New Physics for muon anomalous magnetic moment and its electroweak precision analysis

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Abstract : About 3σ deviation from the standard model prediction of muon anomalous magnetic moment (muon g − 2) has been reported. We consider new physics beyond the standard model which has new Yukawa interactions with muon. We compute new contributions to muon g − 2 and corrections to electroweak observables, and show the consistent region of parameter space. We find that in a simple model where the chirality flip of muon occurs only in the external muon line in one loop muon g − 2 diagrams, it is necessary to introduce the relatively large new Yukawa couplings and the electroweak scale new particles. On the other hand, in a model where the chirality flip can occur in the internal fermion line of the one loop muon g − 2 diagrams, we can obtain favorable g − 2 contributions without large Yukawa coupling, and they are consistent with the precision electroweak observables. Finally, we discuss effects of new particles for muon g − 2 on the Higgs boson decay h → γγ and direct production of these particles at the LHC experiment.

1 The muon g − 2 discrepancy

Anomalous magnetic moment of the muon is one of the most precisely measured quantities in elementary particle physics. The Brookhaven E821 experiment has reported a measurement of muon g − 2 and found the discrepancy between SM prediction and experimental value:

$$\delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0)\times 10^{-10}$$

($a_\mu^Z = -193.89(2)\cdot 10^{-11}$: Z boson contribution to muon g − 2)

which correspond to 3.3σ discrepancy. This result may indicate that some new physics contribute to muon g − 2 . If we assume that a new physics has weak coupling with muon, then the new physics mass scale must be O(100)GeV. However such new light particles may be constrained by electroweak precision measurement.

[1] Kaoru Hagiwara et al., J. Phys. G G 38, 085003 (2011)

2 New physics models for anomaly of muon g − 2

We consider the following Yukawa interaction :

1 Model where right-handed muon has new Yukawa interaction with SU(2) singlet scalar (ϕ) and singlet Dirac fermion (χ)

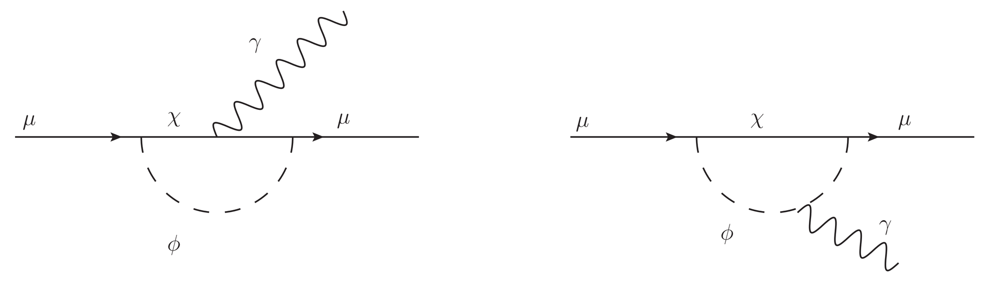
$$\mathcal{L} = -y_N \bar\mu_R \chi_L \phi - m_\chi \bar\chi_R\chi_L + {\rm h.c.} - m_\phi^2 \phi^\dagger\phi + \cdots .$$
$$Q_\chi + Q_\phi = Q_\mu$$

2 Model where both right- and left-handed muons have new Yukawa couplings

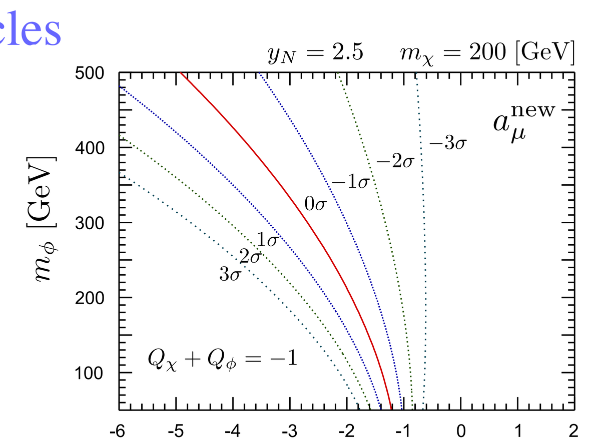
$$\mathcal{L} = -y_L \bar L_2 \Phi \chi_R - y_R \bar\mu_R \phi \chi_L - m_\chi \bar\chi_L\chi_R + {\rm h.c.} - \lambda M (H^\dagger \Phi \phi^\dagger) + {\rm h.c.}$$
$$L_2 = \begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix} \quad \Phi = \begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix} \qquad Q_\chi + Q_{\phi_2} = Q_\mu \qquad Q_\phi = Q_{\phi_2}$$

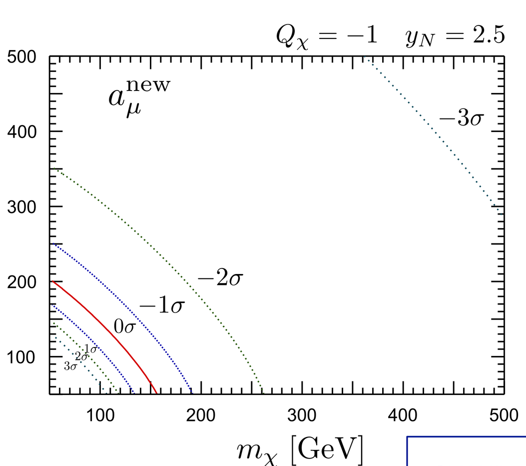
impose Z_2 symmetry as Z_2 odd charge to new particles

New contribution to the muon g − 2

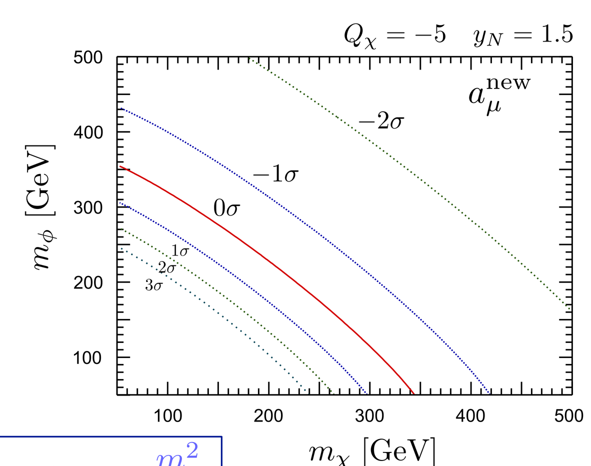


(a) (b)



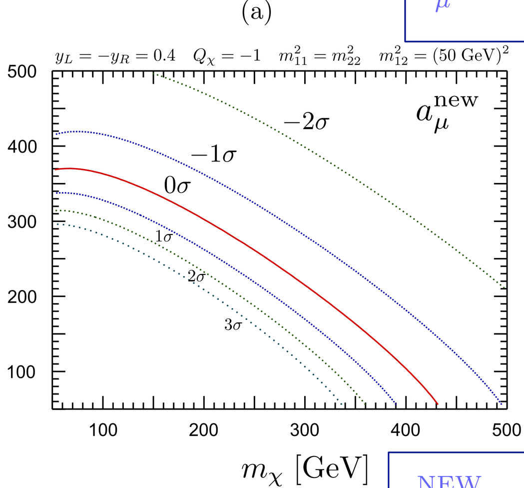


(a)

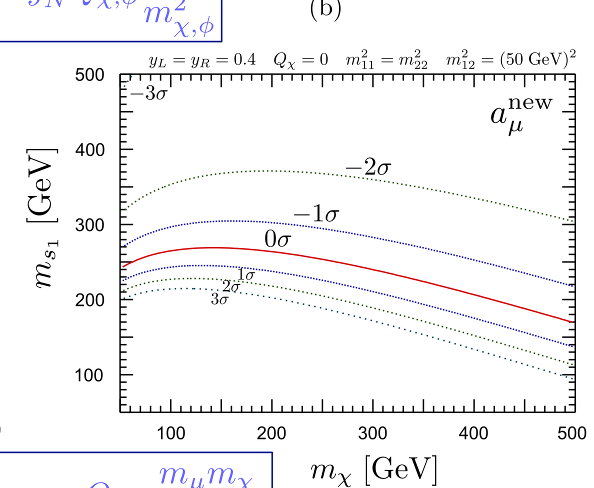


(b)

$a_\mu^{\rm NEW} \propto y_N^2 Q_{\chi,\phi} \dfrac{m_\mu^2}{m_{\chi,\phi}^2}$



(a)



(b)

$a_\mu^{\rm NEW} \propto y_L y_R Q_{\chi,\phi} \dfrac{m_\mu m_\chi}{m_{\chi,\phi}^2}$

New physics contribution to muon g − 2 as a function of

(1) $Q_\chi - m_\phi$ (2) $m_\chi - m_\phi$ (model 1)

$m_\chi - m_{s_1}$ (model 2)

One can see that the region with $Q_\chi > -1$ (which correspond to $Q_\phi < 0$) is disfavored by the data of muon g − 2.

The neutral scalar can potentially accommodate the anomaly if the scalar is not so heavy.

Mixing mass terms and mass eigenstates

$$\mathcal{L} = -\left(\phi^\dagger,\ \phi_2^\dagger\right)\begin{pmatrix} m_{11}^2 & m_{12}^2\\ m_{12}^2 & m_{22}^2\end{pmatrix}\begin{pmatrix}\phi\\ \phi_2\end{pmatrix}$$
$$\begin{pmatrix}\phi\\ \phi_2\end{pmatrix}_i = V_{ij} s_j$$

3 Effects on electroweak observables

We adopt the formalism in Refs. [2,3,4] in order to include the oblique corrections as well as the vertex corrections in the EW observables.

$$\frac{\alpha S}{4 s_W^2 c_W^2} = \frac{\Pi_{ZZ}(M_Z^2)-\Pi_{ZZ}(0)}{M_Z^2} - \frac{c_W^2 - s_W^2}{c_W s_W}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2} \qquad \alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha U}{4 s_W^2} = \frac{\Pi_{WW}(M_W^2)-\Pi_{WW}(0)}{M_W^2} - c_W^2\frac{\Pi_{ZZ}(M_Z^2)-\Pi_{ZZ}(0)}{M_Z^2} - 2 s_W c_W \frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - s_W^2\frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

$$\frac{\alpha R_Z}{4 s_W^2 c_W^2} = \left.\frac{d\Pi_{ZZ}(p^2)}{dp^2}\right|_{p^2=M_Z^2} - \frac{\Pi_{ZZ}(M_Z^2)-\Pi_{ZZ}(0)}{M_Z^2} \qquad \frac{\alpha R_W}{4 s_W^2} = \frac{\Pi_{WW}(M_Z^2)-\Pi_{WW}(M_W^2)}{M_Z^2 - M_W^2} - \frac{\Pi_{WW}(M_W^2)-\Pi_{WW}(0)}{M_W^2}$$

$$i\frac{g}{c_W}\gamma_\mu\left[(g_L^{{\rm SM},\mu}+\Delta g_L^\mu)P_L + (g_R^{{\rm SM},\mu}+\Delta g_R^\mu)P_R\right] \qquad G_F = G_F^{\rm SM+ob.} + \frac{g^2}{4\sqrt2 M_W^2}\Delta\bar\delta_G$$

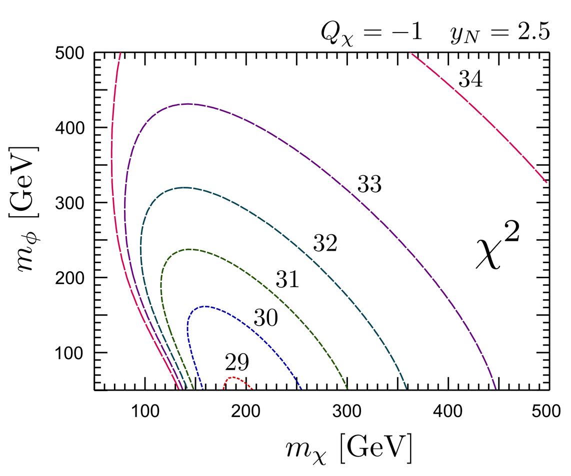
Δg_α^μ: $Z\mu\bar\mu$ vertex corrections
$\Delta\bar\delta_G$: vertex/box corrections in muon decay

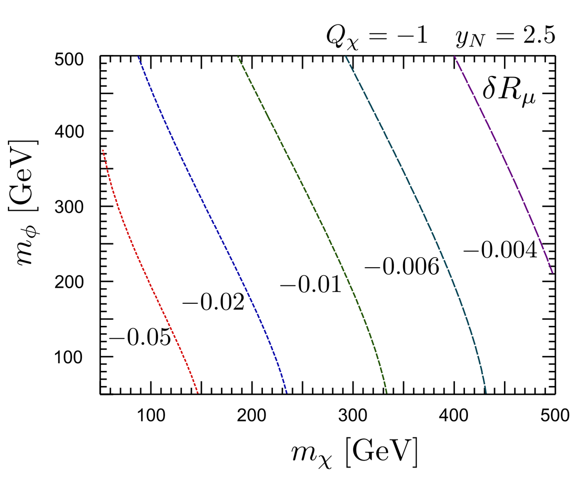
EW observables in Z decay are expressed in terms of the *effective couplings*

$$g_\alpha^f = a_\alpha^f + b_\alpha^f \Delta\bar g_Z^2 + c_\alpha^f \Delta\bar s^2 + \Delta g_\alpha^f$$

----> obtained from $S, T, U, R_Z, R_W, \Delta g_\alpha^f, \Delta\bar\delta_G$

[2] G. –C. Cho et al., Nucl.Phys.B574:623-674, 2000 [3] K. Hagiwara et al., Z.Phys.C64:559-620, 1994
[4] G. –C. Cho et al., JHEP 1111, 068 2011





$R_\mu = \Gamma_h/\Gamma_\mu$ $\delta R_\mu = R_\mu - R'_\mu$

R_μ include all corrections
R'_μ except for the vertex corrections

Model with SU(2) singlet scalar (ϕ) and singlet Dirac femion (χ)

χ^2 is shown as a function of m_χ and m_ϕ

χ^2 is large in the region of small because of the large vertex corrections.

In the region of larger m_χ and m_ϕ , it is difficult to explain the anomaly of muon g − 2 because new particles are too heavy, and hence the χ^2 gets larger

Model with SU(2) doublet (Φ) and singlet (ϕ) scalar, and singlet fermion (χ)

The dominant quantum corrections are represented by S and T parameters.

$S \simeq \frac{Y_\Phi}{6\pi}\Delta + \cdots \quad T \simeq \frac{m_{\phi_1}^2}{16\pi s_W^2 m_W^2}(\Delta)^2 + \cdots$

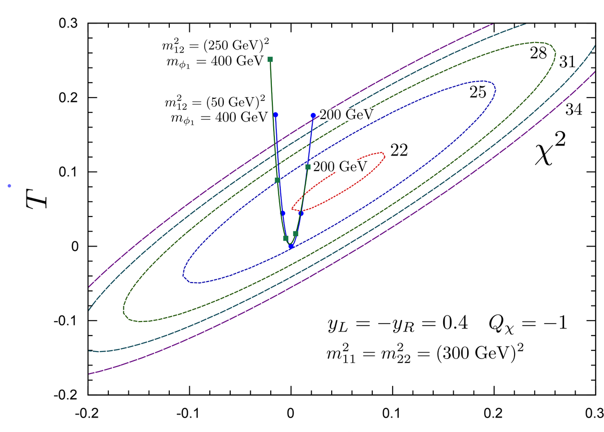
$\Delta = (m_{\phi_2}^2 - m_{\phi_1}^2)/m_{\phi_1}^2$

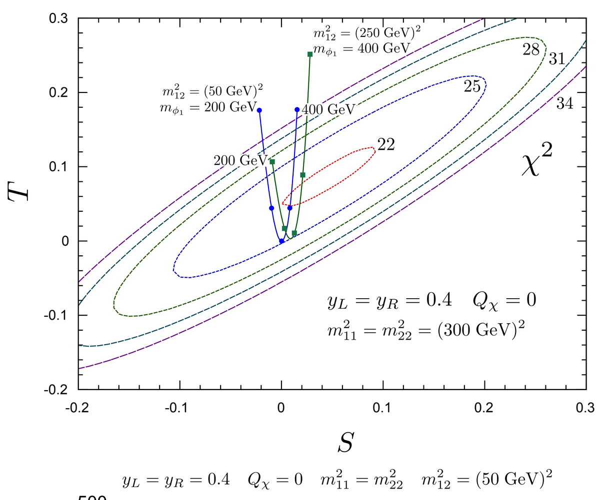
(for simplicity, we assume that $V_{22} = V_{11} = 1,\ V_{12} = V_{21} = 0$)

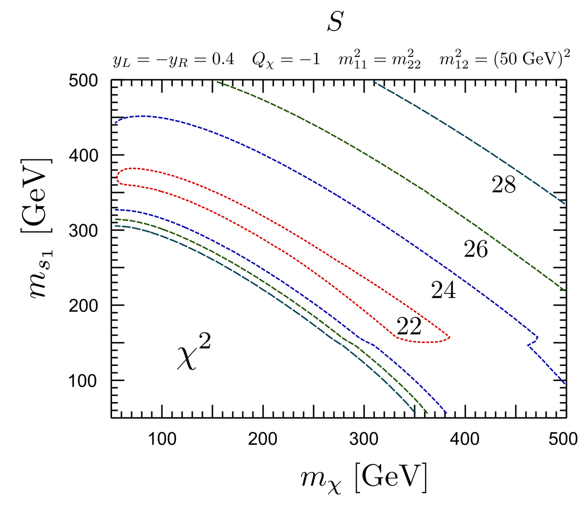
We show numerical result of contours in S-T plane (without including muon g − 2 result), shown in dashed lines. As one can see from the figure, slightly positive S and T (S ~ 0.05 and ~ 0.1) are favored by EW observables.

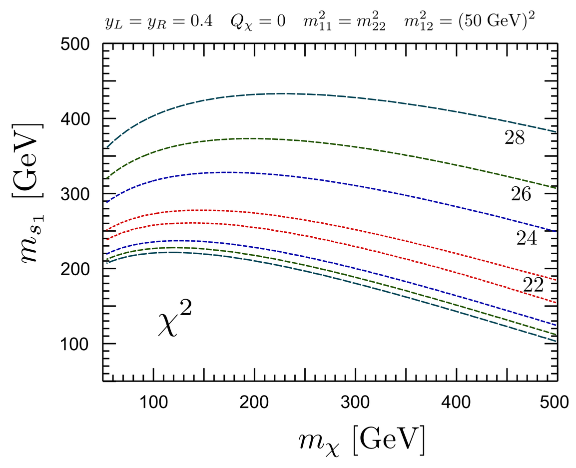
In the next place, we show χ^2 contours as a function of m_χ and m_{s_1}

m_{ϕ_1} is chosen so that the χ^2 becomes the smallest.









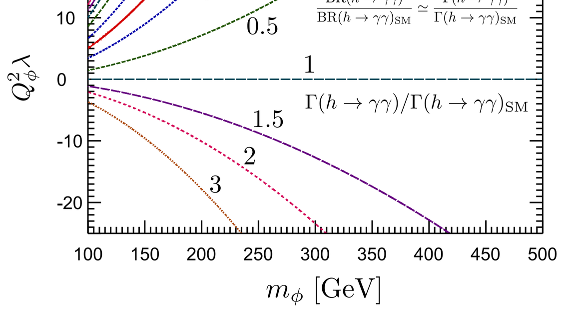
4 Phenomenology at the LHC

In the previous section, we show that in order to explain the anomaly of muon g − 2, it is strongly suggested that there should be the EW scale new particles. Therefore, these particles may be reachable directly and/or indirectly at the LHC.

The effects of these new particles in the Higgs decay h→γγ

The SU(2) singlet and doublet scalars can couple to the Higgs boson through the following interactions:

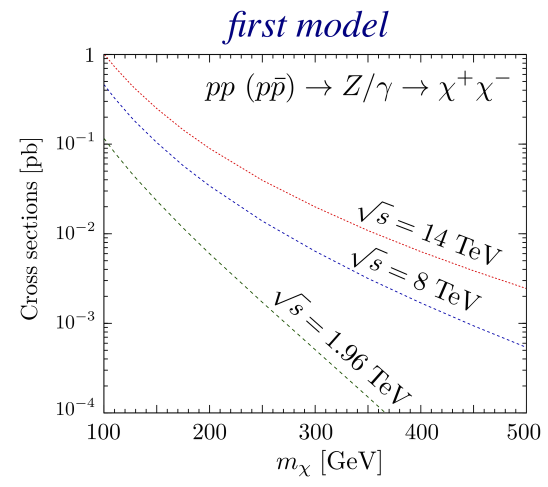
$$\mathcal{L} = -\kappa_1 \phi^\dagger\phi(H^\dagger H) - \kappa_2(\Phi^\dagger\Phi)(H^\dagger H) - \kappa_3(H^\dagger\Phi)(\Phi^\dagger H) - \kappa_4 M\{(H^\dagger\Phi)\phi^\dagger + {\rm h.c.}\}$$



The production cross sections of new particles at the LHC

above figure: production cross section of χ if ϕ is lighter than χ, χ can decay to μ and ϕ. If ϕ is stable neutral particle, th final signature may be a $\mu^+\mu^-$ + missing energy. (SM background $W^+W^-(\to\mu^+\mu^-)$ 0.29 (0.15) pb for $\sqrt{s} = 8$ TeV (14 TeV)

first model



second model