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W boson mass in gauge-Higgs unification

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The CDF collaboration reported an anomaly of the W boson mass in 2022. We discuss the possibility to explain the anomaly in a gauge-Higgs unification model. We evaluate the W boson mass in the $SO(5) \times U(1)_X \times SU(3)_C$ gauge-Higgs unification in the Randall-Sundrum warped space. The muon decay proceeds by the exchange of not only the zero mode of the W boson but also Kaluza-Klein excited states at the tree level. We find that the anomaly can be explained by these effects in the gauge-Higgs unification model.

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1. Introduction

In 2022, the CDF collaboration reported on the mass of the W boson, $m_W^{\rm CDF} = 80.4335 \pm 0.0094$ GeV.[1] The predicted value in the Standard Model (SM) is $m_W^{\rm SM} = 80.354 \pm 0.007$ GeV.[2–4] The discrepancy between the two has triggered huge debates on possible new physics beyond the SM. The ATLAS collaboration also reanalyzed the data in 2011 and obtained $m_W^{\rm ATLAS} = 80.360 \pm 0.016$ GeV.[5] Although the experimental situation has not been settled yet, it is worth to examine models to find whether or not they can lead to a larger value for m_W than $m_W^{\rm SM}$ without conflicting with other observation at low energies.

2. Gauge-Higgs unification model

Gauge-Higgs Unification (GHU) models solve the hierarchy problem. The Higgs boson is a fifth-dimensional component of gauge fields, therefore it is protected from divergence by the gauge principle. And the interactions of the Higgs boson are also governed by the gauge principle. A realistic model of gauge-Higgs unification has been proposed. This model is based on the gauge-Higgs unification in the Randall-Sundrum (RS) warped space, which is described by the gauge group $SO(5) \times U(1)_X \times SU(3)_C$. This kind of higher-dimensional theory incorporates Kaluza-Klein (KK) excitation modes. These particles are constrained by collider experiments and the lower limit of the typical KK mass scale(m_{KK}) is 13 TeV by the LHC experiments.[6] Another important parameter is the Aharonov-Bohm (AB) phase (θ_H). In GHU models, the gauge symmetry is dynamically broken by the AB effect. The parameter is constrained theoretically and experimentally and the bound is $\theta_H \lesssim 0.1$.

KK excited states of the W and W_R gauge bosons contribute to the W boson mass. The relationship between the gauge couplings and the ratio of the W and Z boson masses, m_W/m_Z, changes even at the tree level. The dominant contributions come from large gauge couplings of left-handed leptons to the first KK excited states of the W boson, the change in the W couplings of the leptons (e and μ), and the change of the relation between the gauge couplings and the mass ratio m_W/m_Z.

3. The W boson mass

In the SM the Fermi constant G_μ determined from the μ-decay is given by[7]

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2 s_W^2} \frac{1}{m_W^2} (1 + \Delta r_{\rm SM}^{\rm loop}) \,, \quad s_W^2 = 1 - \frac{m_W^2}{m_Z^2} \,, \tag{1}$$

where $\alpha^{-1} = 137.035999084(21)$, $G_\mu = 1.1663788(6) \times 10^{-5}\,{\rm GeV}^{-2}$ and $m_Z = 91.1876(21)$ GeV.[8] $\Delta r_{\rm SM}^{\rm loop}$ represents the sum of all loop corrections, which depends on α, m_W, m_Z, m_H, strong gauge coupling constant, and masses of quarks and leptons.

In the GHU model, on the other hand, the Fermi constant has additional factor.

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2 \sin^2 \theta_W^0} \frac{\hat{g}^{W^{(0)}}_{\mu\nu_\mu,L} \hat{g}^{W^{(0)}}_{e\nu_e,L}}{m^2_{W^{(0)}}} (1 + \Delta r_G)(1 + \Delta r_{\rm GHU}^{\rm loop}), \tag{2}$$

$\Delta r^{\rm loop}_{\rm GHU}$ represents the sum of loop corrections and we take $\Delta r^{\rm loop}_{\rm GHU} = \Delta r^{\rm loop}_{\rm SM} = 0.0383$. Δr_G is the new tree level contributions for the Fermi constant given by

$$\Delta r_G = \frac{1}{\hat{g}^{W^{(0)}}_{\mu\nu_\mu,L}\hat{g}^{W^{(0)}}_{e\nu_e,L}} \sum_{n=1}^{\infty} \left\{ \hat{g}^{W^{(n)}}_{\mu\nu_\mu,L}\hat{g}^{W^{(n)}}_{e\nu_e,L}\left[\frac{m_{W^{(0)}}}{m_{W^{(n)}}}\right]^2 + \hat{g}^{W_R^{(n)}}_{\mu\nu_\mu,L}\hat{g}^{W_R^{(n)}}_{e\nu_e,L}\left[\frac{m_{W^{(0)}}}{m_{W_R^{(n)}}}\right]^2 \right\}, \tag{3}$$

where $\hat{g}^{W^{(n)}}_{e\nu_e,L}$ and $\hat{g}^{W_R^{(n)}}_{e\nu_e,L}$ are the couplings of $W^{(n)}$ and $W_R^{(n)}$ to $e_L \nu_{e_L}$, respectively. The right-handed couplings are very small and have been omitted. In GHU the W boson mass $m_W = m_{W^{(0)}}$ is determined by solving (2) and (3).

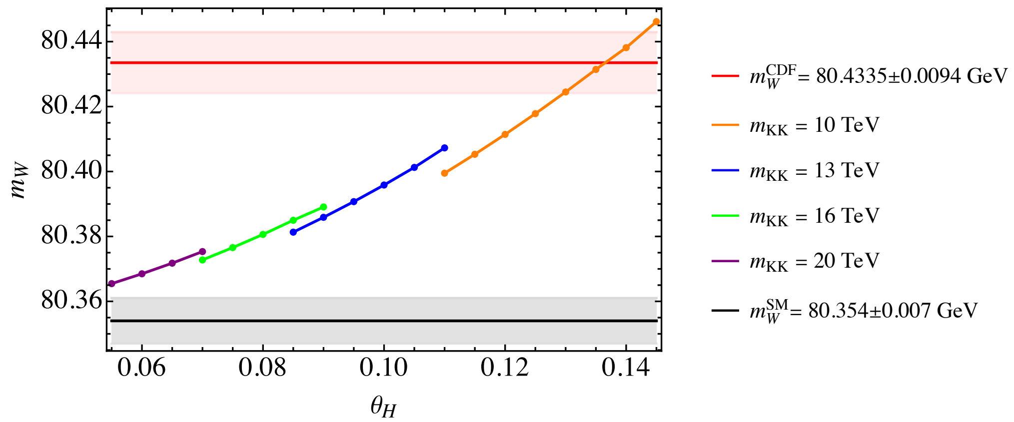

Figure 1: The W boson mass m_W in GHU is plotted as a function of θ_H with various $m_{\rm KK}$. The constraint $m_{\rm KK} \gtrsim 13\,$TeV is obtained from the experimental data at LHC. The predicted m_W in GHU for $13\,{\rm TeV} \leq m_{\rm KK} \leq 20\,$TeV lies between $m_W^{\rm SM}$ and $m_W^{\rm CDF}$.

Fig. 1 shows the predicted values for m_W with different values of $m_{\rm KK}$ and θ_H. It is seen that m_W in GHU model becomes larger than $m_W^{\rm SM}$, but is smaller than $m_W^{\rm CDF}$ for $13\,{\rm TeV} \leq m_{\rm KK} \leq 20\,$TeV. The GHU model in the RS space naturally predicts the W boson mass well above $m_W^{\rm SM}$.

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