the weak charge of atomic cesium has been reported. The most precise atomic parity violating (APV) experiment compares the mixing among S and P states due to neutral weak interactions to an induced Stark mixing [2]. The 1.2% uncertainty on the previous measurement of the weak charge Q_W was dominated by the theoretical calculations on the amount of Stark mixing and on the electronic parity violating matrix elements. In [1] the Stark mixing was measured and, incorporating new experimental data, the uncertainty in the electronic parity violating matrix elements was reduced. The new result

$$Q_W(^{133}_{55}Cs) = -72.06 \pm (0.28)_{\rm expt} \pm (0.34)_{\rm theor} \quad (1)$$

represents a considerable improvement with respect to the previous determination [2, 3, 4]

$$Q_W(^{133}_{55}Cs) = -71.04 \pm (1.58)_{\rm expt} \pm (0.88)_{\rm theor} \quad (2)$$

On the theoretical side, Q_W can be expressed in terms of the S parameter [5] or the ϵ_3 [6]

$$Q_W = -72.72 \pm 0.13 - 102\epsilon_3^{\rm rad} + \delta_N Q_W \quad (3)$$

including hadronic-loop uncertainty. We use here the variables ϵ_i (i=1,2,3) of ref. [7], which include the radiative corrections, in place of the set of variables S, T and U originally introduced in ref. [8]. In the above definition of Q_W we have explicitly included only the Standard Model (SM) contribution to the radiative corrections. New physics (that is physics beyond the SM) is represented by the term $\delta_N Q_W$ including also contributions to ϵ_3. Also, we have neglected a correction proportional to $\epsilon_1^{\rm rad}$. In fact, as well known [5], due to the particular values of the number of neutrons ($N = 78$) and of protons ($Z = 55$) in cesium, the dependence on ϵ_1 almost cancels out.

From the theoretical expression we see that Q_W is particularly sensitive to new physics contributing to the ϵ_3 parameter. This kind of new physics is severely constrained by the high energy experiments. From a recent fit [9], the value of ϵ_3 from the high energy data is $\epsilon_3^{\rm expt} = (4.19 \pm 1.0) \times 10^{-3}$.

To estimate new physics contributions to this parameter one has to subtract the SM radiative corrections, which, for $m_{top} = 175\ GeV$ and for $m_H\ (GeV) = 100,\ 300$, are given respectively by

$$\begin{array}{ll} m_H = 100\ GeV & \epsilon_3^{\rm rad} = 5.110 \times 10^{-3} \\ m_H = 300\ GeV & \epsilon_3^{\rm rad} = 6.115 \times 10^{-3} \end{array} \tag{4}$$

Therefore new physics contributing to ϵ_3 cannot be larger than a few per mill. Since ϵ_3 appears in Q_W multiplied by a factor 102, the kind of new physics which contributes through ϵ_3 cannot contribute to Q_W for more than a few tenth. On the other side the discrepancy between the SM and the experimental data is given by (for a light Higgs)

$$Q_W^{\rm expt} - Q_W^{SM} = 1.18 \pm 0.46 \tag{5}$$

where we have added in quadrature the uncertainties. This corresponds to 2.6(2.8)-σ deviation with respect to the SM for $m_H = 100(300)\ GeV$. The 95%CL limits on $\delta_N Q_W$ are

$$0.28 \leq \delta_N Q_W \leq 2.08 \quad \text{for} \quad m_H = 100\ GeV \tag{6}$$

$$0.38 \leq \delta_N Q_W \leq 2.18 \quad \text{for} \quad m_H = 300\ GeV \tag{7}$$

For increasing m_H both bounds increase. One possible contribution to Q_W which was neglected is the difference between neutron and proton spatial distributions in the nucleus. With the increasing APV measurement precision, this effect has been reconsidered [10] adding an additional $\Delta Q_W^{n-p} = \pm 0.3$ to the theoretical error of eq. (1). Including this additional uncertainty, the theoretical error in eq. (1) becomes $\pm(0.45)$ and the deviation with respect to SM for $m_H = 100\ GeV$ decreases from 2.6-σ to 2.2-σ. Our analysis will be based on the result given in eq. (1). The lower positive bounds from eqs. (6) and (7) exclude the SM at 99%CL and, a fortiori, all the models leading to negative extra contribution to Q_W, as for example models with a sequential Z' [11]. This 2.6(2.8)-σ deviation with respect to the SM for $m_H = 100(300)\ GeV$ could be explained by assuming the existence of an extra Z' from E_6 or $O(10)$ or from Z'_{LR} of left-right (LR) models [1, 11, 12, 13].

2 Bounds on extra Z' from Q_W

Let us now look at models which, at least in principle, could give rise to a sizeable modification of Q_W. In ref. [14] it was pointed out that models involving extra neutral vector bosons coupled to ordinary fermions can do the job. The high energy data at the Z resonance strongly bound the $Z - Z'$ mixing [15]. For this reason we will assume zero mixing in the following calculations. In this case $\delta_N Q_W$ is due to the direct exchange of the Z' and is completely fixed by the Z' parameters:

$$\delta_N Q_W = 16 a'_e [(2Z + N) v'_u + (Z + 2N) v'_d] \frac{M_Z^2}{M_{Z'}^2} \tag{8}$$

a'_f, v'_f are the couplings Z' to fermions.

We will discuss the following classes of models involving an extra Z': the LR models and the extra-U(1) models. The relevant couplings of the Z' to the electron and to the up and down quarks are given in the Table 1 of [11]. The different extra-U(1) models are parameterized by the angle θ_6. In [11] we used a different definition of the angle. The relation between the angle θ_2 of ref. [11] and θ_6 is given by $\theta_6 = \theta_2 - \arctan\sqrt{5/3}$.

In the case of the LR model considered in [11] the extra contribution to the weak charge is

$$\delta_N Q_W = -\frac{M_Z^2}{M_{Z'}^2} Q_W^{SM} \tag{9}$$

For this model one has a 95%CL lower bound on $M_{Z'_{LR}}$ from Tevatron [16] given by $M_{Z'_{LR}} \geq 630\ GeV$. A LR model could then explain the APV data

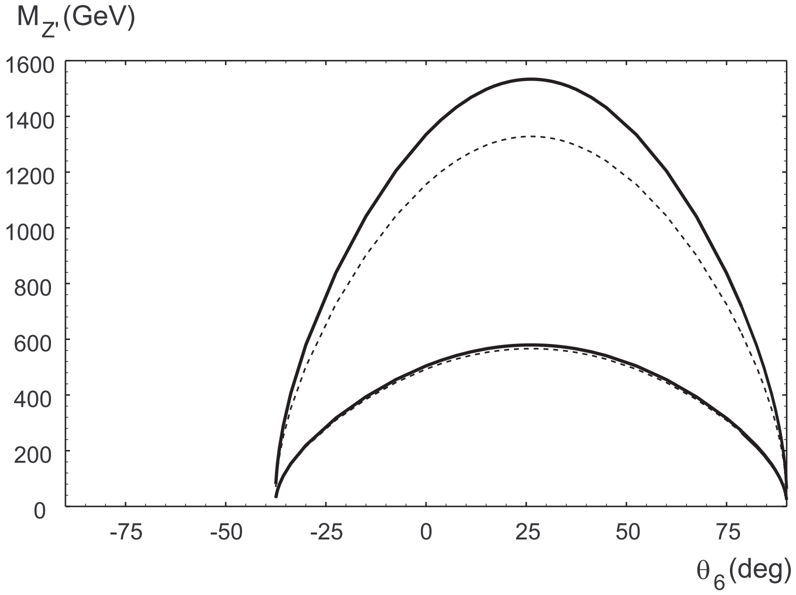

Figure 1 - *The 95%CL lower and upper bounds for $M_{Z'}$ for the extra-U(1) models versus θ_6. The solid and the dash lines correspond to $m_H = 100$ GeV and $m_H = 300$ GeV respectively. The lower bounds from direct search at Tevatron is about* 600 GeV.

allowing for a mass of the Z'_{LR} varying between the intersection from the 95%CL bounds $540 \leq M_{Z'_{LR}}(GeV) \leq 1470$ deriving from eq. (6) and the lower bound of 630 GeV .

In the case of the extra-U(1) models the CDF experimental lower bounds for the masses vary according to the values of the parameter θ_6 which parameterizes different extra-U(1) models, but in general they are about 600 GeV at 95%CL [16]. In particular for the model known in the literature as η (or A), which corresponds to $\theta_6 = \arctan -\sqrt{5/3}$, the 95%CL lower bound is $M_{Z'_\eta} \simeq 620$ GeV, for the model ψ (or C), which corresponds to $\theta_6 = \pi/2$, the lower bound is $M_{Z'_\psi} \simeq 590$ GeV and for the model χ, which corresponds to $\theta_6 = 0$, the lower bound is $M_{Z'_\chi} \simeq 595$ GeV.

By comparing eqs. (6), (7) with eq. (8) we see that the models η and ψ are excluded. The bounds on $\delta_N Q_W$ at 95%CL can be translated into lower and upper bounds on $M_{Z'}$. The result is given in Fig. 1, where the bounds are plotted versus θ_6. In looking at this figure one should also remember that

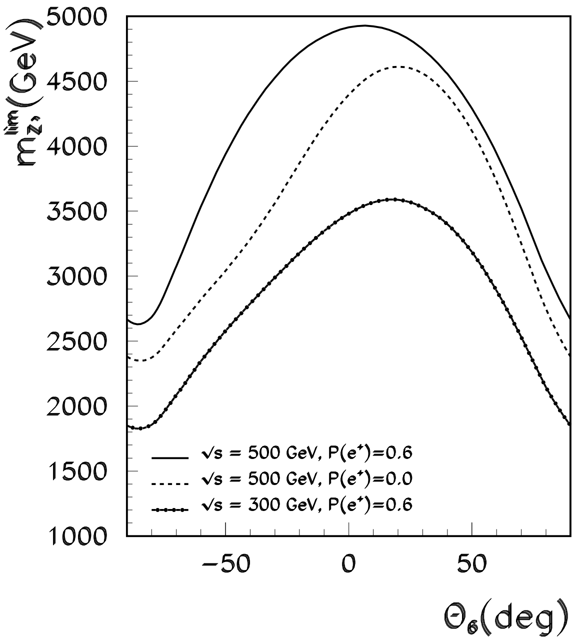

Figure 2 - *95%CL lower bounds for $M_{Z'}$ for the extra-U(1) models versus θ_6 from a LC with $\sqrt{s}=500$ GeV, $L=500$ fb^{-1}, $P_{e^-}=0.9$, $P_{e^+}=0.6$ (solid line), $P_{e^-}=0$ (dash line), $\sqrt{s}=300$ GeV, $L=300$ fb^{-1}, $P_{e^-}=0.9$, $P_{e^+}=0.6$ (solid-dot line).*

the direct lower bound from Tevatron is about 600 GeV at 95%CL. We see that the presence of an extra Z' can explain the discrepancy with the SM prediction for the Q_W for a wide range of θ_6 angle. In particular the χ (or B) model, corresponding to $\theta_6=0$, is allowed for $M_{Z'_\chi}$ less than about 1.2 TeV.

3 Z' at future colliders

The search for a Z' is one of the tasks of future colliders. The existing bounds for E_6 models, $M_{Z'}\sim 600$ GeV from direct search at Tevatron will

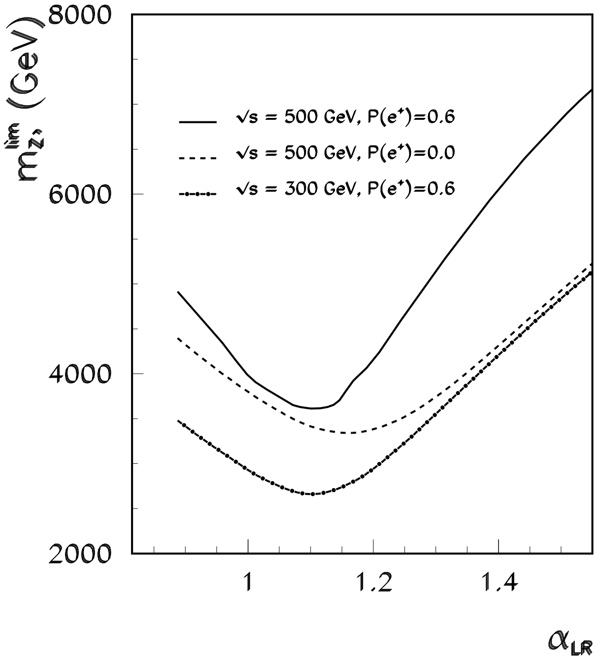

Figure 3 - *Same of Fig. 2 for $M_{Z'_{LR}}$ for the LR models versus α_{LR}.*

be upgraded by the future run with $\sqrt{s} = 2\ TeV$, $L = 1\ fb^{-1}$ to $M_{Z'} \sim 800-900\ GeV$ and pushed to $\sim 1\ TeV$ for $L = 10\ fb^{-1}$. The bounds are based on 10 events in the $e^+e^- + \mu^+\mu^-$ channels and decays to SM final states only is assumed [17]. At the LHC with an integrated luminosity of 100 fb^{-1} one can explore a mass range up to $4-4.5\ TeV$ depending on the θ_6 value. Concerning LR models, the 95%CL lower limits from Tevatron run with $\sqrt{s} = 2\ TeV$, $L = 1(10)\ fb^{-1}$ are $\sim 900(1000)\ GeV$ and extend to $\sim 4.5\ TeV$ at LHC [17]. Therefore if the deviation for Q_W with respect to the SM prediction is not due to a statistical fluctuation but to the presence of new physics like new extra gauge bosons from E_6 or LR models, LHC can verify or disprove this possible evidence. However little can be learned on the Z' properties. With e^+e^- colliders the properties of a Z' can be easily investigated if the center-of-mass energy is large enough to produce it. Anyway, from the measurements

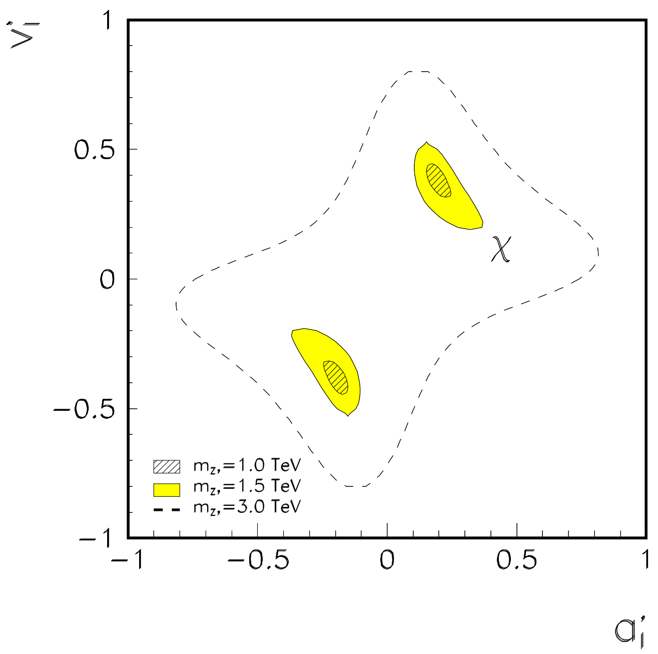

Figure 4 - *95%CL contours for* $(a'_l,\ v'_l)$ *for* $M_{Z'} = 1, 1.5, 3\ TeV$*, and* $\sqrt{s} = 300\ GeV$ *and* $L = 300\ fb^{-1}$.

of $e^+e^- \to \gamma, Z, Z' \to \bar{f}f$ below threshold one can get information about the nature of the Z'. In ref. [18] exclusion limits for M'_Z have been determined from the analysis of all leptonic and hadronic observables. Here we show the upgrading of this analysis for a collider scenario $\sqrt{s} = 500\ GeV$, $L = 500\ fb^{-1}$ and polarized beams: $P_{e^-} = 0.9$, $P_{e^+} = 0.6$ (solid line). The 95%CL lower bounds on $M_{Z'}$ are given in Fig. 2 for different values of θ_6 for E_6 models. Also shown is the case of unpolarized positron beam (dash line) and the case of $\sqrt{s} = 300\ GeV$, $L = 300\ fb^{-1}$ (solid-dot line). The observables which are considered are the total lepton and hadron cross sections, the forward backward asymmetry, the left-right asymmetry (for leptons, hadrons, $c\bar{c}$ and $b\bar{b}$ final states), R_b and R_c. The assumed identification efficiencies are: for leptons $\epsilon_l = 95\%$, for $c\bar{c}$ $\epsilon_c = 40\%$, for $b\bar{b}$ $\epsilon_b = 60\%$ and the corresponding systematic errors $\Delta\epsilon_l/\epsilon_l = 0.5\%$ $\Delta\epsilon_c/\epsilon_c = 1.5\%$, and $\Delta\epsilon_b/\epsilon_b = 1\%$. An

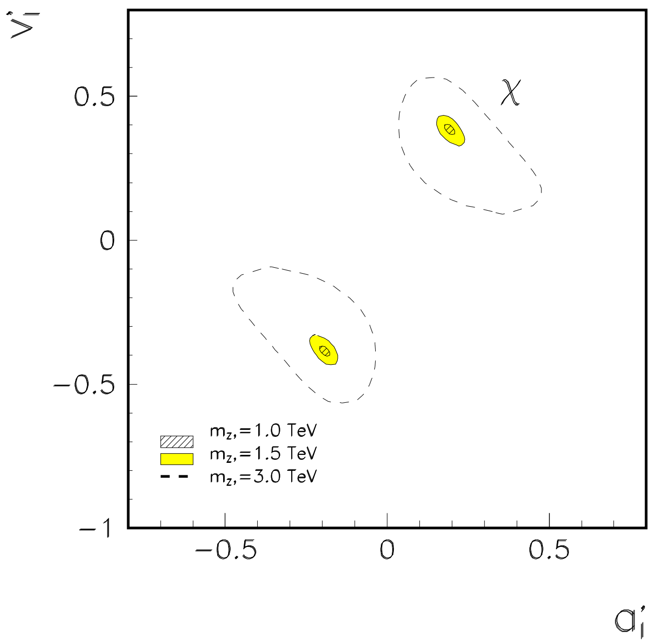

Figure 5 - *Same of Fig. 4 for* $\sqrt{s} = 500\ GeV$ *and* $L = 500\ fb^{-1}$.

uncertainty of 0.5% on the luminosity and $\Delta P/P = 1\%$ are considered.

The same analysis for the LR models leads to a 95%CL lower bound for $M_{Z'_{LR}}$ shown in Fig. 3. For example the particular LR model considered in [11] corresponds to $\alpha_{LR} = \sqrt{\cot^2\theta_W - 1}$ and for this model the bound extracted from Fig. 3 is around $7\ TeV$.

Assuming that the Z' mass is known, one can study the Z' couplings to fermions. The 95%CL contours on $Z'\bar{l}l$ couplings for the χ model for $M_{Z'} = 1, 1.5, 3\ TeV$ are presented in Fig. 4 for $\sqrt{s} = 300\ GeV$ and $L = 300\ fb^{-1}$ and in Fig. 5 for $\sqrt{s} = 500\ GeV$ and $L = 500\ fb^{-1}$. In Fig. 6 the 95%CL contours for $a'_b\ v'_b$ for $M_{Z'} = 1, 1.5\ TeV$, and $\sqrt{s} = 500\ GeV$ and $L = 500\ fb^{-1}$ are shown. The dash lines correspond to $P_{e^+} = 0$.

In conclusion, once a Z'_χ is seen at LHC, already a LC with $\sqrt{s} = 300\ GeV$, $L = 300\ fb^{-1}$ and polarized beams is able to measure the Z'_χ

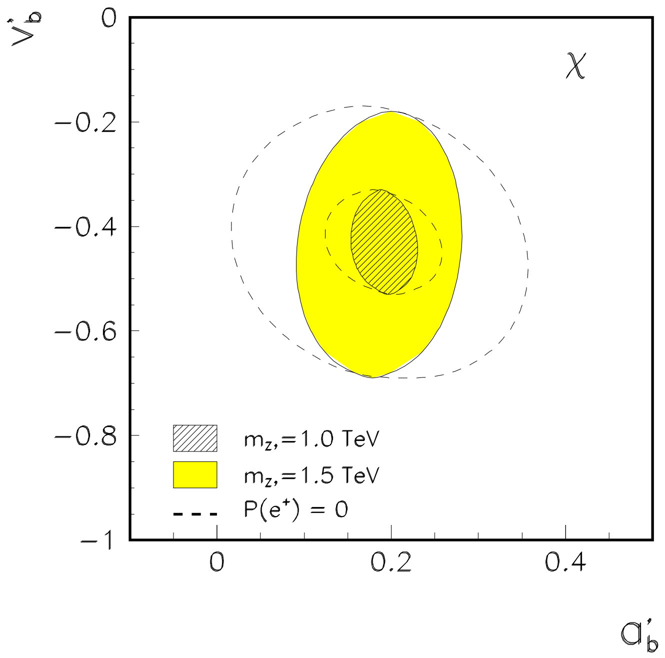

Figure 6 - *95%CL contours for* $(a_b',\ v_b')$ *for* $M_{Z'} = 1, 1.5\ TeV$, *and* $\sqrt{s} = 500\ GeV$ *and* $L = 500\ fb^{-1}$. *The dash lines correspond to* $P_{e^+} = 0$.

couplings to fermions with good precision. For example for a Z'_χ with mass of 1 TeV (which can explain the new APV result) the couplings to leptons can be determined within 10%, unless a sign ambiguity. By increasing the center of mass energy, the precision improves.

References

[1] S.C. Bennett and C.E. Wieman, *Phys. Rev. Lett.* **82** (1999) 2484

[2] C.S. Wood et al., *Science* **275** (1997) 1759

[3] M.C. Noecker, B.P. Masterson and C.E. Wieman, *Phys. Rev. Lett.* **61** (1988) 310

[4] S.A. Blundell, W.R. Johnson and J. Sapirstein, *Phys. Rev. Lett.* **65** (1990) 1411; V. Dzuba, V. Flambaum, P. Silvestrov and O. Sushkov, *Phys. Lett.* **A141** (1989) 147

[5] W.J. Marciano and J.L. Rosner, *Phys. Rev. Lett.* **65** (1990) 2963

[6] See the second reference in [7]

[7] G. Altarelli, R. Barbieri and S. Jadach, *Nucl. Phys.* **B369** (1992) 3; G. Altarelli, R. Barbieri and F. Caravaglios, *Nucl. Phys.* **B405** (1993) 3; *ibidem*, *Phys. Lett.* **B349** (1995) 145

[8] M.E. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65** (1990) 964 and *Phys. Rev.* **D46** (1991) 381

[9] G. Altarelli, private communication

[10] S.J. Pollock and M.C. Welliver, *Phys. Lett.* **B464** (1999) 177

[11] R. Casalbuoni, S. De Curtis, D. Dominici and R. Gatto, *Phys. Lett.* **B460** (1999) 135

[12] J.L. Rosner, hep-ph/9907524

[13] J. Erler and P. Langacker, hep-ph/9910315

[14] G. Altarelli, R. Casalbuoni, S. De Curtis, N. Di Bartolomeo, F. Feruglio and R. Gatto, *Phys. Lett.* **B261** (1991) 146

[15] E. Gross, Contribution to the International Europhysics Conf., Tampere, Finland, 15-21 July

[16] F. Abe et al., *Phys. Rev. Lett.* **79** (1997) 2191

[17] T.G. Rizzo, in "New Directions For High-Energy Physics", Eds. D.G. Cassel, L. Trindle Gennari, R.H. Siemann, Stanford, CA, (1997) and references therein

[18] S. Riemann, in "e^+e^- Linear Colliders: Physics and Detector Studies", Ed. R. Settles, DESY 97-123E, p.227 (1997).