Implication of the ALEPH 30 GeV dimuon resonance at the LHC

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Abstract

Recent reanalysis of ALEPH data on $Z \rightarrow b\bar{b} + X$ seems to indicate an existence of the dimuon excess around 30 GeV with a branching fraction for $Z \rightarrow b\bar{b} \mu^+\mu^-$ around $1.1 \times 10^{-5}$. In this letter, we discuss three different types of simplified models for this possible excess. In the first class of models, we assume a new resonance couples to both $b\bar{b}$ and $\mu^+\mu^-$. Within the allowed parameter space for the ALEPH data, this type of models is excluded because of too large Drell-Yan production of dimuon from the $b\bar{b}$ collision at the LHC. In the second model, we assume that the 30 GeV excess is a new gauge boson $Z'$ that couples to the SM $b$ and a new vectorlike singlet $B$ quark heavier than $Z$ and not to $b\bar{b}$. Then one can account for the ALEPH data without conflict with the DY constraint. The new vectorlike quark $B$ can be pair produced at the LHC 8/13 TeV by QCD with $\sigma(BB) \sim O(100 - 1000)$ pb, and $Bq$ production rate is $\sigma(Bq) \sim$ a few pb which is larger than $\sigma(Bb)$ roughly by an order of magnitude. Their signatures at the LHC would be $2b + 4\mu$, $bj + 2\mu$ and $2b + 2\mu$, respectively, which however might have been excluded already by LHC run I and II data since the multi-muon events have low SM background and are rare at the LHC. In the third model, we consider $Z \rightarrow Z'\phi$ followed by $Z' \rightarrow \mu^+\mu^-$ and $\phi \rightarrow b\bar{b}$ assuming that the Higgs field for $Z'$ mass is also charged under the SM $U(1)_Y$ gauge symmetry. In this class of model, we could accommodate the $Br(Z \rightarrow b\bar{b} \mu^+\mu^-) \sim 1.1 \times 10^{-5}$ if we assume very large $U(1)'$ charge for the $U(1)'$ breaking Higgs field. Finally, we study various kinematic distributions of muons and $b$ jets in all the three models, and find that none of the models we consider in this paper are not compatible with the kinematic distributions extracted from the ALEPH data.
I. INTRODUCTION

A recent reanalysis of the archived ALEPH data on $Z \to b\bar{b} + X$ might suggest an interesting possibility of a new resonance $X$ with mass 30 GeV decaying into $\mu^+\mu^-$ [1]:

$$\text{Br}(Z \to b\bar{b}\mu^+\mu^-) \sim 1.1 \times 10^{-5},$$  \hspace{1cm} (1)

$$\Gamma_{\text{tot}}(X) = (1.78 \pm 1.14) \text{ GeV}. \hspace{1cm} (2)$$

Dielectron channel also shows some excess, which however is less prominent than the dimuon channel. The $\cos\theta^*_\mu$ distribution of a muon in the rest frame of dimuon system with respect to the direction of the dimuon system in the rest frame of $Z$ shows peaks around $\cos\theta^*_\mu \approx \pm 1$, which would prefers $X$ being a spin-1 particle.

In addition, a few interesting kinematic distributions are presented in Ref. [1]. In the signal region, the minimum angle between a muon and the leading $b$ jet is within $15^\circ$ and the angle of the other muon-jet combination is in the range of $5^\circ$ to $20^\circ$. Also the relative transverse momentum distribution of the closest muon-jet pair is smaller than 4 GeV [1]. These distributions have to be reproduced by any working models for the 30 GeV dimuon excess.

In this letter, we consider three types of simplified models for this 30 GeV dimuon excess, for which the relevant Feynman diagrams are shown in Fig. I(a)–(c). Note that these three types of Feynman diagrams exhaust all possible tree-level mechanisms for this dimuon excess.

In Sec. II, we assume a new resonance $X$ couples to both $b\bar{b}$ and $\mu^+\mu^-$ with $X$ being (pseudo)scalar or (axial) vector boson, as shown in Fig. I(a). Then we perform comprehensive phenomenological study on $X \to b\bar{b}\mu^+\mu^-$ and related processes such as $X \to 4\mu, 4b$, finding out the parameter space that can account for the ALEPH data. Then within this parameter space, we study the predictions involving $X$ at the LHC: Drell-Yan (DY) process from $b\bar{b} \to X \to \mu^+\mu^-$, and $X$ productions in $t \to bWX, b\bar{b}X$ and $ttX$ at the LHC. Our finding is that the DY production of dimuon basically rules out this class of models shown in Fig. I(a). Then in Sec. III, we propose a model that can evade the strong constraint from the DY. Here we introduce a new vectorlike down-type singlet quark ($B$) and assume the dimuon resonance $X$ is a spin-1 particle $Z'$. The relevant diagram is shown in Fig. I(b). Assuming that only $Z-b-B, Z'-b-B$ and $Z'-\mu-\mu$ couplings are nonzero, we can identify the parameter space compatible with the ALEPH 30 GeV dimuon excess. Then we discuss the LHC phenomenology of $B$ quarks, calculating its production cross sections and identifying the final states. In Sec. IV, we consider a model with a new $U(1)'$ gauge symmetry with the associated gauge boson $Z'$ and the singlet scalar boson $\phi$ charged under $U(1)_Y \times U(1)'$. From the nonzero value of $Z-Z'-\phi$ vertex, one can account for $Z \to Z'\phi \to \mu^+\mu^-b\bar{b}$ without conflict with any known experimental constraints, but we need a very large $U(1)'$ charge for the $U(1)'$ breaking Higgs field. In Sec. V we obtain the kinematic distributions for the muon and jets and compare them with the ALEPH data presented in Ref. [1]. Finally we will summarize the results in Sec. VI.

II. SIMPLIFIED MODELS–I

For a resolution of the 30 GeV dimuon excess, we introduce a new particle $X$, which could be one of scalar ($s$), pseudoscalar ($a$), vector ($V$), or axial vector ($A$). We assume that
the interaction Lagrangian is one of the following forms for $X = s, a, V, A$:

$$L_{\text{scalar}} = s \sum_f g_f^s \bar{f}f,$$  \hspace{1cm} (3a)  

$$L_{\text{pseudoscalar}} = ia \sum_f g_f^a \bar{f}f \gamma_5,$$  \hspace{1cm} (3b)  

$$L_{\text{vector}} = -V_\mu \sum_f g_f^V \bar{f}f \gamma^\mu,$$  \hspace{1cm} (3c)  

$$L_{\text{axial vector}} = -A_\mu \sum_f g_f^A \bar{f}f \gamma^\mu \gamma_5.$$.  \hspace{1cm} (3d)  

We consider only two couplings are nonzero: $g_X^s$ and $g_X^b$ for $X = s, a, V, A$. In the pseudoscalar and axial vector cases, the phenomenology for the $Z$ decay and LHC phenomenology are similar to the scalar and vector cases, respectively. Hereafter, we discuss the latter cases unless there is significant change in the former cases. For the numerical analysis, we use MadGraph5 [2] with implementing the models, Eqs. (3).

Then $X$ mainly decays into a $b\bar{b}$ or $\mu^+\mu^-$ pair. The decay width of $X$ ($\Gamma_X$) depends on both $g_X^s$ and $g_X^b$. We find that the $X$ boson has a very narrow width for small couplings. For example, $\Gamma^V = 3 \times 10^{-3}$ (0.3) GeV for $g_X^V = g_X^b = 0.03$ (0.3) and $\Gamma^s = 4 \times 10^{-3}$ (0.4) GeV for $g_X^V = g_X^b = 0.03$ (0.3), respectively. In order to achieve a large decay width, $\Gamma_X \sim 1$ GeV, the couplings should be about $g_X^V \sim 0.6$ or $g_X^b \sim 0.5$, respectively. If there are other decay channels, the decay width could be enhanced. However if the decay channels to light quarks or $e^+e^-$ are open, much more stringent constraints on the model would be encountered. Thus one must consider smaller couplings to the light quarks and electron, which mean that the $X$ must be flavor-dependent. Another possibility would be the $X$ decay into extra fermions or dark matter candidates, which often exist in UV complete models with flavor-dependent gauge interactions [3]. The extra decay channels would be model-dependent and the UV completion of the model is out of scope of this paper. In this section, we shall assume that the $X \to b\bar{b}, \mu^+\mu^-$ decay are the only possible decay channels for simplicity.

Since the $X$ boson couples to $b$ and $\mu$, the couplings, $g_X^b$ and $g_X^\mu$ can be constrained by the $Z \to 4b$ and $Z \to 4\mu$ decays, respectively. The branching ratio of the $Z \to 4b$ decay is
FIG. 2: Contour plots for $g^X_b$ and $g^X_\mu$. The solid lines correspond to $\Gamma^X(Z \to b\bar{b}\mu^+\mu^-)$ in unit of GeV while the dashed lines to the sum of $\Gamma(X \to b\bar{b})$ and $\Gamma(X \to \mu^+\mu^-)$ in unit of GeV.

$(3.6 \pm 1.3) \times 10^{-4}$ $[4]$, whose uncertainty corresponds to $\Delta_{4b} = 3.3 \times 10^{-4}$ GeV. We find that the enhancement of the decay width for the $Z \to 4b$ is less than $3 \times 10^{-4}$ GeV for $g^V_b \lesssim 0.5$ and $g^X_b \lesssim 0.7$, respectively, which imply that a little bit large couplings are not excluded by the $Z \to 4b$ decay. However, the $Z \to 4\mu$ decay might constrain this model significantly. The branching ratio of the $Z \to 4\ell$ ($\ell = \text{either } e \text{ or } \mu$) decay was reported by the CMS and ATLAS collaborations at $\sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV}$ $[5]$. By the recasting the ATLAS search, the bound on $g^V_\mu$ is obtained as $g^V_\mu \lesssim 0.025 \sim 0.03$ for $m_V = 30 \text{ GeV}$ in the $L_\mu - L_\tau$ gauge model $[6]$. However, the bound strongly depends on the model, in particular, the total decay width of $X$. For more exact bound, the detailed analysis which would depend on the complete model and information on cuts in experiments is required.

In Fig. 2 we present the contour plots for the couplings, $g^X_b$ and $g^X_\mu$ for $X = s, a, V,$ and
A, respectively. The solid lines represent the decay width of the \(Z \to bbX\) (or \(Z \to \mu^+\mu^- X\)) decay with subsequent decay \(X \to \mu^+\mu^- (X \to bb)\) in unit of GeV, which is denoted by \(\Gamma^X(bb\mu^+\mu^-)\), while the dashed lines to the sum of the decay widths of the \(X \to bb\) and \(X \to \mu^+\mu^-\), which is approximately equal to the total decay width of the \(X\) boson. There are other diagrams in the SM, which interfere with the \(X\)-mediated diagrams. We find that the interference effects are negligible because the dimuon excess occurs near the \(X\) resonance and its decay width is quite narrow. The required decay width for the 30 GeV dimuon excess is \(\Gamma^X(bb\mu^+\mu^-) \sim 2.7 \times 10^{-5}\) GeV. In the cases of the scalar and pseudoscalar mediator, a little large couplings of about \(g^s,a_\mu \sim g^s,a_b \sim 0.4\) are required to achieve the dimuon excess at ALEPH. In this region, the total decay width of the \(s\) (\(a\)) is about \(0.5 \sim 0.7\) GeV, which is marginally consistent with the observed one within the 1\(\sigma\) level. We note that it is possible to achieve \(\Gamma^s,a \sim 1.7\) GeV for \(g^s,a_\mu \sim 0.7\) or \(g^s,a_b \sim 0.7\) while satisfying the required decay width for \(Z \to bb\mu^+\mu^-\). In the cases of the vector and axial vector mediators, we find that the required decay width for the dimuon excess could be achieved for \(g^{V,A}_\mu \sim g^{V,A}_b \sim 0.015\), but the total decay width of the \(V\) \((A)\) is much smaller; \(\Gamma^{V,A} \sim 0.05\) GeV. We note that \(\Gamma^{V,A} \sim 1\) GeV with the required decay width for the dimuon excess is possible for \(g^{V,A}_\mu \sim 0.01\) and \(g^{V,A}_b \sim 0.7\), but this region would be excluded by the \(Z \to 4b\) decay.

Next, we consider some phenomenology of the vector-mediator model at the LHC with \(\sqrt{s} = 13\) TeV (and at the Tevatron). Now we call the \(V\) as a \(Z'\) boson. Since the \(Z'\) couples with \(b\) quark and \(\mu\), the processes which include both or either of \(b\) or \(\mu\) would provide stringent constraints. Among them, we investigate three processes: the Drell-Yan process, \(pp \to Z' \to \mu^+\mu^-\), the top decay, \(t \to bWZ'\), and the \(Z'\) production associated with a \(bb\) pair, \(pp \to bbZ'\).

Here, we consider two benchmark points. In Table I, the couplings are taken to be \(g^{Z'}_\mu = g^{Z'}_b = 0.1\), which yield \(\Gamma^{Z'}(Z \to bb\mu^+\mu^-) = 2.72 \times 10^{-5}\) GeV. Since the branching ratio of \(Z' \to \mu\mu\) is 0.25, the cross section for \(pp \to bbZ'\) with the subsequent decay \(Z' \to \mu\mu\) could be about 34 pb, which can be a probe of this model. For the top decay, the branching ratio of \(t \to bWZ'\) followed by \(Z' \to \mu\mu\) would be about \(2 \times 10^{-5}\), which could be another probe at the LHC. The most constraining process for this class of models is the Drell-Yan process, whose cross section is about 715 pb at the LHC and about 55.8 pb at the Tevatron, which is already excluded by the CMS data [7].

In Table II, we take the couplings to be \(g^{Z'}_\mu = 0.1\) and \(g^{Z'}_b = 0.7\), which yield \(\Gamma^{Z'}(Z \to bb\mu^+\mu^-) = 0.0322\) pb, and \(\Gamma^{Z'}(Z \to bb\mu^+\mu^-) = 1.19\) pb, which could be another probe at the LHC.

### Table I: Benchmark point I (vector mediator) at 13 TeV LHC and Tevatron.

| \(g^{Z'}_\mu\) | \(g^{Z'}_b\) | \(\Gamma^{Z'}(Z \to bb\mu^+\mu^-)\) | \(\Gamma(Z' \to bb\mu^+\mu^-)\) |
|----------------|-------------|----------------------------------|----------------------------------|
| 0.1            | 0.1         | \(2.72 \times 10^{-5}\)          | 0.0322                           |

### Table II: Benchmark point II (vector mediator) at 13 TeV LHC and Tevatron.

| \(g^{Z'}_\mu\) | \(g^{Z'}_b\) | \(\Gamma^{Z'}(Z \to bb\mu^+\mu^-)\) | \(\Gamma(Z' \to bb\mu^+\mu^-)\) |
|----------------|-------------|----------------------------------|----------------------------------|
| 0.7            | 0.1         | \(3.036 \times 10^{-5}\)         | 1.19                             |

\(\sigma^{13}(\mu\mu)/\sigma^{13}(\mu\mu)\) = 714.5/55.8 pb \(\sigma^{13}(\mu\mu)/\sigma^{13}(\mu\mu)\) = 920.5/71.1 pb.
Ref. [8]): down-type quark $b$. One can avoid this problem by making $Z$ section by increasing the decay width of $X$. In general, one can find the preferred points, and the simplest benchmark points (and also other points) are easily excluded by the LHC data, in particular, by the Drell-Yan process. One might decrease the Drell-Yan cross section for the invariant mass of the $bb$ pair, depending on the couplings of the $X$. So far the $bb$ peak in $Z \rightarrow bb\mu^+\mu^-$ has not been observed in the $Z$ decay yet. The search for the resonance of the $bb$ pair would be another probe of those models.

Summarizing this section, we investigated some benchmark points to predict the required decay width for the ALEPH 30 GeV dimuon excess reported in Ref. [11] in simplified models defined by Eqs. (3a)–(3d) and Fig. 1(a). In general, one can find the preferred points, but they predict too large cross sections or branching ratios in other productions or decay channels. Most notably the Drell-Yan process turns out to be the most stringent constraints, and the simplest benchmark points (and also other points) are easily excluded by the LHC data, in particular, by the Drell-Yan process. One might decrease the Drell-Yan cross section by increasing the decay width of $X$, but it necessarily decreases the decay width for $Z \rightarrow bb\mu\mu$ and the dimuon excess would not be explained with the $X$ boson with interactions defined in Eqs. (3a)–(3d).

III. SIMPLIFIED MODEL–II

The Model–I in Sec. II has a problem with DY production through $bb \rightarrow Z' \rightarrow \mu^+\mu^-$. One can avoid this problem by making $Z'$ decouple from $bb$ and introducing a new vectorlike down-type quark $B$ which has a nonzero $Z$-$b$-$B$ and $Z'$-$b$-$B$ couplings.

Let us assume a down-type vectorlike singlet quark $B$ with the following interactions (see Ref. [8]):

$$\mathcal{L} = g'_\mu Z'_\mu \bar{\mu} \gamma^\mu \mu + g_s G^s_{\mu} \bar{B} \gamma^\mu T^s B - \frac{1}{2} g_\mu Z'_\mu \bar{b} \gamma^\mu b B + \frac{g_W \sin 2\theta_W}{4c_W} Z'_\mu \bar{b} \gamma^\mu P_L B + h.c. \bigg] .$$

(4)

Here the $Z'$ coupling to the quark sector is assumed to always involve the vectorlike quarks so that $Z' \rightarrow bb$ is zero (or highly suppressed) and the DY process is not allowed (or highly suppressed).

The ALEPH 30 GeV dimuon excess in the $Z$ decay is explained by $Z \rightarrow bb^* \rightarrow bb\mu^+\mu^-$ assuming that $B$ is heavier than $Z$ so that $Z \rightarrow BB + C.C.$ involves a virtual $B$ quark. The main decay channels of $B$ would be $B \rightarrow bZ'$. As for $Z'$, we assume that the $Z' \rightarrow \mu^+\mu^-$ is the only kinematically allowed decay channel, so the $g'_\mu$ parameter is not relevant to the partial decay width of $Z \rightarrow bb^* \rightarrow bb\mu^+\mu^-$ decay and will be set to $g'_\mu = 0.01$ according to the $Z \rightarrow 4\mu$ measurement [3].

$bb\mu\mu) = 3.04 \times 10^{-5}$ GeV. As we already discussed, this set would be excluded because it predicts a large decay width for $Z \rightarrow 4b$ via the $Z'$ exchange. Actually, the decay width is about $1.7 \times 10^{-3}$ GeV, which is much larger than the PDG value. The cross section for $pp \rightarrow bbZ'$ is about 6600 pb and, then, it for $pp \rightarrow bbZ'$ followed by $Z' \rightarrow \mu\mu$ is about 45 pb, which can be easily proved at the LHC. In this case, the Drell-Yan process strongly constrains this model, too. The predicted cross section reaches about 900 pb at the LHC and about 71.1 pb at the Tevatron, which is already excluded by the CMS data [7].

We also investigate some benchmark points in the scalar-mediator model. We find that the cross section for the Drell-Yan cross section exceed 380 pb at $\sqrt{s} = 13$ TeV for $g_\mu^s = g^sa = 0.1$, which is also excluded by the CMS data. We note that those couplings are too small to provide the required decay width for the dimuon excess.

Since the $X$ boson can couple to both $bb$ and $\mu^+\mu^-$ in the models discussed in this section, one may observe a similar peak of the $X$ boson for the invariant mass of the $bb$ pair, depending on the couplings of the $X$. So far the $bb$ peak in $Z \rightarrow bb\mu^+\mu^-$ has not been observed in the $Z$ decay yet. The search for the resonance of the $bb$ pair would be another probe of those models.

Summarizing this section, we investigated some benchmark points to predict the required decay width for the ALEPH 30 GeV dimuon excess reported in Ref. [11] in simplified models defined by Eqs. (3a)–(3d) and Fig. 1(a). In general, one can find the preferred points, but they predict too large cross sections or branching ratios in other productions or decay channels. Most notably the Drell-Yan process turns out to be the most stringent constraints, and the simplest benchmark points (and also other points) are easily excluded by the LHC data, in particular, by the Drell-Yan process. One might decrease the Drell-Yan cross section by increasing the decay width of $X$, but it necessarily decreases the decay width for $Z \rightarrow bb\mu\mu$ and the dimuon excess would not be explained with the $X$ boson with interactions defined in Eqs. (3a)–(3d).
In Fig. 3, we show the partial width of \( Z \rightarrow bB^{*} \rightarrow bb\mu^{+}\mu^{-} (\Gamma^Z(Z \rightarrow bb\mu\mu)) \) in terms of the parameters of the Model–II, i.e. \( m_B, g_b' \) and \( \sin 2\theta_L \). From the left panel of Fig. 3, we can observe the \( \sin^2 2\theta_L \) behavior of \( \Gamma^Z(Z \rightarrow bb\mu\mu) \), while the dependence on \( g_b' \) is more complicated because it could change the total width of \( B \) which is important for \( \Gamma^{Z'}(Z \rightarrow bb\mu\mu) \). So in the right panel, fixing \( \sin \theta_L = 0.5 \), we show the \( \Gamma^{Z'}(Z \rightarrow bb\mu\mu) \) in the 2-dimensional plane of \( g_b' \) and \( m_B \). From the figure, we can find the ALEPH dimuon excess can be addressed in the parameter space with \( m_B \sim 100-200 \text{ GeV}, g_b' \sim 0.5-3 \) and \( \sin \theta_L \sim 0.5 \), requiring that \( g_b' \) remains within the perturbative regime.

Two benchmark points with appropriate dimuon excess and different masses for the vectorlike \( B \) are given in Table III and Table IV. For the relatively heavy \( B \), a coupling \( g_b' \) that approaches the perturbativity limit (\( g_b' = 2 \)) is required, rendering very large decay width of \( B \) whose main decay channel is assumed to be \( bb\mu\mu \). It will be important to study the signals of those two benchmark points at the LHC. The process with the largest cross section is the pair production of \( BB \) through QCD coupling, followed by the \( B \rightarrow bZ' \) decay which produces the \( bb + 4\mu \) signal. The corresponding production cross section at the 13/8 TeV LHC for benchmark points (\( \sigma^{13}(BB)/\sigma^{8}(BB) \)) are given in the Tables III and IV for \( m_B = 110 \text{ GeV} \) and 180 GeV, respectively. The cross section is quite sensitive to the mass of \( B \), raising the \( m_B \) from 110 GeV to 180 GeV can reduce the cross section by one order of magnitude. Even though there is no LHC search for \( bb + 4\mu \) final states so far, the signal is almost background free and \( bb + \text{multi muon events} \) are rare. Therefore it is very likely that this kind of model has been excluded already [9].

Because of the \( b-B-Z \) coupling, there could also be signals of \( pp \rightarrow Z \rightarrow bB \) and \( qb \rightarrow qB \) with \( t- \) channel \( Z \) exchange, where \( q = u, d, s, c \). These processes will generate the signal of \( b\mu\mu \) that is associated with an additional \( b \)-jet or light flavor jet, the cross sections of which
are proportional to $\sin^2 2\theta_L$. Those cross section for benchmark points are also presented in Table III and Table IV, where we find both processes have production cross section of $\mathcal{O}(1)$ pb at the 13/8 TeV LHC and t-channel process has much larger production rate than the s-channel process. Moreover, as we can expect, the production cross section of the $125$ GeV Higgs signal strengths is $\sin \alpha \lesssim 0.4$ depending on the $\phi$ mass $\mathcal{O}(10^{10})$.

The following constraints have to be applied to be consistent with experimental measurements in order that we try to explain the dimuon excess:

$$\frac{m_b}{v} \sin \alpha \sim \frac{1}{50} \sin \alpha \lesssim 10^{-3}.$$
The mixing between $Z'$ and SM gauge field should be small, so we have $(M_{V}^2)_{33} \sim \frac{1}{2} m_{Z'}^2$, where $m_{Z'} \sim 30 \text{ GeV}$ according to the observed excess. Then, we can express $v_{\phi} = \frac{m_{Z'}}{\sqrt{2}g'Y_{\phi}}$.

The current measurements imply the mixing between $Z'$ and SM $Z$ to be $\sin \theta_{ZZ'} < \mathcal{O}(10^{-2}) \sim \mathcal{O}(10^{-3})$ and the mixing between $Z'$ and photon to be $\sin \theta_{\gamma Z'} < \mathcal{O}(10^{-2})$ for $m_{Z'} = 30 \text{ GeV}$. This requires very small off-diagonal component of the gauge boson mass matrix, e.g. $(M_{V}^2)_{13} < 5 \text{ GeV}^2$, which corresponds to $\sin \theta_{ZZ'} < 5.1 \times 10^{-4}$ and $\sin \theta_{\gamma Z'} < 9.8 \times 10^{-3}$ result in $\frac{Y_{\phi}}{V_{\phi}} \lesssim 3.2 \times 10^{-2} g'$.

As we have discussed in Sec. II, the $g'$ should be $g' \lesssim 0.02$ in order to suppress the $Z \rightarrow 4\mu$ decay. Then we find the condition for the ratio of $U(1)$ charges, $\frac{V_{\phi}}{V_{\phi}} \gtrsim 1575$, which implies a large gap between two $U(1)$ charges or $Y_{\phi} = 0$.

The $Z$-$Z'$-$\phi$ coupling is $C_{ZZ'\phi} = -\frac{g_{1}}{\sqrt{g_{1}^{2}+g^{2}}}2g_{Y_{\phi}}m_{Z'} + \sin \theta_{ZZ'} \sin \alpha \frac{m_{Z'}}{v}$, where only $Y_{\phi}$ is the free parameter. Taking $\sin \theta_{ZZ'} = 5.1 \times 10^{-4}$ (correspond to $(M_{V}^2)_{13} = 5 \text{ GeV}^2$) and $\sin \alpha = 0.2$, we plot the contours of $\Gamma(Z \rightarrow bbZ')$ on the $m_{\phi}$-$Y_{\phi}$ plane in Fig. 4. Assuming $\text{Br}(Z' \rightarrow \mu\mu) = 100\%$, $Y_{\phi}$ in very large range of $\mathcal{O}(10^{-2}) - \mathcal{O}(10^{2})$ can explain the dimuon excess.

Finally $\phi \rightarrow b\bar{b}$ will occur through $\phi-h$ mixing, whose mixing angle $\sin \alpha$ is constrained to be $\sin \alpha \lesssim 0.2$ by the present LHC data on the Higgs signal strengths. Including the Yukawa coupling of the SM Higgs to the SM fermions, $\phi-b\bar{b}$ will be given by $(m_{b}/v) \sin \alpha \sim (1/50) \sin \alpha$.

In this model, we find that a very large $U(1)'$ charge for the scalar $\phi$ is required in order to accommodate the observed dimuon excess. For a reasonable hypercharge, say $Y_{\phi} \sim 1$, the required value for $Y_{\phi}'$ is $\mathcal{O}(10^4)$. This implies that a reasonable or natural model building for the $U(1)'$ model might be difficult to be accommodated with the dimuon excess.

The mixing of the $Z$ and $Z'$ may also be generated by the kinetic mixing, $\frac{e}{2c_{W}}B_{\mu\nu}Z'_{\mu\nu}$ [14]. Assuming no mass mixing ($Y_{\phi} = 0$) for simplicity, we find that the coupling related to the
FIG. 5: The event fractions as functions of the minimum angle between a muon and a leading jet (top left panel), the other muon angle defined in the text (top right panel), the relative transverse momentum of the closest muon-jet pair (bottom left panel), and the decay angle $\cos \theta^*$ distribution for muons ($\mu^-$) in the dimuon rest frame with respect to the boost axis in the simplified models (I, II, and III), and 2HDM proposed in Ref. [15].

$Z$ boson decay is

$$C_{Z\phi} = (\sin \xi - \varepsilon t_W \cos \xi) \sqrt{2}g' Y' m_{Z'} + \sin \xi \sin \alpha \frac{m_Z^2}{v},$$  \hspace{1cm} (6)

with the mixing angle $\tan 2\xi = \frac{2t_W}{1-(\varepsilon t_W)^2-m_{Z'}^2/m_Z^2}$. The model independent bound on kinetic mixing when $m_{Z'} = 30$ GeV is $\varepsilon \lesssim 0.03$ [12]. In the small $\varepsilon$ limit,

$$\sin \xi = 0.62\varepsilon + \mathcal{O}(\varepsilon^3),$$  \hspace{1cm} (7)

$$\cos \xi = 1 - 0.2\varepsilon^2 + \mathcal{O}(\varepsilon^4).$$  \hspace{1cm} (8)

so we get $C_{Z\phi} \sim (3.04g'Y' + 20.87\sin \alpha)\varepsilon$ GeV. Taking $\varepsilon = 0.03$ and $\sin \alpha = 0.2$, we find that $g'Y'$ should be at least $\sim 1.3$ in order to have $\Gamma(Z \to Z'\phi) \gtrsim 1.8 \times 10^{-5}$ GeV. Since $g' \lesssim 0.02$ from $Z \to 4\mu$ constraint, $Y' \gtrsim 65$ is required. Again, we find that a large $Y'$ is required in order to accommodate with the ALEPH dimuon excess.
V. KINEMATIC DISTRIBUTIONS

In this section, we present a few kinematic distributions by making use of the parton level events that are generated by MadGraph5. Those distributions could play crucial roles in distinguishing or excluding new physics models for the 30 GeV dimuon excess. The kinematic distributions in Ref. [1] include both signal and background, while the distributions in Fig. 5 contain only signal from new physics models. Thus, care should be exercised when we compare our predictions with the data. However, we note that the continuum background events in Ref. [1] are just about half of all data in the signal region, our predictions for the kinematic distributions are not diluted. In addition, some kinematic distributions in new physics models can definitely be distinguished from the background as we will show later.

Among many of the kinematic variables studied in Ref. [1], the following four are chosen for representation and comparison purpose in this work (We denote the two muons and two b-jets of each signal events as $\mu_i$, $i = 1, 2$ and $b_i$, $i = 1, 2$, respectively):

- $\text{min angle}(\mu, b) \equiv \text{angle}(\mu_{i_0}, b_{j_0}) \equiv \text{min}_{i,j} \text{angle}(\mu_i, b_j)$,
- the other muon angle($\mu, b) \equiv \text{min}_{i,j} \text{angle}(\mu_i, b_j)$, where $i \neq i_0$,
- $p_T^{\text{rel}}(\text{closest pair}) \equiv |p(\mu_{i_0})| \times \sin(\text{angle}(\mu_{i_0}, b_{j_0}))$,
- $\cos \theta^*(\mu^-$), which is the angle of the muon in the dimuon rest frame with respect to the boost axis.

The distributions of those four variables are depicted in Fig. 5. In the left top panel, we show the minimum angle($\mu_{i_0}, b_{j_0}$) between a muon and a leading jet. For the benchmark points I (Model–I) and III (Model–II) and for $m_\phi = 50$ or 80 GeV in the Model–III, we can see peaks between 50° to 70° in the top left panel of Fig. 5. However, for $m_\phi = 10$ GeV in the Model–III, the peak appears around 130°. The difference of two cases mainly comes from kinematics. In the latter case, the muon pair is produced from the on-shell $\phi$ because $\phi$ is very light. Then the muon pair and two b-jets would be produced back-to-back so that the direction of both muons would be opposite to that of the leading jet. However, in the former case, the muon pair is produced in the off-shell 3-body decay so that the distribution could be milder and the peak is shifted to the lower angle.

A similar thing happens in the other muon angle($\mu, b$) as shown in the top right panel of Fig. 5. In the former case, the peak of this angle appears around 100°, while in the latter case, the peak around 150°. We note that the angle of the other pair of the muon and jet, which do not take part in the minimum angle of a muon and a leading jet, has similar distribution to the top right panel of Fig. 5 but the peaks are slightly shifted to larger angles.

In the bottom left panel of Fig. 5, the relative transverse momentum of the closest muon-jet pair has a peak at 16 GeV in the latter case, while in the former case it has much broader distribution and its maximum values can reach about 30 GeV.

In the bottom right panel, we show the distributions of the decay angle $\cos \theta^*$ distribution for muons in the dimuon rest frame with respect to the boost axis for each model. We find that only the benchmark point III (Model–II) shows the $\cos \theta^*$ distributions closer to the data, but not quite.

In summary, we find that all the three models we considered in this paper have difficulty to accommodate the kinematic distributions. Especially the third model discussed in
Sec. IV could accommodate the rate without conflicting with other present data, but not the kinematic distributions. Note that we have exhausted all the models [16] generating three topologically distinct Feynman diagrams for $Z \to b\bar{b}\mu\mu$ at tree level. And we do not find any model could fit the kinematic distributions correctly. Since the ALEPH data seem to indicate that muons for the excess are likely produced with similar directions to the $b$ jets, some muons might be from semileptonic $b$ decays. In order to understand this incompatibility of the kinematic distributions presented in Ref. [1], more detailed study of ALEPH data as well as other data on the $Z$ decays may be necessary.

VI. CONCLUSIONS

In this letter we considered three different types of simplified models for the ALEPH 30 GeV dimuon excess in $Z \to b\bar{b}\mu\mu$. The first class of models where a new resonance couples to $b\bar{b}$ and $\mu^+\mu^-$ are basically ruled out by the DY production of dimuon through $b\bar{b} \to X \to \mu^+\mu^-$. In order to avoid the strong constraint from this DY process, we considered the second model where the 30 GeV dimuon excess is a spin-1 vector boson $Z'$ and proposed a new vectorlike singlet quark $B$, which has nonzero couplings for $Z-b-B$ and $Z'-b-B$. Then we could account for the ALEPH data without conflict with the DY constraint. One can test this model at the LHC by $BB$, $Bb$ and $Bj$ (with $j \neq b$) productions. The subsequent decay of $B$ quark will result in the following final states: $bb + 4\mu$, $bj + 2\mu$ and $bb + 2\mu$, respectively, with $O(nb), O(pb)$, as summarized in Tables III and IV. These $B$-quark production cross sections are sensitive to the $B$-quark mass $m_B$, and the current/future experimental studies of these channels will shed light on this class of models. Since the multi-muon final states have low background and rarely seen at the LHC, this scenario is likely to be excluded already although there is no explicit search for these final states.

Finally we considered a new $U(1)'$ gauge symmetry which is spontaneously broken by a nonzero VEV of a singlet scalar $\phi$ which has nonzero $U(1)_Y$ and $U(1)'$ charges. Then there appears a nonzero vertex for $Z-Z'\phi$ which can accommodate Eq. (1) through $Z \to Z'\phi \to b\bar{b}\mu\mu$. A natural choice for $U(1)'$ would be $U(1)_{L_\mu-L_\tau}$ gauge symmetry. For both simplified models II and III, the model building issue will be nontrivial, since we need to introduce a new gauge symmetry associated with $Z'$, most likely with flavor dependence, and the simplest gauge symmetry might be $U(1)_{L_\mu-L_\tau}$ gauge symmetry. In the model III, we considered the case where $\phi$ is an $SU(2)_L$ singlet case, and found that the $U(1)'$ charge of $\phi$ should be very large $\sim O(10^4)$ (or $O(10^2)$ for the model with the kinetic mixing). The case $\phi$ being an $SU(2)_L$ doublet or higher representation is beyond the scope of this letter. We hope to address it in separate publications in the near future.

We also obtained some kinematic distributions in all the three models. We find that the kinematic distributions in the three models are not consistent with the ALEPH data. In this letter, we considered all possible scenarios to interpret the muon excess as the decay of a resonance, but the kinematic distributions in the ALEPH data might imply that the muon excess is not likely due to the decay of a resonance.

Note Added: While this paper was being reviewed, there appeared a paper which considers $Z \to HA$ in a certain type of 2HDM [15]. In Fig. 5 we included the kinematic distributions in this model too, and conclude that the predictions from this new model are not consistent with the data [1] either.
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