please insert the following text after section **1.2.7**

Excited $Z^\star$ boson

The Z' minimal gauge couplings to the Standard Model fermions discussed in the previous section are not general ones. Additional gauge-invariant anomalous (magnetic moment type) couplings with the known fermions are also possible [1]

$$\mathcal{L}_{\rm NC}^{\rm anom} = \frac{g}{2\Lambda}\,\bar\psi\,\sigma^{\mu\nu}\psi\,\left(\partial_\mu Z^\star_\nu - \partial_\nu Z^\star_\mu\right). \tag{1}$$

Such couplings can demonstrate the compositeness of nature and the excited origin of new bosons, where the parameter Λ is connected to the compositeness mass scale of the new physics.

The existence of such states with masses not far from the weak scale is also motivated by the hierarchy problem [2]. The effective interaction (1) can be induced by quantum loop corrections from a renormalizable underlying theory and represents the lowest order effective Lagrangian for the excited bosons interacting with the Standard Model fermions.

In contrast with the minimal gauge couplings, where either only left-handed or right-handed fermions participate in the interactions, the tensor currents mix both left-handed and right-handed fermions. Therefore, like the Higgs particles, the excited bosons carry a nonzero chiral charge and according to the symmetry of the Standard Model they should be introduced as the electroweak doublets $(Z^\star\ W^\star)$ [3] with the internal quantum numbers identical to the Higgs doublet.

Here we focus on the discovery potential and the exclusion limits at the hadron colliders for the excited bosons $Z^\star$, rather for the well-known Z' bosons from the previous section. Compared to other heavy bosons, interactions mediated by $(Z^*\ W^*)$ are additionally suppressed in low-energy processes by powers of the small momentum transfer. Thus, the search of the excited bosons is especially motivated at the LHC and future colliders and at present is conducted by the ATLAS Collaboration [4, 5]. Besides, the derivative couplings lead to unique signatures for detection of such bosons at the hadron colliders. The excited bosons possess unexplored previously angular distribution, which leads to a new strategy of the resonance search [6, 7].

The dilepton final states, like e^+e^- and $\mu^+\mu^-$, are the most clear channels for new heavy neutral resonance search. We have used the simplified reference model ESM [8] for the excited bosons. The only down-type neutral $Z^\star$ boson interacts with quarks and charged leptons. Therefore, it can be produced at hadron colliders and can be seen in the leptonic final states in the Drell–Yan process. The reach at the LHC and HL-LHC are presented in Fig. 1 (see [9] for details). In particular, LHC Run 2 can discover $Z^\star$ up to about 5.5 TeV, while the HL-LHC can extend that reach

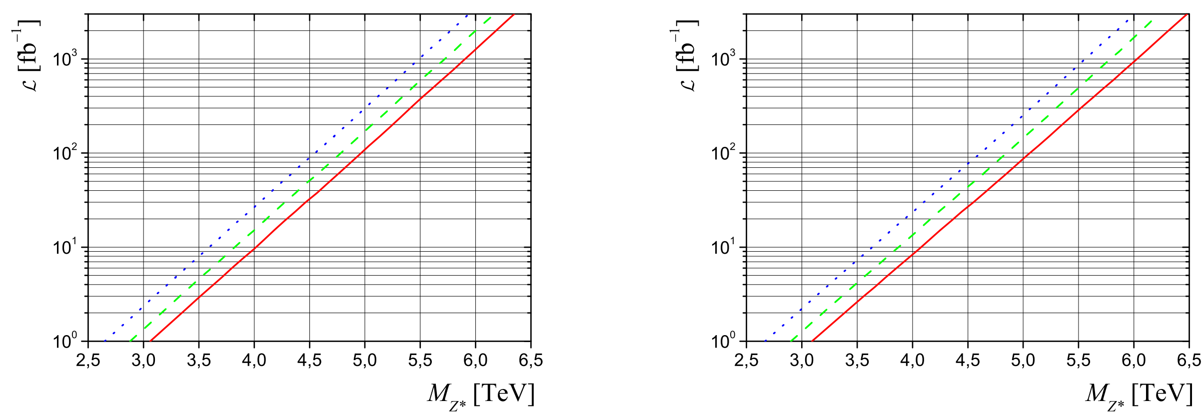
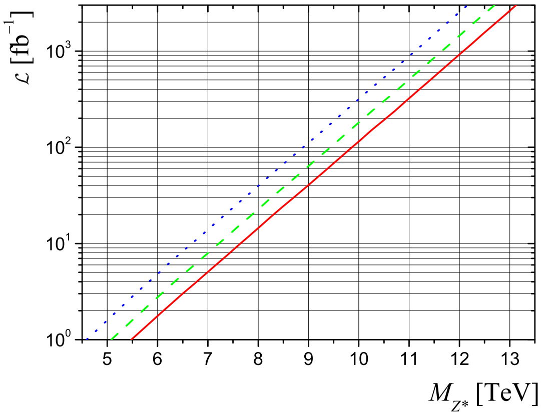


FIG. 1: The discovery potential (left) and the expected 95% CL exclusion limits (right) at $\sqrt{s} = 14$ TeV from muon (dotted), electron (dashed) and combined (solid) channels.

to about 6.5 TeV. The HE-LHC, of course, can extent it further (see Fig. 2).

[1] M.V. Chizhov, V.A. Bednyakov, J.A. Budagov, Phys. Atom. Nucl. 71 (2008) 2096-2100, arXiv:0801.4235 [hep-ph].



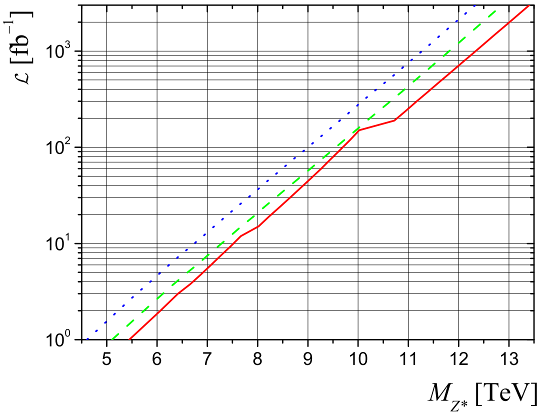


FIG. 2: The discovery potential (left) and the expected 95% CL exclusion limits (right) at $\sqrt{s} = 33$ TeV from muon (dotted), electron (dashed) and combined (solid) channels.

[2] M.V. Chizhov, Gia Dvali, Phys. Lett. B703 (2011) 593-598, arXiv:0908.0924 [hep-ph].
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[5] ATLAS Collaboration, Eur. Phys. J. C72 (2012) 2241, arXiv:1209.4446 [hep-ex].
[6] M.V. Chizhov, V.A. Bednyakov, J.A. Budagov, Phys. Part. Nucl. Lett. 10 (2013) 144-146, arXiv:1109.6876 [hep-ph].
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[9] M.V. Chizhov, V.A. Bednyakov, J.A. Budagov, arXiv:1307.7274 [hep-ph].