SEARCH FOR NEW PHYSICS IN CHARM PROCESSES*

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Charm processes are usually not considered to be favorable candidates in the search for new physics. Recent disagreement between experimental and lattice QCD results on the D_s decay constant has motivated us to systematically reinvestigate role of leptoquarks in charm meson decays. We include constraints coming from the light meson decays.

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1. Introduction

Appearance of new physics in the charm processes is known to be screened either due to long distance contribution, or due to special interplay of the GIM mechanism and CKM parameters in the charm processes amplitudes.

The $c \to u$ transition, however, gives a chance to study effects of new physics in the up-like quark sector. The QCD corrected effective Lagrangian gives $\mathrm{BR}(c \to u\gamma) \simeq 3 \times 10^{-8}$ [1]. A variety of models beyond the standard model were investigated and it was found that the gluino exchange diagrams within general minimal supersymmetric SM (MSSM) might lead to the enhancement of the order 10^2. The leading contribution to $c \to ul^+l^-$ in general MSSM with the conserved R parity comes from one-loop diagram with gluino and squarks in the loop (*e.g.* [1]). It proceeds via virtual photon and significantly enhances the $c \to ul^+l^-$ spectrum at small dilepton mass m_{ll}. The experimental results on parameters describing the D^0–$\bar{D}^0$ oscillations have stimulated studies of new physics in charm sector. Also,

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it was found that the result of experimental measurements for the leptonic decay rates of D_s mesons (see Refs. [3–6] in [2]) and the lattice results for the relevant f_{D_s} decay constant (Refs. [7–9] in [2]) disagree by $2.3\,\sigma$, while the corresponding values for f_D are in perfect agreement.

We reinvestigate possible explanation of this puzzle by the leptoquark mediation. In our approach leptoquarks transform as a weak interaction triplet, doublet, or singlet in a model independent approach. Generally, leptoquarks which also couple to diquarks mediate fast proton decay and are therefore required to be much above the electroweak scale, making them uninteresting for other low energy phenomena. "Genuine" leptoquarks on the other hand, couple only to pairs of quarks and leptons, and may thus be inert with respect to proton decay. In such cases, proton decay bounds would not apply and leptoquarks might affect low-energy phenomena. We consider whether light scalar "genuine" leptoquarks can explain the f_{D_s} puzzle and at the same time comply with all other measured flavor observables. Then we consider a SU(5) GUT model in which the leptoquarks are accommodated in the 45-dimensional Higgs representation. Using the current experimental measurements in τ, kaon and charm sectors, we find that scalar leptoquarks cannot naturally explain the $D_s \to \mu\nu$ and $D_s \to \tau\nu$ decay widths simultaneously.

We construct all possible renormalizable scalar leptoquark interactions with SM matter fields. There are a few such dimension-four operators containing leptoquarks which are either singlets, doublets or triplets under the $\mathrm{SU}(2)_\mathrm{L}$. If we furthermore require that such leptoquarks contribute to leptonic decays of charged mesons at tree level, we are left with three possible representation assignments for the $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge groups: $(\mathbf{3}, \mathbf{3}, -1/3)$, $(\bar{\mathbf{3}}, \mathbf{2}, -7/6)$ and $(\mathbf{3}, \mathbf{1}, -1/3)$. Only the weak doublet leptoquark is "genuine" in the above sense. However, using a SU(5) GUT model where the relevant leptoquarks are embedded into the 45-dimensional Higgs representation ($\mathbf{45}_H$), we show how leptoquark couplings to matter can arise and in particular, how the dangerous couplings to diquarks — both direct and indirect — can be avoided.

In our study we assume that leptoquark multiplets are degenerate in mass to bypass constraints from the electroweak precision tests (observable T). We study only role of leptoquark mediation at tree level since these already involve processes forbidden in the SM at tree level, *i.e.*, flavor changing neutral currents (FCNCs) and lepton flavor violation (LFV) processes. Finally, since the present f_{D_s} deviation is of mild significance, we require all the measured constraints to be satisfied within one standard deviation (at 68 % C.L.) except upper bounds, for which we use published 90 % C.L. limits.

After the electroweak (EW) symmetry breaking, quarks and leptons acquire their masses from their respective Yukawa interactions. Since these are not diagonal in the weak basis, a physical CKM and PMNS rotations are present between the upper and the lower components of the fermion doublets, when these are written in term of the physical (mass eigen-) states. Consequently, it is impossible to completely isolate leptoquark mediated charged current interactions to a particular quark or lepton generation in the left-handed sector *irrespective of the initial form of the leptoquark couplings to SM matter fields, unless there is some special alignment with the right-handed quark sector.* We work in a basis where the SM Yukawa couplings of the up-quarks and charged leptons are flavor-diagonal from the outset.

2. Triplet, doublet and singlet leptoquarks

The triplet leptoquark interaction Lagrangian has only one term

$$\mathcal{L}_3 = Y_3^{ij}\, \overline{Q_i^c} i\tau_2\, \vec{\tau} \cdot \vec{\Delta}_3^*\, L_j + \text{h.c.}\,, \tag{1}$$

where $\overline{Q^c} = Q^T C$, $C = i\gamma^2\gamma^0$ and τ are the Pauli matrices. The 3×3 coupling matrix Y_3 is arbitrary, and we use the following parametrization $Y_3^{q\ell} = y_3^\ell(\sin\phi, \cos\phi, 0)^q$. Analogous parametrizations are applied for the doublet and singlet leptoquarks, too. In the concrete SU(5) model, the above couplings are due to the contraction of $\mathbf{10}$ and $\overline{\mathbf{5}}$ with $\mathbf{45}_H^*$ — also responsible for giving masses to the down quarks and charged leptons. We consider constraints coming from the following processes: $D_s \to \mu(\tau)\nu_{\mu(\tau)}$, $\tau \to \eta, \phi, \pi, K\nu_\tau$, $K \to \mu\nu_\mu$, $K^+ \to \pi^+\nu\bar{\nu}$, $K_\mathrm{L} \to \mu^+\mu^-$ and ratios $\mathrm{BR}(\tau \to K\nu)/\mathrm{BR}(K \to \mu\nu)$ and $\mathrm{BR}(\tau \to \pi\nu)/\mathrm{BR}(\pi \to \mu\nu)$. In our calculations [2], the coupling denoted by $\tilde{Y}_3$ contains an additional V_CKM rotation for the down-type quarks

$$\tilde{Y}_3^{q\ell} \equiv \begin{cases} Y_3^{q\ell}; & q = u\,,\, c\,,\, t\,, \\ (V_\mathrm{CKM}^T Y_3)^{q\ell}; & q = d\,,\, s\,,\, b\,. \end{cases} \tag{2}$$

Bounds from $K^+ \to \pi^+\nu\bar{\nu}$ and $K_\mathrm{L} \to \mu^+\mu^-$ constrain the sum of leptoquark coupling combinations

$$\tilde{Y}_3^{s\ell} Y_3^{d\ell *} = (y_3^\ell)^2 \cos\theta_c \cos\phi (\tan\phi - \tan\theta_c)(1 + \tan\theta_c \tan\phi) \tag{3}$$

and fix *very accurately* $\tan\phi = \tan\theta_c$ or $\tan\phi = -\cot\theta_c$. The constraints presented in Fig. 1 clearly disfavor a triplet leptoquark explanation of the $D_s \to \mu\nu$ excess.

The doublet leptoquarks are innocuous as far as proton decay is concerned. The allowed dimension four interactions in this case are

$$\mathcal{L}_2 = Y_{2\mathrm{L}}^{ij}\, \overline{Q}_i\, i\tau_2 \Delta_2^*\, e_j + Y_{2\mathrm{R}}^{ij}\, \overline{u}_i \Delta_2^\dagger L_j + \text{h.c.} \tag{4}$$

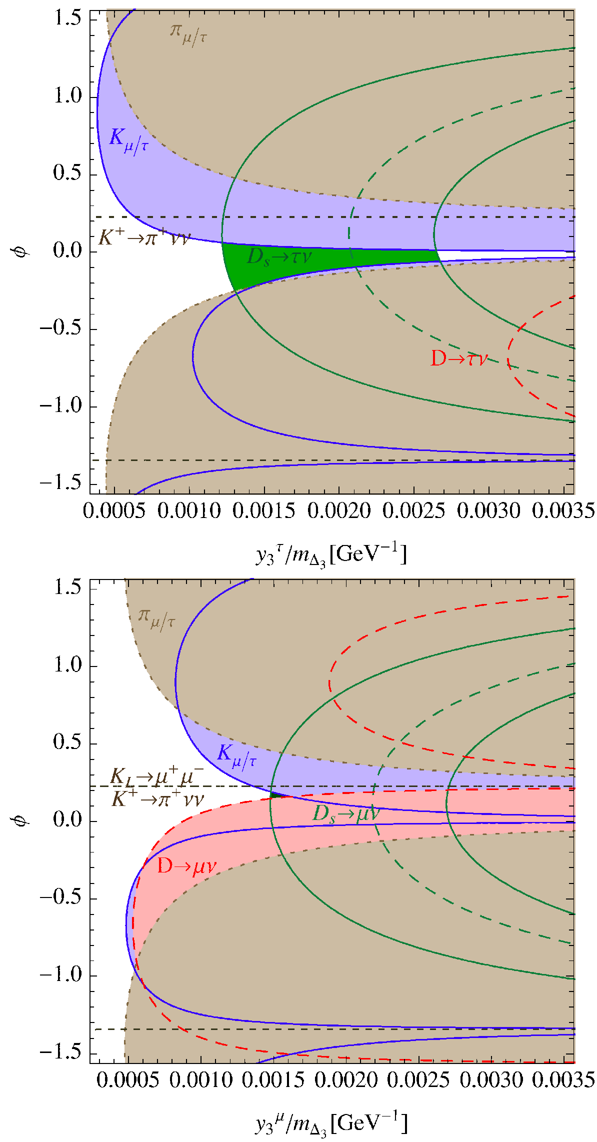

Fig. 1. Combined bounds on the triplet leptoquark parameters in the two-generation limit in the tau (upper plot) and muon (lower plot) sectors. The $K^+ \to \pi^+\nu\bar{\nu}$ and $K_{\rm L} \to \mu^+\mu^-$ constraints can only be satisfied on the two horizontal dashed lines. The $D_s \to \ell\nu$ excess can be accounted for within the dark gray (green) band in the upper plot, and the tiny black (dark green) band in the lower plot.

In the particular SU(5) model, the term proportional to $Y_{2\mathrm{R}}$ stems from the contraction of **10** and $\overline{\mathbf{5}}$ with $\mathbf{45}_H^*$ while the $Y_{2\mathrm{L}}$ term is due to **10** and **10** being contracted with $\mathbf{45}_H$. In our study we use bounds coming from the following decay rates: $D_s \to \ell\nu$, $D^0 \to \mu^+\mu^-$ and $K_\mathrm{L} \to \mu^+\mu^-$. Recently, Belle Collaboration has presented new bound on the decay rate $\mathrm{BR}(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7}$. Including this bound we find that the doublet leptoquark cannot explain the D_s puzzle. As one sees from Fig. 2, the bound coming from the $K_\mathrm{L} \to \mu^+\mu^-$ does not pass the black (dark green) allowed region.

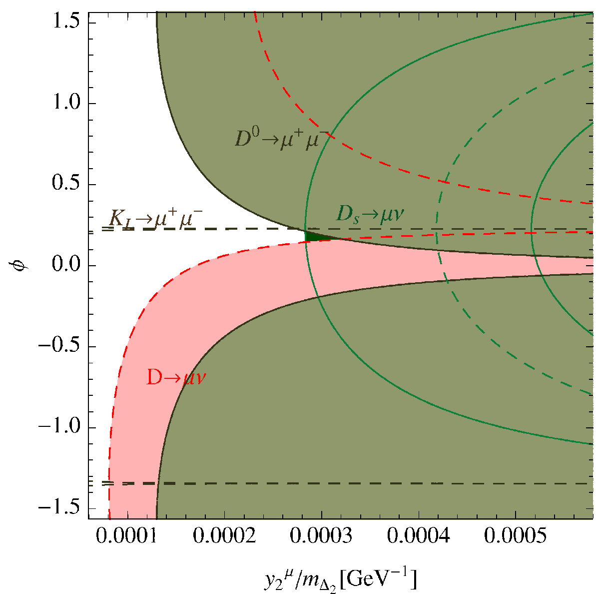

Fig. 2. Combined $D^0 \to \mu^+\mu^-$ and $D \to \mu\nu$ bounds on the doublet leptoquark parameters in the two-generation limit in muon sector. Within the tiny black (dark green) band, the $D_s \to \ell\nu$ excess can be accounted for. However, the bound coming from $K_\mathrm{L} \to \mu^+\mu^-$ lies out of this region, making the doublet of leptoquark inadequate for the explanation of the D_s puzzle.

The most general Lagrangian describing singlet leptoquarks has two terms:

$$\mathcal{L}_1 = Y_{1\mathrm{L}}^{ij} \overline{Q_i^c} i\tau_2 \Delta_1^* L_j + Y_{1\mathrm{R}}^{ij} \overline{u_i^c} \Delta_1^* e_j + \mathrm{h.c.} \tag{5}$$

In order to constrain leptoquark couplings we use: $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$, the Belle Collaboration bound for $D^0 \to \mu^+\mu^-$, and the ratios of experimental rates and the standard model values for the decay $D_s \to \tau\nu_\tau$ and $\tau \to K\nu_\tau$. The lack of experimental information on up-quark FCNCs involving only tau leptons leaves the verdict on the singlet leptoquark contribution to the

$D_s \to \tau\nu$ decay width open. What is certain is that due to the $K^+ \to \pi^+\nu\bar{\nu}$ constraint any such contribution has to be aligned with the down-type quark Yukawas such that $\tilde{Y}_1^{d\tau} \approx 0$ can be ensured.

By performing a numerical fit of the relevant parameters [2] to the above mentioned constraints we obtain the result, that the experimental value for $\mathrm{BR}(D_s \to \mu\nu)$ cannot be reproduced within one standard deviation without violating any of the other constraints, thus excluding the singlet leptoquark as a natural explanation of the $D_s \to \mu\nu$ puzzle. Same conclusions can be drawn for the R-parity violating minimal supersymmetric SM [4], where the interaction term of a down squark to quark and lepton doublets is present and corresponds to first term in (5), while the second term is absent in that case.

Existing constraints coming from precision kaon, tau, and D meson observables imply in a model independent way, that a single scalar leptoquark cannot explain enhanced $D_s \to \ell\nu$ decay widths for both $\ell = \mu$ and τ.

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