Hint on new physics from the $W$-boson mass excess—axion-like particle, dark photon or Chameleon dark energy

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The $W$-boson mass ($m_W = 80.4335 \pm 0.0094$ GeV) measured by the CDF collaboration is in excess of the standard model (SM) prediction at a confidence level of 7σ, which is strongly in favor of the presence of new particles or fields. In the literature, various new particles and/or fields have been introduced to explain the astrophysical and experimental data and their presence in principle may also enhance the $W$-boson mass. Here we examine the models of axion-like particle (ALP), dark photon as well as Chameleon dark energy to see whether one of them can provide a solution of the $W$-boson mass excess. We find that the ALP interpretation is marginally consistent with the astrophysical constraints except for a mass of $\sim 1$ GeV. For the dark photon, the constraint on the $\xi$ parameter has been significantly narrowed down but no other astrophysical bounds are found available to further check this possibility. The possibility of attributing $W$-boson mass anomaly to the Chameleon dark energy has been ruled out by other experiments.

I. INTRODUCTION

With the discovery of the higgs particle, the Standard Model (SM) [1–4] achieves unprecedented success and interprets almost all phenomenons measured by the colliders. The astrophysical data, anyhow, bring the community the puzzles. The observations of the galaxy rotation curves [5], gravitational lensing [6], and the Cosmic Microwave Background (CMB) power spectrum [7] have demonstrated that the total mass of the Universe cannot be accounted for by the ordinary matter in the SM and dark matter (DM) has been introduced to explain the missing mass [8–11]. The data of the SN Ia supernova [12], the baryon acoustic oscillations [13], the large-scale structure [14] as well as the CMB also call for the presence of dark energy (DE) that makes up of 68% the total energy density of the current Universe [15]. Though extensively explored, the nature of DM and DE are still essentially unknown. Various new particles or fields have been introduced in the literature [16–20]. Some of these particles or fields are also well theoretically motivated. For instance, the Axion, a hypothetical sub-eV particle beyond SM and one of the promising candidates of cold DM, has been initially introduced to solve the CP violation in strong interaction [21, 22].

Interestingly, some anomalies are also reported in some physical experiments in the past few years. For example, in 2021 the muon anomalous magnetic moment had been measured by E989 at Fermilab with a relative precision of 368 parts-per-billion. The combination with the previous measurement from Brookhaven National Lab yields a deviation from the SM prediction at a confidence level of $4.2\sigma$ [23]. The electroweak fit, including $Z$-pole data and $m_W$, as well as $m_h$, measurements, yields a well determined mass $m_{W,SM} = 80.361 \pm 0.006$ GeV of the $W$-boson that mediates the electroweak interactions. The precision measurement of the $W$-boson mass is hence of great importance in probing the internal consistency of the SM. Very recently, CDF Collaboration reported a precise measurement on $W$-boson mass [24], which is $80433.5 \pm 9.4$ MeV. The deviation from the SM prediction is about $7\sigma$. Such a remarkable discovery is the focus of this work. The $W$-boson mass equals to $g v / 2$ at tree level, where $v = 245$ GeV is vacuum expectation value of the Higgs field and $g$ is the weak-isospin coupling parameter. Like other particles in the SM, its mass also suffers from loop corrections. New particles/fields interacting with $W$-boson also have loop corrections to its mass. This fact motivates us to examine whether some DM/DE models could explain the latest CDF $W$-boson measurement. For such a purpose, in this work we examine a few models, including the axion-like particle, the dark photon and the Chameleon dark energy. We find out that the first two scenarios are still viable while the last one is not.

II. METHODOLOGY

The $W$-boson mass can be measured at hadron collider through charged current Drell-Yan process, i.e. $pp \rightarrow W^\pm + X \rightarrow l^\pm + v(\bar{v}) + X$. Then there are three observ-
ables in this process which are the lepton-pair transverse mass, missing transverse momentum, and charged lepton transverse momentum. The measurement accuracy of \(W\)-boson mass improves rapidly with the growing experimental data and advancement of detection technology. Previously, the mass of \(W\)-boson has been measured to a precision of 33 MeV at the Large Electron-Positron (LEP) collider [25] and 16 MeV at the Tevatron [26] by averaging the measurement of CDF [27] and D0 [28]. The global fit result of the electroweak experiments available in 2018 is 7 MeV [29], which is 58% of 2021 PDG average of direct measurements [30].

The precision electroweak measurements in colliders involve fermions scattering each other. In these inelastic scattering processes, the new gauge bosons can be exchanged by fermions and induced a oblique correction, which would shift the SM coupling [31–33]. This correction dominates, we may use the freedom from new physics, particles or fields, to perform field re-definitions, which would shift the SM coupling [31–33]. When this scattering processes, the new gauge bosons can be exchanged by fermions and put all of the new physics effect into the vacuum polarization [34, 35].

For new physical models, the loop contribution to the \(W\)-boson mass can be described in terms of the oblique parameters of \((S, T, U)\) [34, 35], i.e.,

\[
m_w^2 = m_{W,\text{SM}}^2 + \frac{\alpha C_W m_W^2}{\sin^2 \theta_W} \left[ \frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2} U \right],
\]

where \(s_W \equiv \sin \theta_W, c_W \equiv \cos \theta_W, \) and \(\theta_W\) is Weinberg mixing angle. \(\alpha\) and \(m_Z\) are the fine structure constant and \(Z\)-boson mass, respectively. The SM predicted \(W\)-boson mass is \(m_{W,\text{SM}} = 80.361 \pm 0.006\text{GeV} \) [30]. Additionally, the complete electroweak precision measurements are parameterized by \(S, T, U\) that are given by [34, 35].

By performing the global electroweak fit with the CDF II \(W\)-boson mass, the oblique parameters are reported to be \(S_0 = -0.01 \pm 0.10, T_0 = 0.03 \pm 0.12, U_0 = 0.02 \pm 0.11\), with correlation coefficients among \((S, T, U)\) are \(C_{ST} = 0.92, C_{SU} = -0.8\) and \(C_{TU} = -0.93\), respectively. These parameters are far more different with the old \(S, T, U\) values from PDG [30]. Comparison between the new physics and experiments though the \(\chi^2\) calculation based on \(S, T, U\) is [37]

\[
\chi^2_{STU} = \left( \begin{array}{ccc} \Delta S & \Delta T & \Delta U \end{array} \right) \left( \begin{array}{ccc} \sigma^2_v & C_{SU} & C_{ST} \\ C_{SU} & \sigma^2_t & C_{TU} \\ C_{ST} & C_{TU} & \sigma^2_u \end{array} \right) \left( \begin{array}{c} \Delta S \\ \Delta T \\ \Delta U \end{array} \right),
\]

where \((\sigma_v, \sigma_t, \sigma_u)\) are the errorbar, \(\Delta \chi = \chi_{\text{model}} - \chi_0\), and \(\chi\) denote \(S, T, U\). \(\chi^2_{STU}\) is dependent on the parameters in different models, thus we could obtain the allowed parameter regions. Below we discuss three specific models and set the constraints.

II. THE MODELS AND CONSTRAINTS

A. Axion-like Particle

Axion-like Particle (ALP), which is a kind of pseudo-scalar particle, appears in string theory and some well-motivated models as one kind of dark matter [38–46]. The difference between ALP and axion models is that for the former both mass and coupling are free parameters. The effective interactions of ALP and electroweak gauge bosons, which considering in our work, are given by the following dimension-5 effective lagrangian [47–50]

\[
\mathcal{L}^{D=5}_{\text{eff}} = \frac{1}{2} (\partial \mu a) (\partial^\mu a) - \frac{M_a^2}{2} a^2 + g^2 C_{WW} \frac{a}{\Lambda} W^A W_{\mu \nu} B^{\mu \nu, A} + g^2 C_{BB} \frac{a}{\Lambda} B_{\mu \nu} B^{\mu \nu},
\]

where \(W^A_{\mu \nu}\) and \(B_{\mu \nu}\) are gauge field strengths of \(SU(2)_L\) and \(U(1)_Y\), and \(g\) and \(g'\) denote the corresponding coupling constants, respectively. \(\tilde{B}^{\mu \nu} = \frac{1}{2} \epsilon^{\mu \nu \rho \sigma} B_{\rho \sigma}\) (with \(\epsilon^{0123} = 1\)) etc. The \(\Lambda \sim 1\text{TeV}\) is the energy scale of new physics. The ALP field and its mass are denoted by \(a\) and \(M_a\), respectively. The interactions between ALP gauge bosons are contributed by the last two terms of Eq. (3). The dimensionful couplings \(C_{\gamma \gamma} = C_{WW} + C_{BB}\) describe the coupling strength of the interactions between ALP and photon in leading order.

Since we only consider the ALP much lighter than the electroweak scale, the corrections to electroweak precision observables can be generally described by the usual oblique parameters \(S, T,\) and \(U\), and the effect from the mass of ALP can be neglected. In Ref. [47] the oblique parameters have been expressed by calculating vacuum polarization function to one loop order (please see Sec 6.3 therein for more details), and we adopt these expressions in our analysis.

With the \(\chi^2\) defined in eq. (2), we get the allowed parameter spaces of Wilson coefficients. The results are shown in Fig. 1, where the separated two red regions are favored by the new result of CDF II. In comparison to that for the 2021 PDG results (i.e., the re-
FIG. 1: Allowed parameter regions of ALPs coefficients $C_{WW} - C_{BB}$ obtained from a global electroweak fit $S$, $T$ and $U$ at 68% (dark red), 95% (red) and 99% (light red) confidence level (CL). As a comparison, we also plot the parameters space favored by 2021 PDG results [30] at 68% (dark grey), 95% (grey) and 99% (light grey) CL. Additionally, the blue region is allowed by LEP collider at $M_\alpha \sim 1$ GeV and the black line is set by the CAST observation [47].

FIG. 2: Allowed parameter regions of dark photon obtained from a global electroweak fit $S$, $T$ and $U$ at 95% (red) and 99% (light red) CL. As a comparison, we also present the parameters space favored by 2021 PDG results [30] at 68% (dark grey), 95% (grey) and 99% (light grey) CL.

The general renormalizable Lagrangian for the SM with an extra $U(1)'$, neglecting the fermionic part, is given by [51]:

$$\mathcal{L}_{Z'} \supset -\frac{1}{4} \hat{Z}_{\mu\nu}' \hat{Z}^{\mu\nu} + \frac{1}{2} M_Z^2 \hat{Z}_{\mu}' \hat{Z}^{\mu}_1 + \frac{1}{2} \alpha \hat{Z}_{\mu}' \hat{B}^{\mu\nu} + \kappa \hat{Z}_1 \hat{Z}^{\mu},$$

where $\hat{B}_{\mu\nu}$ and $\hat{Z}_{1\mu}$ are the field strength tensors for $U(1)'$ and $U(1)'$, $\hat{Z}$ is Z-boson in the SM, and $\hat{Z}'$ represents the boson of the new $U(1)'$, i.e. dark photon (dark $Z'$). In addition, $\sin\alpha$ and $\kappa$ correspond kinetic mixing with photon and mass mixing with $Z$-boson, respectively. The physical eigenbasis can obtain by diagonalizing the mass terms from $U(1)'$ breaking and $SU(2) \times U(1)$ breaking. The non-diagonal mass terms give a mixing between $Z'$ and $Z$, therefore affect the precision electroweak measurements and the coupling with neutrinos [52, 53, 59]. In the end, one mass eigenstate is massless (the photon $A_\mu$), while the other two (denoted as $Z_1$ and $Z_2$) receive masses (Here we assume $m_{Z_1} < m_{Z_2}$, and $Z_1$ is the Z-boson in SM, $Z_2$ represents the dark $Z'$).

After defining

$$\tan 2\xi = \frac{-2 \cos \alpha (\kappa + M_Z^2 s_W \sin \alpha)}{M_{Z'}^2 - M_Z^2 \cos^2 \alpha + M_Z^2 s_W^2 \sin^2 \alpha + 2 \kappa s_W \sin \alpha},$$

we can replace the mixing parameters $\sin\alpha$ and $\kappa$ with $\xi$ and $\tan\alpha$. Furthermore, the $Z - Z'$ contribution to $S, T, U$ (the leading order) could expressed conveniently, which have been calculated in Ref. [51].

The precision electroweak measurement is weakly correlated with the mass of $Z'$ ($m_{Z'}$). If $m_{Z'}$ is sufficiently large, the contribution to the precision electroweak measurement is mainly governed by the $\xi$ [61]. Therefore,
in this work we take a $m_{Z'} = 500$ GeV. With the above information and the new range $S$, $T$, $U$ resulting in the global electroweak fit [36], we take eq. (2) to calculate the favored regions (see the contours in red), which are clustered around $\xi \sim 6 \times 10^{-3}$ (see Fig. 2). For comparison, we also show the allowed regions with PDG 2021 results. Clearly, similar to Fig. 1, the inclusion of the CDF II $W$-boson has significantly tightened the constraints, which is in particular the case on $\xi$, though the ranges of $\tan(\alpha) \leq 0.3$ are comparable with the previous one. In the future, supposing the parameters of $\xi$ and $\tan(\alpha)$ have been independently constrained by other experiments or astrophysical data, the interpretation of $W$-boson mass excess with dark photon will be further tested.

C. Chameleon Dark Energy

DE is one of the most mysterious topic in modern cosmology since the discovery of cosmic acceleration of the present universe [12, 62–68]. The prevailing dynamical model is to introduce a scalar field rolling along a flat potential so that a negative pressure can be achieved. However, such a scalar field is beyond the SM and suffers from several conceptual issues such as the test of the Equivalence Principle [69]. One of the methods to release this tension is the so-called Chameleon mechanism, which involves a scalar field with mass depending on the local matter density [70–74]. Models involving these fields can give rise to acceleration naturally at late time of universe, and remaining consistent with local constraints. Such models attract wide attention, as the requirement the scalar field can vary with the local density of matter means that coupling to SM states are compulsory. Therefore, in the early universe chameleon fields are constrained by precision measurements, such as Big Bang Nucleosynthesis and red-shift of recombination. As the universe cools down, the background chameleon fields remain fixed in the minimum potential, and there will have a slow drift in location. This induced a variation in the mass of any species particles, which could couple with chameleon fields. These couplings imply that there may exist an interesting collider phenomenology.

The precision electroweak measurements are screened from the indirect effect of DE, making such corrections effectively unobservable at present colliders, and limiting the DE discovery potential at CDF. In this work, we shall choose to work with a theory of the broken phase of the electroweak force, in which the photon and the massive vector bosons could interact with chameleon scalar $\phi$ according to the action [75]

$$S = -\frac{1}{4} \int d^4x \left( 2\mathcal{F}(\phi) \left( \partial^a W^{+b} - \partial^b W^{+a} \right) \left( \partial_a W^{-b} - \partial_b W^{-a} \right) + 4m^2_W J(\phi) W^{+a} W^{-a} \right) + \mathcal{F}(\phi) \left( \partial^a Z^b - \partial^b Z^a \right) \left( \partial_a Z_b - \partial_b Z_a \right) + 2m^2_Z J(\phi) Z^a Z_a + \mathcal{F}(\phi) \left( \partial^a A^b - \partial^b A^a \right) \left( \partial_a A_b - \partial_b A_a \right) \right),$$

where $W^{\pm a}$ and $Z_a$ are the gauge fields associated with the $W^{\pm}$ and $Z$, respectively, and $A_a$ is the gauge field associated with the photon. In addition, we have introduced two functions $\mathcal{F}(\phi)$ and $J(\phi)$ which describe how the chameleon scalar $\phi$ couples to the gauge bosons kinetic and mass terms, namely

$$\mathcal{F}(\phi) = \exp(\beta_m \phi / M_{Pl}), \quad J(\phi) = \exp(\beta_\gamma \phi / M_{Pl}),$$

where $\beta_\gamma$ and $\beta_m$ are the dimensionless chameleon couplings to photon and matter, and $M_{Pl}$ is the reduced Planck mass. The matter coupling $\beta_m$ is assumed to be universal to all species of matter, and the chameleon scalar is much smaller than the electroweak scale.

In Ref. [75] the forms of $S$, $T$, $U$ have been expressed in the terms of $\beta_m$ and $\beta_\gamma$ (please see Sec 4.2 therein for the details). With the new ranges of $S$, $T$, $U$ found in the recent global electroweak fit [36], now we can constrain the distribution of $\beta_m$ and $\beta_\gamma$ with eq. (2). The resulting favorable parameter space is presented in Fig. 3 and it is almost line like (see the ribbon red region).
IV. SUMMARY AND DISCUSSION

The $W$-boson mass ($m_W = 80.4335 \pm 0.0094\text{GeV}$) measured by the CDF collaboration is in excess of the SM prediction at a confidence level of 7$\sigma$, which provides strong evidence for the presence of new physics beyond standard model. In the literature, various new particles or fields have been introduced to account for the dark matter or dark energy suggested by the astrophysical observations. The presence of new particles or fields will modify the oblique parameters of $S$, $T$ and $U$ and in principle can enhance the loop corrections of the $W$-boson mass. It is thus interesting to examine whether these widely-investigated scenarios are in tension with the new $S$, $T$, $U$ parameters found in the global electroweak fit including the CDF II $W$-boson mass measurement. For such a purpose, in this work we have discussed three models involving either very light particles or scalar fields, including the axion-like particle, the dark photon (dark $Z'$) and the chameleon dark energy. Different from the relatively loose constraints on $C_{BB}$ and $C_{WW}$ with the 2021 PDG data, now the favored regions are separated and narrowly distributed. The interpretation of the CDF II $m_W$ measurement with the axion-like particle is found to be just marginally consistent with the CAST constraint (see Fig.1) except in the case of $m_a \sim 1\text{GeV}$. As for the dark photon, the latest global electroweak fit results yield a $\xi \sim 6 \times 10^{-3}$ and $\tan(\alpha) \geq 0.3$ (see Fig.2) for $m_{Z'} \gg O(EW)$. In the future, if independent constraints on these two parameters are yielded in other experimental/astrophysical data, this possibility can be further tested.

As for the Chameleon dark energy model, again we find almost a line-like parameter region for the $m_W$ excess (see Fig. 3). However, such a region has been convincingly excluded by the CAST, KWISP and neutron interferometry experiments. In this work we have addressed the possible new light particle or the scalar field origin of the $W$-boson mass excess, and certainly there are many other interesting possibilities. For instance, it is argued that the inert two Higgs doublet model can naturally handle the CDF II $W$-boson mass without violating other experimental/astrophysical constraints, and the preferred dark matter mass is between 54 and 74 GeV [84]. In light of these facts, we conclude that the CDF II $W$-boson mass measurement can initiate a new window for the new physics and significant progresses are expected in the near future.

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