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Relevance of the decay $W' \to W\gamma$ at the early LHC

E. Salvioni(*)

CERN, Physics Department, Theory Unit
CH-1211 Geneva 23, Switzerland

Dipartimento di Fisica, Università di Padova and INFN, Sezione di Padova
Via Marzolo 8, I-35131 Padova, Italy

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Summary. — We study, employing an effective approach, the early LHC phenomenology of an isospin-singlet W', focusing on the process $pp \to W' \to W\gamma$. We discuss how observation of this decay would be a hint of the compositeness of the resonance, and present an estimate of the experimental reach in the 7 TeV LHC run.

PACS 12.60.-i – Models beyond the standard model.

1. – Introduction

In an effective approach, a W' can be broadly defined as a spin-1, color-singlet, unit electric charge state. If we further require a renormalizable coupling to quarks (needed for a sizable production cross section at the LHC), only 2 irreducible representations of the Standard Model (SM) gauge group contain such a state: an isospin singlet with hypercharge $Y = 1$, and an iso-triplet with $Y = 0$ [1]. The latter contains also a neutral Z', which is almost degenerate with the charged W': the strong constraints on Z' from electroweak precision tests and Tevatron/LHC then imply that, in general, an iso-triplet W' needs to be heavier and more weakly coupled than its iso-singlet counterpart, which has no associated Z'(1). In what follows we consider the early LHC phenomenology of a "weakly constrained" iso-singlet W', focusing on the $W' \to W\gamma$ decay channel. For more details, including a discussion of the "first discovery" channels $W' \to jj, tb$, see ref. [2] and references therein.

(*) E-mail: Ennio.Salvioni@cern.ch
(1) This needs not be the case if the coupling to leptons of the isospin triplet is suppressed with respect to its coupling to quarks.

2. – Phenomenological Lagrangian

The Lagrangian containing all the renormalizable interactions between the extra vector and the SM fields reads $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_V + \mathcal{L}_{V-SM}$, where $\mathcal{L}_{SM}$ is the SM Lagrangian, and

$$\begin{aligned}\mathcal{L}_V &= D_\mu V_\nu^- D^\nu V^{+\mu} - D_\mu V_\nu^- D^\mu V^{+\nu} + \tilde{M}^2 V^{+\mu} V_\mu^- \\ &\quad + \frac{g_4^2}{2}|H|^2 V^{+\mu} V_\mu^- - i g_B B^{\mu\nu} V_\mu^+ V_\nu^- \,, \\ \mathcal{L}_{V-SM} &= V^{+\mu}\left(i g_H H^\dagger (D_\mu \tilde{H}) + \frac{g_q}{\sqrt{2}} (V_R)_{ij} \overline{u_R^i} \gamma_\mu d_R^j \right) + \text{h.c.}\end{aligned}$$

We denoted the extra vector by $V_\mu^\pm$. The right-handed (RH) quark mixing matrix V_R is arbitrary in our effective approach; we choose $|V_R| = \mathbf{1}_3$, which gives the weakest bounds from K and B meson mixing [3]. Then, only few parameters describe the resonance: in addition to the W' mass, the couplings $g_H, c_B \equiv g_B/g'$ and g_q will be relevant for our discussion (the coupling g_4 only affects, in a subleading way, the decay $W' \to Wh$). In the mass-eigenstates basis for both vectors and fermions, the W' couples dominantly to RH quark currents. However, W-W' mixing induces couplings of the resonance to $WZ, W\gamma, Wh$ and left-handed lepton currents. All these trilinear vertices are proportional to the W-W' mixing angle $\hat{\theta}$, which is given by $\tan(2\hat{\theta}) = 2\Delta^2/(m_{\hat{W}}^2 - M^2)$, where $m_{\hat{W}}^2 = g^2 v^2/4$, $\Delta^2 = g_H g v^2/(2\sqrt{2})$ and $M^2 = \tilde{M}^2 + g_4^2 v^2/4$ (we denote by g the $SU(2)_L$ gauge coupling).

3. – $W' \to W\gamma$ decay

The partial decay width for $W' \to W\gamma$ can be written, in the limit $M_{W'}^2 \gg M_W$, as $\Gamma(W' \to W\gamma) \approx M_{W'}(e^2/96\pi)(c_B + 1)^2 \hat{\theta}^2 (M_{W'}^2/M_W^2)$, and is therefore controlled by the parameters c_B and $\hat{\theta}$. Before we discuss the LHC phenomenology, we need to ask what are the current bounds on these two parameters.

3·1. *Theoretical constraints on* c_B. – The coupling c_B is not significantly constrained by current data. However, perturbative unitarity arguments imply that if the W' is an elementary gauge boson, then its gyromagnetic ratio $g_{W'}$ must be equal to 2 at the tree level [4]. Since $g_{W'} = 2 - \cos^2\hat{\theta}\,(1 + c_B)$, this implies $c_B = -1$ at tree level. Therefore, if the W' is a gauge boson, the decay $W' \to W\gamma$ is expected to be very suppressed, and out of the LHC reach. On the other hand, if the W' is a composite vector, the requirement of preservation of perturbative unitarity is relaxed, and $c_B \neq -1$ can be realized (however, one still needs to check that the cutoff is sufficiently larger than $M_{W'}$, see ref. [2]).

3·2. *Bounds on* $\hat{\theta}$. – The W-W' mixing angle is constrained both by the electroweak T parameter, and by semi-leptonic $u \to d, s$ transitions. A detailed analysis of the bounds can be found in ref. [2]. For example, for a W' mass of 800 GeV, the bound from T is $|\hat{\theta}| < 10^{-3}$, whereas semi-leptonic processes give $-1.6 \times 10^{-3} < g_q\hat{\theta} < 1.7 \times 10^{-3}$ in the limit of negligible CP phases in V_R [5]. If such phases are larger, however, the latter bound gets relaxed: $|g_q\hat{\theta}| < 10^{-1\div-2}$ is obtained for maximal CP phases [3].

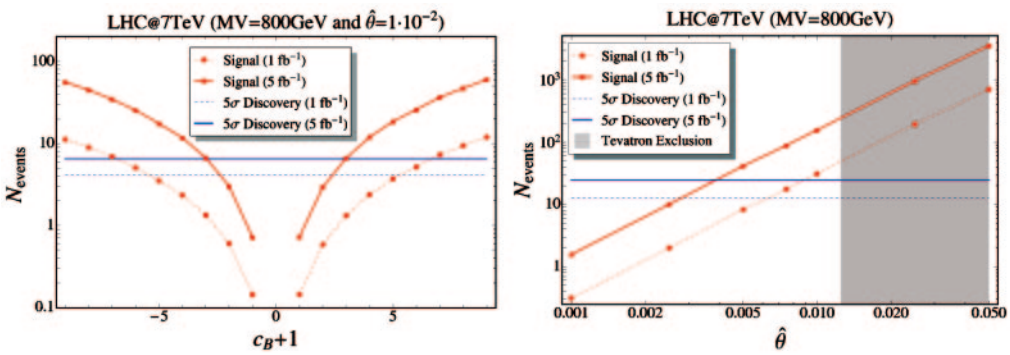

Fig. 1. – (Colour on-line) 5σ discovery prospects of the 7 TeV LHC for the $W' \to W\gamma \to e\nu\gamma$ process, for $M_{W'} = 800\,\text{GeV}$, $g_q = 0.84g$. The red curves show the expected number of events as a function of the parameters of our phenomenological Lagrangian, whereas the blue flat lines represent the number of events needed for a 5σ discovery, taking into account the SM background. The region shaded in grey is excluded at 95% CL by searches for resonances decaying into WZ at the Tevatron.

4. – Search for $W' \to W\gamma$ at the early LHC

To illustrate the early LHC prospects in the $W' \to W\gamma$ channel, we choose a benchmark point, namely a W' mass of 800 GeV and a coupling to quarks $g_q = 0.84g$, which is the largest value allowed by current bounds [2]. We select decays of the W into an electron and a neutrino, and apply a set of simple cuts on the $e\gamma\not{E}_T$ final state, to enhance the signal-to-background ratio [2]. The background considered is irreducible $W\gamma$ production in the SM. Our results for the benchmark point chosen are displayed in fig. 1: discovery of the $W' \to W\gamma$ decay is possible, with $5\,\text{fb}^{-1}$ of integrated luminosity at a LHC center-of-mass energy of 7 TeV, for $|c_B + 1| > 2 \div 3$ and few $\times\, 10^{-3} < \hat{\theta} < 10^{-2}$. While such values of the mixing angle are in tension with the constraint from the T parameter, it is conceivable that a positive contribution to T from additional new physics (such as, *e.g.*, a Z') may relax this tension. On the other hand, measurements of semi-leptonic transitions are compatible with such relatively large values of $\hat{\theta}$, provided the phases in V_R are non-negligible.

5. – Conclusion

We have presented the prospects for discovering at the early LHC the decay $W' \to W\gamma$, where the W' is an iso-singlet charged heavy vector. This process is of special interest, since it is very suppressed if the W' is an elementary gauge boson, but could be observable if the W' is a composite state, as discussed above. To conclude, the decay $W' \to W\gamma$ should be searched for at the early LHC, because its observation would be a hint of the compositeness of the W', and would thus shed some light on the theoretical origin of the resonance after its first discovery in the jj or tb channels.

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