Implication of ALEPH 30 GeV dimuon excess at the LHC

Chaehyun Yu

Collaboration with P. Ko (KIAS), Jinmian Li (KIAS)
Based on arXiv:1610.07526
Dimuon excess at Z decay

- re-analyze the archived ALEPH data at the Z resonance
- dimuon excess observed in $Z \rightarrow b\bar{b}\mu^+\mu^-$ at $m_X = 30.40$ GeV
- significance $= 2.6\sigma$

$$\text{Br}(Z \rightarrow b\bar{b}\mu^+\mu^-) \sim 1.1 \times 10^{-5}$$

$$\Gamma_{\text{tot}}(X) = (1.78 \pm 1.14) \text{ GeV}$$
Minimum angle of b jet and $\mu$

- Left: the minimum angle between a muon and the leading b jet $< 15^\circ$

- Right: the angle of the other muon-jet combination is in the range of $5^\circ$ and $20^\circ$
Relative $P_T$ of closest $\mu$-jet pair

$P_{T,\text{rel}} \leq 4$ GeV

Arno Heister, arXiv:1610.06536
\[ \cos \theta_{\mu}^* \] distribution

- peaks at \( \cos \theta_{\mu}^* \approx \pm 1 \)
- would prefer X being a spin-1 particle
- close to the b jets
Short summary

• The distribution of dimuon invariant mass seems to imply a resonance $X$ at 30 GeV with $2.6\sigma$ significance

\[
\text{BR}(Z \rightarrow b\bar{b}\mu^+\mu^-) \sim 10^{-5}
\]
\[
\Gamma(Z \rightarrow b\bar{b}\mu^+\mu^-) \sim 1.7 \text{ GeV}
\]

• But, some kinematical distributions disfavor the resonance interpretation of the excess

• We assume the resonance interpretation and find its implication to the LHC phenomenology in a few simplified models
Simplified Model I

- Assume \( X (=s,a,V,A) \) couples with \( b \) and \( \mu \)
- \( X \) decays into a \( b\bar{b} \) or \( \mu^+\mu^- \) pair

\[
\Gamma^X \sim 1 \text{ GeV for } g_f^s \sim 0.5 \text{ or } g_f^V \sim 0.6
\]

- but may yield large decay widths for \( Z \to 4b,4\mu \)

\[
g_b^s \lesssim 0.7 \quad g_b^V \lesssim 0.5 \quad \text{from} \quad Z \to 4b
\]

\[
g_\mu^V \lesssim 0.03 \quad \text{from} \quad Z \to 4\mu \quad \text{in the U}(1)_\mu-\text{U}(1)_\tau
\]
Scalar Mediator Model

\[ \Gamma(\text{Z} \rightarrow bb\mu\mu) \sim 2.7 \times 10^{-5} \text{ GeV} \]

\[ \Gamma^s \sim 0.4 \text{ GeV} \]

\[ \Gamma^s \sim 1.7 \text{ GeV} \]
Scalar Mediator Model

Scalar Mediator

$\Gamma_s \sim 0.4 \text{ GeV}$

$\Gamma_s \sim 1.7 \text{ GeV}$

$\Gamma(Z \rightarrow bb\mu\mu) \sim 2.7 \times 10^{-5} \text{ GeV}$

marginally consistent with $\Gamma_s$ in the 1$\sigma$ level
Scalar Mediator Model

Scalar Mediator

marginally consistent with $\Gamma^s$ in the $1\sigma$ level

acceptable by $\Gamma(Z \to 4b)$

$\Gamma(Z \to bb\mu\mu) \sim 2.7 \times 10^{-5}$ GeV

$\Gamma^s \sim 0.4$ GeV

$\Gamma^s \sim 1.7$ GeV
Vector Mediator Model

\[ \Gamma(Z \rightarrow bb\mu\mu) \sim 2.7 \times 10^{-5} \, \text{GeV} \]

\[ \Gamma^s \sim 0.05 \, \text{GeV} \]

\[ g^V_b \]

\[ \Gamma^s \sim 1.7 \, \text{GeV} \]
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LHC Phenomenology (vector)

- the models can be constrained by DY, top decay, Z’bb production

### Benchmark point I

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<thead>
<tr>
<th>$g_Z^{Z'}$</th>
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<th>$\Gamma^{Z'}(Z \rightarrow bb, \mu\mu)$</th>
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<td>0.1</td>
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<td>$2.72 \times 10^{-5}$</td>
<td>0.0322</td>
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<td>$\sigma^{13}(\mu\mu)/\sigma^{1.96}(\mu\mu)$</td>
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**LHC Phenomenology (vector)**

- the models can be constrained by DY, top decay, $Z'bb$ production

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- too large Drell-Yan production cross section excludes this type of models
- similar features in the scalar, pseudoscalar, and axial-vector models
Simplified Model II

One way to avoid large DY cross section is to make $Z'$ decouple from $b\bar{b}$ and introduce a new vectorlike down-type quark $B$

\[ \mathcal{L} = g'_\mu Z'_\rho \bar{\mu} \gamma^\rho \mu + g_s G^a_\mu \bar{B} \gamma^\mu T^a B - \left[ \frac{1}{2} g'_b Z'_\rho \bar{b} \gamma^\rho b B + \frac{g_W \sin 2\theta_W}{4c_W} Z_\mu \bar{b} \gamma^\mu P_L B + h.c. \right] \]

- $Z'$ decay: only $Z' \rightarrow \mu\mu$ is allowed kinematically by assuming $m_B \gg m_{Z'}$
- $g'_\mu$ is irrelevant to $\Gamma(Z \rightarrow b\bar{b}\mu\mu)$ and is taken to be 0.01
The dimuon excess could be explained for
\[
\sin 2\theta_L = 0.5 \\
m_B = 100 \sim 200 \text{ GeV} \\
g'_\mu = 0.5 \sim 3
\]
Bench Mark Points (Model II)

- the models can be constrained by BB, bB, qB production at the LHC

Benchmark point III

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- signals would be $bb+4\mu$, $bb+2\mu$, $bj+2\mu$
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• signals would be $bb+4\mu$, $bb+2\mu$, $bj+2\mu$

• too large BB production cross section ($bb+4\mu$) disfavors this model
Simplified Model III (U(1)')

U(1)' could be U(1)_{\mu}-U(1)_{\tau}

A real scalar \( \phi \) is charged under both U(1)_{\gamma} and U(1)'

\[
D_\mu \phi = \partial_\mu \phi - i g_1 Y_\phi B_\mu \phi - i g' Y'_\phi Z' \mu \phi
\]

\( \phi \) couples with \( bb \) via a mixing with \( H \)

• mass terms in the interaction eigenstates with \( g_1, g, g' \) for U(1)_{\gamma}, SU(2)_{L}, U(1)'

\[
M^2_V = \begin{pmatrix}
g_1^2 \frac{v^2}{8} + g_1^2 Y_\phi^2 v_\phi^2 & -gg_1 \frac{v^2}{8} & g_1 Y_\phi Y'_\phi v_\phi^2 \\
-gg_1 \frac{v^2}{8} & g^2 \frac{v^2}{8} & 0 \\
g_1 g' Y_\phi Y'_\phi v_\phi^2 & 0 & g'^2 Y'_\phi^2 v_\phi^2
\end{pmatrix}
\]
Simplified Model III (U(1)')

U(1)' could be U(1)_{\mu}-U(1)_{\tau}

A real scalar $\phi$ is charged under both U(1)$_Y$ and U(1)'

$$D_{\mu}\phi = \partial_{\mu}\phi - ig_1 Y_\phi B_{\mu}\phi - ig' Y'_\phi Z'_\phi \phi$$

$\phi$ couples with $\bar{b}b$ via a mixing with $H$

- Mass terms in the interaction eigenstates with $g_1$, $g$, $g'$ for U(1)$_Y$, SU(2)$_L$, U(1)'

$$M_V^2 = \begin{pmatrix}
    g_1^2 \nu^2 & g_1^2 Y_\phi^2 \nu^2 & -gg_1 \nu^2 & g_1 g' Y_\phi Y'_\phi \nu^2 \\
    -gg_1 \nu^2 & g^2 \nu^2 & 0 & 0 \\
    g_1 g' Y_\phi Y'_\phi \nu^2 & 0 & g'^2 Y'_\phi^2 \nu^2 \\
    0 & 0 & g'^2 Y'_\phi^2 \nu^2 & 0
\end{pmatrix} \sim \frac{1}{2} m_{Z'}^2$$

$$v_\phi = \frac{m_{Z'}}{\sqrt{2g' Y'_\phi}}$$
Simplified Model III (U(1)')

U(1)' could be U(1)\(_\mu\) - U(1)\(_\tau\)

A real scalar \(\phi\) is charged under both U(1)\(_Y\) and U(1)'

\[
D_{\mu}\phi = \partial_{\mu}\phi - ig_1 Y_\phi B_{\mu}\phi - ig' Y'_{\phi'} Z'_{\mu}\phi
\]

\(\phi\) couples with \(bb\) via a mixing with \(H\)

• mass terms in the interaction eigenstates with \(g_1, g, g'\) for U(1)\(_Y\), SU(2)\(_L\), U(1)'

\[
M^2_{Y'} = \begin{pmatrix}
g_1^2 \frac{v^2}{8} + g_1^2 Y_\phi^2 v^2_\phi & -gg_1 \frac{v^2}{8} \\
-gg_1 \frac{v^2}{8} & g_1^2 Y_\phi^2 v^2_\phi + g' Y' Y'^{\prime 2} v^2_\phi
\end{pmatrix}
\sim \sin \theta_{Z'Z} < 10^{-2}
\]

\[
\frac{Y_\phi}{Y'_{\phi'}} \leq 3.2 \times 10^{-2} g'
\]
Simplified Model III \((U(1)')\)

\(U(1)'\) could be \(U(1)_\mu - U(1)_\tau\)

A real scalar \(\phi\) is charged under both \(U(1)_Y\) and \(U(1)'

\[D_{\mu}\phi = \partial_{\mu}\phi - ig_1Y_\phi B_{\mu}\phi - ig'Y'_\phi Z'_\mu\phi\]

\(\phi\) couples with \(bb\) via a mixing with \(H\)

- mass terms in the interaction eigenstates with \(g_1, g, g'\) for \(U(1)_Y, SU(2)_L, U(1)'\)

\[M^2_V = \begin{pmatrix} g_1^2v^2/8 + g_1^2Y_\phi^2v_\phi^2 & -gg_1v^2/8 & g_1g'Y_\phi Y'_\phi v_\phi^2 \\ -gg_1v^2/8 & g^2v^2/8 & 0 \\ g_1g'Y_\phi Y'_\phi v_\phi^2 & 0 & g'^2Y'_\phi v_\phi^2 \end{pmatrix} \sim \sin \theta_{ZZ'} < 10^{-2}\]

\[\frac{Y_\phi}{Y'_\phi} \leq 3.2 \times 10^{-2} g'\]

\[g' \leq 0.02 \Rightarrow \frac{Y'_\phi}{Y_\phi} \geq 1575\]
Simplified Model III (U(1)′)

- The partial decay width strongly depends on the mass of φ
Kinematical distributions

- the minimum angle between a $\mu$ and the leading jet
- the angle of the other muon-jet combination

- black line: muon’s directions tend to be opposite to those of $b$ jets
- other lines: milder, but still have larger angles than data
Kinematical distributions

- the relative transverse momentum of closest pair has a peak at more than 5 GeV
- only blue lines has peaks at $\cos \theta^*_\mu \approx \pm 1$
Dark matter

• $Z'$ might decay into extra particles or dark matter candidates according to the model building

• Then some experimental bounds (DY, BB production) might be avoided, for example, by reducing the branching ratio of $Z'$ to a muon pair

• However it does not help resolving the problem because it increases the total decay width of $Z'$ and we cannot obtain the correct partial $Z$ decay width

• Kinematical distributions are not affected by the extra decay channels and disfavor a resonance interpretation of $X$
Conclusions

• We consider three types of simplified models for a resolution of the dimuon excess observed in the re-analysis of archived ALEPH data

• One can find the parameter spaces satisfying the ALEPH data, but

• Model I predicts too large Drell-Yan production rate at the LHC

• Model II predicts too large BB production rate at the LHC

• Model III might be consistent with LHC data, but we need a large U(1)' charge for $\phi$, which means that the model-building is not easy

• Kinematical distributions of the dimuon excess disfavor the interpretation of dimuon excess as a resonance