Dimuon enhancement at 28 GeV and tentative (pseudo)scalar partner of the \( Z \) boson at 57.5 GeV

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Abstract

The CMS Collaboration at the LHC recently reported an accumulation of data around 28 GeV in the invariant-mass distribution of muon pairs in association with a \( b \) quark jet and at least a second jet. This is analysed here in the light of the possible existence of a (pseudo)scalar boson with mass of about 57.5 GeV. We find that part of the data may originate in the radiative decay of \( Z \) bosons into pairs consisting of the lighter boson and a photon, giving rise to dimuon decay products that either stem from the photon or from the (pseudo)scalar boson.

However, recently the interest in weak substructure has been renewed \(^{20}\)\(^{24}\), also due to the detection of the Higgs boson at the LHC \(^5\)\(^{25}\).

In Ref. \(^19\) a comparison of gauge-boson partner states to mesons with matching quantum numbers led to mass predictions of the order of 300 GeV, with the exception of the scalar state, being identified with the Higgs. The corresponding pseudoscalar boson, not discussed in Ref. \(^19\), would then most likely be lighter than the \( W^\pm \) and \( Z \), just like the pion is (much) lighter than the \( \rho \) meson. Furthermore, in the meson sector the scalar \( f_0(500) \) (alias \( \sigma \)) is even lighter than the \( \rho \).

Now, very recently the CMS Collaboration reported \(^{26}\) on a data analysis that appears to support the hypothesis of a \( Z \rightarrow \gamma Z_0 \) decay process, with a \( Z_0 \) mass of 57.5 GeV and a photon energy of about 28 GeV. Namely, in the latter study an excess of 19.7 fb\(^{-1}\) at the LHC \(^{25}\) was observed near a dimuon invariant mass of 28 GeV, with a significance of 4.2 standard deviations. The data had been collected in 2012 with the CMS detector in proton-proton collisions at the LHC, for centre-of-mass (CM) energies of 8 TeV and with an integrated luminosity of 19.7 fb\(^{-1}\). The event selection required at least one jet in the central and the forward pseudorapidity region, respectively. The result is depicted in Fig. \(^2\).

The reader should be aware that the data in Fig. \(^2\) are to be considered with some caution. In a different dimuon data selection with higher statistics, the CMS Collaboration obtained a signal near 28 GeV with a significance of only 2.9 standard deviations. The data had been collected in 2011 with the CMS detector in proton-proton collisions at the LHC, for CM energies of 7 TeV and with an integrated luminosity of 5.1 fb\(^{-1}\). The event selection required at least one jet in the central and the forward pseudorapidity region, respectively. The result is depicted in Fig. \(^3\).

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In three previous papers \(^{1,3}\) we argued that data indicate the possible existence of a (pseudo)scalar boson with mass of about 57.5 GeV. In Ref. \(^1\) we focused on a dip at about 115 GeV in diphoton data published \(^4\) by the Compact-Muon-Solenoid (CMS) Collaboration at the Large Hadron Collider (LHC), corroborated by similar data by the ATLAS Collaboration \(^5\). We interpreted this dip as the threshold for the production of a pair of (pseudo)scalar bosons with a mass of about 57.5 GeV. In the following we will refer to such a boson as \( Z_0 \).

In Ref. \(^2\) we showed that the dip at about 115 GeV in the diphoton data of the CMS and ATLAS Collaborations is also corroborated by four-lepton signals published by CMS \(^6\) and ATLAS \(^7\). This dip is compatible with older data for \( \tau\tau \) in \( e^+e^- \rightarrow \tau\tau(\gamma) \) and \( \mu\mu \) in \( e^+e^- \rightarrow \mu\mu(\gamma) \) by the L3 Collaboration \(^8\). All data, shown in Fig. \(^1\) indeed seem to indicate that the total signal in the 115–133 GeV mass interval is in fact the sum of two different contributions viz. a broad non-resonant threshold enhancement preceded by a sharp dip at about 115 GeV and a resonance around 125 GeV.

![FIGURE 1: Diphoton signals published by CMS \(^9\) (●) and ATLAS \(^7\) (●), four-lepton signals by CMS Collaboration \(^6\) (●) and ATLAS \(^7\) (●), invariant-mass distributions for \( \tau\tau \) in \( e^+e^- \rightarrow \tau\tau(\gamma) \) (●) and \( \mu\mu \) in \( e^+e^- \rightarrow \mu\mu(\gamma) \) (●) by L3 \(^8\).](image1)

![FIGURE 2: Data on the dimuon mass distribution in \( Z \) decays, taken from Ref. \(^{25}\).](image2)
deviations. Moreover, in related dimuon events selected from data collected at the LHC in 2016, for proton-proton collisions at CM energies of 13 TeV and corresponding to an integrated luminosity of 35.9 fb\(^{-1}\), CMS found near 28 GeV signals of 2.0 standard deviations and a 1.4 standard-deviation deficit for the two mutually exclusive dimuon-event categories. Accordingly, CMS concluded [26] that more data and additional theoretical input are required to understand the results.

At present there are in the literature interpretations that the CMS dimuon signal may explain the discrepancy between the experimentally measured and theoretically predicted muon anomalous magnetic moment [27], or might be modelled as a pseudoscalar mixture of toponium and gluonium [28].

A closer look at the data depicted in Fig. 2 reveals a second accumulation of data near 57 GeV. Now, if we assume that the \(Z_0\) does exist, then in the reaction \(Z \rightarrow \gamma Z_0\) the \(Z_0\) and the intermediate photon have masses of 57.5 and 28 GeV, respectively. Moreover, both particles couple to dimuons. This would partly explain why the data show two enhancements, i.e., one near 28 GeV and one near 57 GeV. We say “partly”, because one would expect the \(Z_0\) to be much less likely to decay into muon pairs than the photon. Actually, one expects the \(Z_0\) to dominantly couple to \(\gamma\gamma\).

In Fig. 3 we collect data for the reaction \(Z \rightarrow \gamma Z_0 \rightarrow \gamma\gamma\gamma\) published by the L3 Collaboration [29] and for the diphoton mass distribution from the CMS Collaboration [30]. The L3 Collaboration used 65.8 pb\(^{-1}\) of data taken during the 1991–1993 runs at the Large Electron-Positron Collider (LEP) on top of and around the \(Z\) peak, for CM energies between 88.5 and 93.7 GeV. On the other hand, the CMS analysis is based on 5 fb\(^{-1}\) isolated diphoton production cross sections collected at 7 TeV pp CM energies in the year 2011.

![Figure 3](image)

**Figure 3:** (a): Experimental data for the three one-photon CM energies of the 87 candidate \(Z \rightarrow 3\gamma\) events measured by the L3 Collaboration [29], assuming \(\sqrt{s} = M_Z\). The histogram was obtained by L3 from a Monte-Carlo simulation for the expected number of events predicted by QED. With the green band we indicate where we expect photons from the radiative process \(Z \rightarrow \gamma Z_0\) for the case that \(Z_0\) has a mass of 57.5 GeV. (b): The same data as shown in (a), but now measured events divided by QED-expected events. (c), (d): Measured over expected events for diphoton invariant-mass distributions published by the CMS Collaboration [30], for (c) DIPHOX and (d) RESBOS.

In Fig. 3b we depict the L3 data for the three one-photon CM energies for each of the candidate events. L3 expressed the one-photon CM energies as a function of \(M_{\gamma\gamma}\). Here, we convert this information into \(M_{\gamma\gamma}\), while assuming \(\sqrt{s} = M_Z\). Moreover, we indicate where we expect the photons from the radiative process \(Z \rightarrow \gamma Z_0\) by a green band. One sees that most of the L3 data agree well with the expectation from QED. Nevertheless, be it a coincidence or not, in the mass region where we expect a signal from \(Z \rightarrow \gamma Z_0\) events, we observe a small enhancement. This can be demonstrated better by showing the ratio of measured signal over QED prediction, as depicted in Fig. 3c. Now one clearly observes a modest enhancement, for exactly the expected \(Z_0\) mass of 57.5 GeV.

Finally, in Fig. 3d we show diphoton invariant-mass distributions measured by the CMS Collaboration [30] for predictions of a DIPHOX data simulator and in Fig. 3d for CMS predictions using RESBOS. In both figures one again observes an excess of three times more data than predicted in the 40–60 GeV mass interval. This could be in agreement with diphotons stemming from the reaction \(Z_0 \rightarrow \gamma\gamma\).

Summarising, we have shown in the foregoing that our prior work on a possible weak substructure [1–3] is compatible with the observed enhancements in dimuon invariant-mass distributions recently reported by the CMS Collaboration [26]. Moreover, the decay mode \(Z_0 \rightarrow \mu\mu\) favours a pseudoscalar assignment for the \(Z_0\).

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