Dimuon resonance near 28 GeV and muon anomaly

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Abstract

We discuss if the resonance recently observed by CMS can be responsible for the deviation of the experimentally measured muon anomalous magnetic moment from the theoretical prediction.
I. INTRODUCTION

The CMS collaboration has recently reported a peak at invariant mass

\[ m_X = 28.3 \pm 0.4 \text{ GeV} \] (1)

of \( \mu^+\mu^- \) pairs produced in association with \( b \) jet in \( pp \)-collisions at the LHC \[1\]. The peak appeared in the 8 TeV data with \( 19.7 \text{ fb}^{-1} \) of integrated luminosity, while no significant excess was found in the 13 TeV data with \( 35.9 \text{ fb}^{-1} \) of integrated luminosity. The observation was made for two event categories with different cuts on jets directions with the local significancies of 4.2 and 2.9 standard deviations (see the paper for the details). The fiducial cross section for both categories is at the level of 4 \( \text{fb} \). Signal selection efficiency can strongly depend on the production process, so to evaluate the total \( \sigma \times \text{Br}(X \rightarrow \mu^+\mu^-) \) a particular model is required. The CMS paper does not study any specific model, so only the fiducial cross sections were provided.

The reported width of the peak is

\[ \Gamma_X^{(\text{exp.})} = 1.8 \pm 0.8 \text{ GeV} \] (2)

which is several times larger than the expected mass resolution for a dimuon system \( \sigma_{\mu\mu} = 0.45 \text{ GeV} \).

We shall study whether the resonance \( X \) (if its existence will be confirmed in the future) can explain the deviation of the measured value of the muon anomalous magnetic moment \( a_\mu \equiv (g - 2)_\mu/2 \) from the Standard Model value

\[ \delta a_\mu \equiv a_\mu^{\text{exp.}} - a_\mu^{\text{SM}} = \begin{cases} (31.3 \pm 7.7) \times 10^{-10}, & \text{see } [2], \\ (26.8 \pm 7.6) \times 10^{-10}, & \text{see } [3]. \end{cases} \] (3)

In the following numerical estimates we will use the average of these two values:

\[ \delta a_\mu = (29 \pm 8) \times 10^{-10}. \] (4)

II. \( X \) CONTRIBUTIONS TO \( \delta a_\mu \)

Let us consider the Standard Model extended with a field \( X \). Its contribution to the muon anomalous magnetic moment depends on \( X \) spin. We will consider the following four possibilities:
scalar $S$, pseudoscalar $P$, vector $V$, axial vector $A$. Their coupling to muons is described by the following terms in the Lagrangian:

$$\Delta L_{S\mu\mu} = Y_{S\mu\mu} \bar{\mu} \mu S$$  \hspace{1cm} \text{(scalar $X$)},

$$\Delta L_{P\mu\mu} = i Y_{P\mu\mu} \bar{\mu} \gamma_5 \mu P$$  \hspace{1cm} \text{(pseudoscalar $X$)},

$$\Delta L_{V\mu\mu} = Y_{V\mu\mu} \bar{\mu} \gamma_\mu \mu V$$  \hspace{1cm} \text{(vector $X$)},

$$\Delta L_{A\mu\mu} = Y_{A\mu\mu} \bar{\mu} \gamma_\mu \gamma_5 \mu A$$  \hspace{1cm} \text{(axial vector $X$)}. \hspace{1cm} (5)$$

An exchange of $X$ contributes at one loop to $a_\mu$ (see Fig. 1). The following results were obtained in [4, Eq. (260)]:

$$\delta a^S_\mu = \frac{Y_{S\mu\mu}^2}{4\pi^2} \left( \frac{m_\mu}{m_X} \right)^2 \left[ \ln \frac{m_X}{m_\mu} - \frac{7}{12} \right]$$  \hspace{1cm} \text{(scalar $X$)}, \hspace{1cm} (6)

$$\delta a^P_\mu = \frac{Y_{P\mu\mu}^2}{4\pi^2} \left( \frac{m_\mu}{m_X} \right)^2 \left[ - \ln \frac{m_X}{m_\mu} + \frac{11}{12} \right]$$  \hspace{1cm} \text{(pseudoscalar $X$)}, \hspace{1cm} (7)

$$\delta a^V_\mu = \frac{Y_{V\mu\mu}^2}{4\pi^2} \left( \frac{m_\mu}{m_X} \right)^2 \cdot \frac{1}{3}$$  \hspace{1cm} \text{(vector $X$)}, \hspace{1cm} (8)

$$\delta a^A_\mu = \frac{Y_{A\mu\mu}^2}{4\pi^2} \left( \frac{m_\mu}{m_X} \right)^2 \cdot \left( \frac{-5}{3} \right)$$  \hspace{1cm} \text{(axial vector $X$)}, \hspace{1cm} (9)

where $m_X \gg m_\mu$ is supposed. Only the scalar and vector $X$ can resolve the discrepancy [4]. Equating (4) to $\delta a^S_\mu$ and $\delta a^V_\mu$ results in

$$Y_{S\mu\mu} = 0.041 \pm 0.006,$$

$$Y_{V\mu\mu} = 0.16 \pm 0.02.$$  \hspace{1cm} (10)
In this case the $X \to \mu^+\mu^-$ decay width

$$
\Gamma(S \to \mu^+\mu^-) = \frac{Y^2_{\rm S\mu\mu}}{8\pi} m_X \left(1 - \frac{4m_\mu^2}{m_X^2}\right)^{3/2} = 1.8 \pm 0.5 \text{ MeV},
$$

$$
\Gamma(V \to \mu^+\mu^-) = \frac{Y^2_{\rm V\mu\mu}}{8\pi} m_X \sqrt{1 - \frac{4m_\mu^2}{m_X^2}} = 28 \pm 8 \text{ MeV},
$$

and the corresponding branching ratios

$$
\text{Br}(X \to \mu^+\mu^-) = \frac{\Gamma(X \to \mu^+\mu^-)}{\Gamma_{\text{exp.}}^{X}} = \begin{cases} 
(1.0 \pm 0.5) \cdot 10^{-3} & \text{for } S \to \mu^+\mu^-, \\
(1.5 \pm 0.8) \cdot 10^{-2} & \text{for } V \to \mu^+\mu^-.
\end{cases}
$$

Since the uncertainty in the measurement of $\Gamma_X$ is rather large, the $X \to \mu^+\mu^-$ decay can dominate or even be the only decay of $X$.

Another possibility is that $X$ can decay to other particles. For the scalar, such a small branching ratio can be naturally explained if $S$ couples to $\tau^+\tau^-$ as well, and the coupling constants are proportional to $\mu$ and $\tau$ masses correspondingly. Then

$$
\Gamma(S \to \tau^+\tau^-) = \left(\frac{m_\tau}{m_\mu}\right)^2 \Gamma(S \to \mu^+\mu^-) = 0.52 \pm 0.15 \text{ GeV},
$$

which is in agreement with the reported value (2).

One of the most natural generalizations of the SM is the model with additional heavy Higgs doublet, the so-called two Higgs doublets model (2HDM). Quite unexpectedly, the leading contributions to $a_\mu$ in this model for some values of parameters arise at the two-loop level (see Fig. 2), and light spin zero particle is needed to compensate the two-loop suppression [5–14]. It was found that a light pseudoscalar boson $P$ with strong couplings to leptons could explain the current value of $\delta a_\mu$ (4). According to a recent paper [15], in a very small parameter region around $m_A = 20$ GeV the extra contribution to $a_\mu$ even exceeds the one needed to explain deviation (1). That is why it looks very appealing to identify the resonance found in [1] as the pseudoscalar boson $P$ from 2HDM, resolving simultaneously the problem with muon anomaly. For this reason we will not discard pseudoscalar $P$ from consideration yet.

III. LEP DATA AND $X$

If $X$ is responsible for the muon anomaly then we know $X$ coupling to muons, see Section [11]. In this section we are going to investigate how $X$ modifies $Z$ boson properties.
FIG. 2. Two-loop contribution of $P$ to $\delta \alpha$. 

The width of $Z$ decay to a fermion-antifermion pair and a pseudoscalar is

$$\Gamma(Z \to f \bar{f} X) = \frac{\alpha}{128\pi^2 \sin^2 \theta_W \cos^2 \theta_W} \frac{m_Z}{3} N_c \gamma^2 \chi^2 \left((g_A^2 + g_V^2)F_1 + (g_V^2 - g_A^2)F_2\right),$$  \hspace{1cm} (14)

where $N_c$ is the number of fermion colors, $g_V$ and $g_A$ are the axial and vector couplings of the fermion to the $Z$ boson ($g_V = T_3$, $g_A = T_3 - 2Q \sin^2 \theta_W$, $T_3$ is the third component of the weak isospin, and $Q$ is the electric charge of the fermion),

$$F_1 = -2(1 + 3a) \ln a + \frac{1}{3}(1 - a)(a^2 - 8a - 17),$$

$$F_2 = 2a(5 + 3a) \ln a - \frac{1}{3}(1 - a)(a^2 - 44a - 5)$$

$$+ 4a^2 \left[\frac{1}{2} \ln^2 a - \ln a \ln(1 + a) + \Li_2 \left(\frac{a}{1 + a}\right) - \Li_2 \left(\frac{1}{1 + a}\right)\right],$$  \hspace{1cm} (15)

where $a = m_X^2/m_Z^2$, and $\Li_2(x)$ is the dilogarithm,

$$\Li_2(x) = -\int_0^x \frac{\ln(1 - z)}{z} \, dz.$$

In this formula the fermion is assumed to be massless, and in this limit it also works for the scalar $X$.

The $X$ particle will provide an extra contribution to $Z \to 4\mu$ decay through the following process: $Z \to \mu^+\mu^-X(\to \mu^+\mu^-)$. According to (14),

$$\Gamma(Z \to \mu^+\mu^-X) = 6.4 \cdot 10^{-5} \times Y_{S\mu\mu}^2 \text{ GeV} \approx 105 \text{ eV},$$  \hspace{1cm} (16)

where the value of $Y_{S\mu\mu}$ from (10) was substituted. Hence

$$\Br(Z \to \mu^+\mu^-X(\to \mu^+\mu^-)) \approx 4.2 \cdot 10^{-8} \Br(X \to \mu^+\mu^-),$$  \hspace{1cm} (17)

and even for $\Br(X \to \mu^+\mu^-) = 1$, it is one order of magnitude less than the experimental error:

$$\Br(Z \to 4\ell) = (3.5 \pm 0.4) \cdot 10^{-6} \text{ [17]}.\hspace{1cm}$$
The width of $X$ of the order of 1 GeV may be explained by $X \rightarrow \tau^+\tau^-$ and/or $X \rightarrow \nu\bar{\nu}$ decays. The upper limit on the $Y_{X\tau\tau}$ coupling can be obtained from the results of the DELPHI collaboration on the search of $Z \rightarrow \tau^+\tau^-h(\rightarrow \tau^+\tau^-)$ decays. According to [18, Fig. 11], the value of $Y_{X\tau\tau} = 100 m_\tau/v \approx 0.7$ is allowed at 95% C.L., where $v \approx 246$ GeV is the Higgs boson expectation value. In this case $\Gamma_X \approx 0.6$ GeV both for the scalar and pseudoscalar $X$, which is in agreement with the estimate [13].

$X \rightarrow \nu\bar{\nu}$ decay increases the invisible $Z$ boson width by the following quantity:

$$\Gamma(Z \rightarrow \nu\bar{\nu}X) = 0.4 Y_{X\nu\bar{\nu}}^2 \text{ MeV}. \quad (18)$$

Since experimental uncertainty in the value of $\Gamma(Z \rightarrow \text{invisible})$ is about 1.5 MeV, the value of $Y_{X\nu\bar{\nu}}$ of the order of one is allowed leading to a GeV width of $X \rightarrow \nu\bar{\nu}$ decay.

IV. CAN $X$ BE PRODUCED VIA RADIATION FROM $b$ QUARK?

The $X$ boson is seen by the CMS in association with at least one $b$-tagged jet. Let us consider if it can be produced via radiation from $b$ quark. Let the coupling of $X$ with $b$-quarks be described by interactions analogous to (5):

$$\Delta L_{Sbb} = Y_{Sbb} \bar{b}b S \quad \text{(scalar } X),$$
$$\Delta L_{Pbb} = i Y_{Pbb} \bar{b}\gamma_5 b \hspace{1pt} P \quad \text{(pseudoscalar } X),$$
$$\Delta L_{Vbb} = Y_{Vbb} \bar{b}\gamma_\mu b V_\mu \quad \text{(vector } X),$$
$$\Delta L_{Abb} = Y_{Abb} \bar{b}\gamma_\mu\gamma_5 A_\mu \quad \text{(axial vector } X). \quad (19)$$

In Ref. [1], the CMS collaboration reports fiducial cross sections for two event categories. In both cases exactly two jets with high $p_T$ are required, one of which is $b$-tagged, and the $b$-tagged jet has to be in the barrel region. The main difference between the categories is in the direction of the untagged jet: it can be in either the endcap or the barrel regions. In the following the first event category will be considered since it possesses the highest significance of 4.2 standard deviations. The corresponding fiducial cross section is

$$\sigma_{\text{fid.1}} = 4.1 \pm 1.4 \text{ fb}, \quad (20)$$

and the cuts are summarized in Table 1 from [1].

To calculate the cross section of $X$ production at the LHC, CalcHEP 3.6.30 [19] was used. CalcHEP parameters were updated to their modern values according to Ref. [17].
MMHT2014nnlo68cl \cite{20} from the Les Houches PDF library \cite{21} was used as the set of parton distribution functions.

Calculated cross sections for the first event category cuts (fiducial cross sections) are presented in Table I. Thus, the events with two $b$ jets correspond to approximately one sixth of the reported fiducial cross section \cite{20}.

The search for the light pseudoscalar boson, produced in association with two $b$ jets and decaying into two muons, was performed at $\sqrt{s} = 8$ TeV in the previous CMS paper \cite{22}. It was found that $\sigma \left( pp \rightarrow bbP \right) \times \text{Br} \left( P \rightarrow \mu \mu \right) > 350$ fb is excluded at 95\% confidence level for $M_P = 30$ GeV. To compare the observed excess with this result we are going to separate the processes with two $b$ jets in the final state and find the total cross section which corresponds to the observed fiducial one. In order to do that we have to find the cut efficiency for the subprocesses with two $b$ jets in the final state, i.e. we need the total cross sections for these subprocesses. The CalcHEP results for these cross sections are summarized in the Table II.

With the help of the data from Table I we can find the contribution of each subprocess into the reported fiducial cross section \cite{20} without knowing the coupling constants $Y_{Xbb}$ and $Y_{X\mu\mu}$:

$$\sigma_{\text{fid}} \left( \text{subprocess} \right) = \frac{\sigma_{\text{fid}} \left( \text{subprocess} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}{\sigma_{\text{fid}} \left( \text{All} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}} \times \sigma_{\text{fid},1}. \quad (21)$$

Signal selection efficiency $\varepsilon$ depends on the subprocess. We will calculate it using data from Tables I and II:

$$\varepsilon \left( \text{subprocess} \right) = \frac{\sigma_{\text{fid}} \left( \text{subprocess} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}{\sigma \left( \text{subprocess} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}. \quad (22)$$

Then we obtain the cross section for individual subprocesses:

$$\sigma \left( \text{subprocess} \right) = \frac{\sigma_{\text{fid}} \left( \text{subprocess} \right)}{\varepsilon \left( \text{subprocess} \right)} = \frac{\sigma \left( \text{subprocess} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}{\sigma_{\text{fid}} \left( \text{All} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}} \times \sigma_{\text{fid},1}. \quad (23)$$

Then for cross section of subprocesses with two $b$ jets in final state we get

$$\sigma \left( pp \rightarrow X + 2b\text{-jets} \right) \times \text{Br} \left( X \rightarrow \mu\mu \right) = \sum_{\text{subprocesses with 2b jets}} \sigma \left( \text{subprocess} \right) = \sum_{\text{subprocesses with 2b jets}} \frac{\sigma \left( \text{subprocess} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}{\sigma_{\text{fid}} \left( \text{All with 2b jets} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}} \times \sigma_{\text{fid},1} = \frac{\sigma \left( \text{All with 2b jets} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}}{\sigma_{\text{fid}} \left( \text{All} \right) \big|_{Y_{Xbb}=10^{-2},Y_{X\mu\mu}=1}} \times \sigma_{\text{fid},1} = \frac{2.07 \text{ pb}}{76.6 \cdot 10^{-5} \text{ pb}} \times 4.1 \text{ fb} \approx 11 \text{ pb},$$

where in the last line we substituted the values for the pseudoscalar. Let us note that according to A.N. Nikitenko (private communication) the cut efficiency for the whole first event category in case of pseudoscalar is approximately $2.7 \cdot 10^{-4}$, so the total cross section is about 15 pb.
TABLE I. Fiducial cross sections $\sigma_{\text{fid}}$ for the $pp \rightarrow bX + \text{jet} + \ldots$ reaction and its subprocesses for $Y_{Xbb} = 0.01$ and $Y_{X\mu\mu} = 1$ at $\sqrt{s} = 8$ TeV. We took such a small value of $Y_{Xbb}$ to suppress multiple $X$ exchanges. The errors correspond to integration errors reported by CalcHEP. When summing up one should multiply the value by two if there are two reactions in left column. The second column corresponds to the multiplicity due to the two possibilities of the quark and its parent proton combination and due to the fact that each $b$ jet can be directed into barrel if there are more than one $b$ jet.

| Subprocess       | Mult. | $\sigma_{\text{fid}} \cdot 10^5$ [pb], $S$ | $\sigma_{\text{fid}} \cdot 10^5$ [pb], $P$ | $\sigma_{\text{fid}} \cdot 10^5$ [pb], $V$ | $\sigma_{\text{fid}} \cdot 10^5$ [pb], $A$ |
|------------------|-------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| $bu \rightarrow ub\mu\mu$ | 2     | $5.23(2)$                                 | $5.22(2)$                                 | $16.0(1)$                               | $16.3(1)$                               |
| $\bar{bu} \rightarrow \bar{ub}\mu\mu$ | 2     | $0.298(1)$                                | $0.293(2)$                                | $0.86(1)$                               | $0.89(1)$                               |
| $b\bar{u} \rightarrow \bar{ub}\mu\mu$ | 2     | $2.30(1)$                                 | $2.30(1)$                                 | $6.91(4)$                               | $7.14(4)$                               |
| $bd \rightarrow db\mu\mu$ | 2     | $0.359(2)$                                | $0.355(2)$                                | $1.05(1)$                               | $1.08(1)$                               |
| $\bar{bd} \rightarrow \bar{db}\mu\mu$ | 2     | $0.209(2)$                                | $0.202(1)$                                | $0.593(4)$                              | $0.617(5)$                              |
| $bs \rightarrow sb\mu\mu$ | 2     | $0.206(2)$                                | $0.205(1)$                                | $0.602(5)$                              | $0.618(6)$                              |
| $\bar{bs} \rightarrow \bar{sb}\mu\mu$ | 2     | $0.113(1)$                                | $0.114(1)$                                | $0.336(2)$                              | $0.350(3)$                              |
| $bc \rightarrow cb\mu\mu$ | 2     | $0.115(1)$                                | $0.114(1)$                                | $0.337(3)$                              | $0.340(2)$                              |
| $\bar{bc} \rightarrow \bar{cb}\mu\mu$ | 2     | $0.082(1)$                                | $0.085(3)$                                | $0.286(3)$                              | $0.222(3)$                              |
| $bg \rightarrow gb\mu\mu$ | 2     | $7.42(8)$                                 | $7.54(8)$                                 | $22.1(2)$                               | $23.4(3)$                               |
| $\bar{bg} \rightarrow \bar{gb}\mu\mu$ | 2     | $0.0323(4)$                               | $0.0309(3)$                               | $0.0869(9)$                             | $0.0881(9)$                             |
| $bb \rightarrow bb\mu\mu$ | 4     | $0.0636(3)$                               | $0.0631(3)$                               | $0.182(2)$                              | $0.184(2)$                              |
| $\bar{bb} \rightarrow \bar{bb}\mu\mu$ | 4     | $0.0036(2)$                               | $0.0039(1)$                               | $0.0103(1)$                             | $0.0106(1)$                             |
| $gg \rightarrow gb\mu\mu$ | 4     | $0.00160(5)$                              | $0.00165(1)$                              | $0.0044(1)$                             | $0.0041(2)$                             |

| All              | 76.4(4) | 76.6(4) | 241(1) | 247(1) |
TABLE II. Cross sections for the $pp \to bbX + \ldots$ reaction and its subprocesses for $Y_{Xbb} = 0.01$ and $Y_{X\mu\mu} = 1$ at $\sqrt{s} = 8$ TeV. The errors correspond to integration errors reported by CalcHEP.

| Subprocess       | Mult. | $\sigma$ [pb], $S$ | $\sigma$ [pb], $P$ | $\sigma$ [pb], $V$ | $\sigma$ [pb], $A$ |
|------------------|-------|--------------------|--------------------|--------------------|--------------------|
| $bb \to bb\mu\mu$ | 1     | 0.024(2)           | 0.025(1)           | 0.048(3)           | 0.061(2)           |
| $bb \to bb\mu\mu$ | 2     | 0.034(3)           | 0.029(1)           | 0.072(1)           | 0.056(2)           |
| $gg \to bb\mu\mu$ | 1     | 1.66(3)            | 1.96(3)            | 5.68(9)            | 5.57(3)            |
| $u\bar{u} \to bb\mu\mu$ | 2     | 0.00109(1)         | 0.00091(1)         | 0.00250(1)         | 0.00279(1)         |
| $d\bar{d} \to bb\mu\mu$ | 2     | 0.00077(1)         | 0.000640(1)        | 0.001735(3)        | 0.001957(6)        |
| $s\bar{s} \to bb\mu\mu$ | 2     | 0.000267(1)        | 0.000217(2)        | 0.000554(1)        | 0.000639(1)        |
| $c\bar{c} \to bb\mu\mu$ | 2     | 0.000133(1)        | 0.000107(1)        | 0.000270(1)        | 0.000315(1)        |
| All with 2$b$ jets|       | 1.78(3)            | 2.07(2)            | 5.93(9)            | 5.82(3)            |

Substituting the data from Tables II and III into (24) we get $\sigma (pp \to X + 2b$-jets) $\times$ Br ($X \to \mu\mu$) much larger than the bound at the level of 350 fb observed in the previous CMS paper [22]. Therefore, the mechanism discussed in this section cannot be responsible for $X$ production at LHC for any of $S, P, V, A$.

In the $2HDM$ discussed in Section III pseudoscalar $P$ is produced mainly by radiation from $b$ quark, just like it is described in this section. Therefore, this model cannot explain experimental data.

V. CONCLUSIONS

An extra scalar or vector can describe the resonance discovered in [1], and simultaneously resolve the disagreement between the SM prediction for the muon anomalous magnetic moment and its measured value.

Though $X$ was found in association with at least one $b$ jet, the simplest model of its production via radiating from $b$ quark line contradicts the previous CMS paper [22]: while the cuts in the new paper are much stronger (mostly cuts on muons) the fiducial cross section is at the level of the upper limit on fiducial cross section from previous paper. To resolve this contradiction, stronger
cuts on muons transverse momentum should not significantly diminish the number of events, i.e. X should be produced with high transverse momentum. This can be achieved if X is produced in decays of some heavy particle, for example, vector-like B quark via $\bar{B}_L b_R X$ interaction term.

Since the New Physics responsible for the observed resonance is coupled to $b$ quarks in some way, it also can be responsible for the deviations from SM predictions observed in $B$ decays.

If the existence of $X$ will be confirmed by future experimental data, it will be a strong additional argument in favor of muon collider construction.

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