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Scalar diquark in $t\bar{t}$ production and constraints on Yukawa sector of grand unified theories

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A colored weak singlet scalar state with hypercharge 4/3 is one of the possible candidates for the explanation of the unexpectedly large forward-backward asymmetry in $t\bar{t}$ production as measured by the CDF and D0 experiments. We investigate the role of this state in a plethora of flavor changing neutral current processes and precision observables of down-quarks and charged leptons. Our analysis includes tree- and loop-level mediated observables in the K and B systems, the charged lepton sector, as well as the $Z \to b\bar{b}$ width. We perform a fit of the relevant scalar couplings. This approach can explain the $(g-2)_\mu$ anomaly while tensions among the CP violating observables in the quark sector, most notably the nonstandard CP phase (and width difference) in the B_s system cannot be fully relaxed. The results are interpreted in a class of GUT models which allow for a light colored scalar with a mass below 1 TeV.

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1. Introduction

Recent CDF and DØ results on the forward-backward asymmetry (FBA) in top quark pair production have attracted a lot of attention and a number of proposals have been made in order to explain all the relevant observables (for a review see e.g. [1]). Among these, a colored scalar, called here Δ, with SM charges $(\overline{\mathbf{3}},\mathbf{1},4/3)$ couples to two up-quarks, hence it is also called a diquark. With large coupling g_{ut} of Δ to u_R and t_R one can accommodate most of the present measurements of FBA and production cross section of $t\bar{t}$ [2, 3]. Only flavor-changing couplings of Δ to up-quarks are allowed and we study also the remaining two couplings in charm meson mixing observables as well as in dijet and single top quark production measurements at Tevatron.

On the other hand, rare processes involving down-type quarks and charged leptons have played an important role in revealing possible signs of new physics at low energies. A prominent example is the anomalous magnetic moment of the muon, whose most precise experimental measurement [4] deviates from theoretical predictions within the SM [5] by about three standard deviations. The scalar Δ could play an important role in those processes by an independent set of leptoquark couplings $Y_{\ell d}$ to right-handed charged leptons and down-quarks.

2. Processes with up-quarks

Yukawa couplings of Δ to up-quarks are

$$\frac{g_{ij}}{2}\varepsilon_{abc}\bar{u}_{ia}P_L u^C_{jb}\Delta^c + \text{h.c.}\,, \tag{2.1}$$

where $P_{L,R}=(1\mp\gamma_5)$, i,j are flavor indices, a,b,c are color indices, and the totally antisymmetric tensor ε_{abc} is defined with $\varepsilon_{123}=1$. Matrix g must be antisymmetric due to antisymmetry in color contraction.

Exchange of Δ contributes to $t\bar{t}$ production amplitude in the u-channel. It was emphasized in [2] that Δ at and below 1 TeV can enhance the SM prediction of the forward-backward asymmetry $A^{t\bar{t}}_{FB}$ while not altering the production cross section $\sigma_{t\bar{t}}$. This is achieved by finding the parameter space of m_Δ and coupling g_{ut}, contributing to partonic subprocess $u\bar{u}\to t\bar{t}$ in $p\bar{p}$ collisions, which together with SM reproduce the measured values of $A^{t\bar{t}}_{FB}$ and $\sigma_{t\bar{t}}$. The region where experimental constraints can be satisfied within 1σ roughly corresponds to a region, where mass of Δ and the coupling g_{ut} are correlated as (Fig. 1, left graph)

$$|g_{ut}| = 0.9(2)+2.5(4)\,\frac{m_\Delta}{1\ \text{TeV}}. \tag{2.2}$$

Finite value of g_{ut} allows us to constrain also the remaining two couplings to up-quarks.

Potential contributions of Δ in $D-\bar{D}$ mixing can affect the dispersive amplitude M_{12} via box diagrams consisting of Δ and t-quark. Assuming m_Δ is between 300 GeV and 1 TeV [2] we can safely integrate out both the top quark and Δ at a common scale $\mu=m_\Delta$ and find an operator with right handed currents

$$\mathscr{H}^{\Delta C=2} = \frac{(g_{ut}g^*_{ct})^2 h(m_\Delta^2/m_t^2)}{32\pi^2 m_t^2}Q_6, \qquad Q_6=(\bar{u}_R\gamma^\mu c_R)(\bar{u}_R\gamma_\mu c_R)\,. \tag{2.3}$$

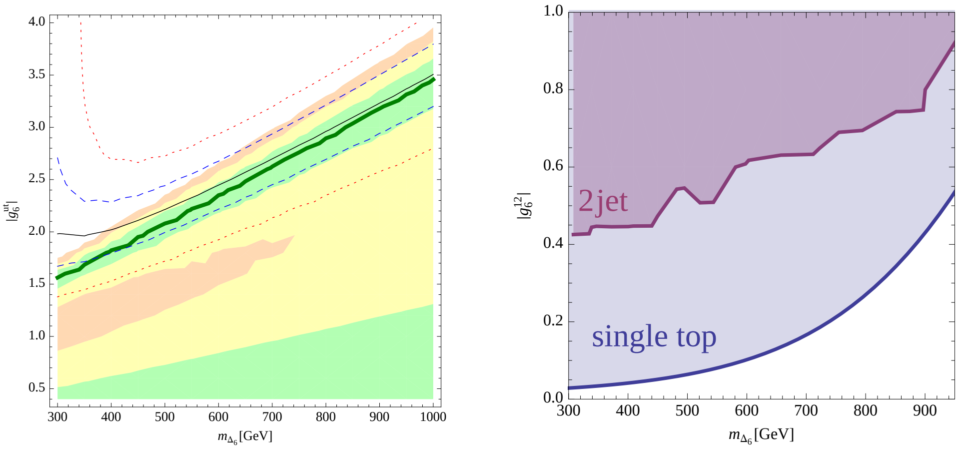

Figure 1: Left: the 68, 95, 99% CL regions in production cross section are shaded in green, yellow and orange respectively. The corresponding 68 (95)% CL regions in the FBA are bounded by blue dashed (red dotted) contours. The best-fit contours are drawn in thick (thin) full lines for the cross section and the FBA respectively. Right: constraint on the $|g_{uc}|$ coupling and Δ mass from the single top production and di-jet at the Tevatron. The shaded areas are excluded.

Using the HFAG averages [6] of $D-\bar{D}$ mixing parameters and a set of formulas [7, 8] that connect experimental parameters x, y, $|q/p|$, and ϕ to the underlying theoretical parameters M_{12}, $\arg(\Gamma_{12}/M_{12})$, we can constrain the magnitude of M_{12}. The upper bounds at 95 % (2σ) confidence level are [9]

$$2|M_{12}|/\Gamma < 9.6\times 10^{-3}, \qquad 2|\mathrm{Im}M_{12}|/\Gamma < 4.4\times 10^{-3}. \tag{2.4}$$

The imaginary part of M_{12} and the resulting bound depends on a relative phase between g_{ct} and g_{ut}. A robust bound

$$|g_{ct}| < 0.0038, \tag{2.5}$$

at 2σ CL comes from bound on $|M_{12}|$ and is independent of complex phases in couplings. Here the central value for $|g_{ut}|$, as given in Eq. (2.2), has been assumed.

The effects of coupling g_{uc} could be observed in the CDF search for resonances in the invariant mass spectrum of dijets [10] as well as from the single top production cross section measurements at the Tevatron [11]. The first measurement constrains the $|g_{uc}|$ coupling directly since the process can be mediated by Δ through s-, u- and t-channel exchange diagrams interfering with leading order QCD contributions at the partonic level. As shown above, the tc channel is severely constrained by experimental results on $D-\bar{D}$ oscillations and can be neglected. We compare our prediction for the dijet spectra (for details see [9]) with the experimental results [10]. We obtain the bounds on $|g_{uc}|$ as a function of m_Δ by comparing the obtained theoretical spectrum for given values of Δ parameters against the experimental spectra. The results are shown as the purple shaded area in the right graph of Fig. 1.

The single top production cross-section is sensitive to the product of $|g_{uc}g_{ut}|$ [9]. On the partonic level we have a u-channel $u\bar{u}\to t\bar{c}$ and an s-channel $uc\to tu$ contributions. A bound on $|g_{uc}|$ can then be obtained by using the $t\bar{t}$ FBA preferred values of $|g_{ut}|$ in Eq. (2.2). We employ a conservative approach and only compare NP contributions with the experimental error on the combined Tevatron result for the total single-top production cross-section (summed over both t and $\bar{t}$) of $\sigma_{1t} = 2.76^{+0.58}_{-0.47}$ pb [11]. Excluded parameter is shown as blue shaded area in the right graph of Fig. 1.

3. Leptoquark processes

Yukawa couplings of Δ to down quarks and leptons are

$$Y_{ij}\bar{\ell}_i P_L d^C_{ja} \Delta^{a*} + \text{h.c.}\,, \tag{3.1}$$

Together with the diquark couplings, g, leptoquark couplings can destabilize the proton. However, the tree-level dimension-6 proton decay mediating operator is forbidden by the antisymmetry of g in flavor space.

The leptoquark couplings endow the scalar Δ with a potential to cause large effects in (flavor changing) neutral current processes of down quarks and charged leptons (see [12] for a recent analysis of scalar leptoquark constraints from K and B sectors). The couplings Y_{ij} in Eq. (3.1) must therefore pass constraints coming from many precisely measured or bounded from above low energy observables.

Potentially most severe are the tree-level constraints on the Y matrix. These are neutral K meson decays ($K_L \to \mu^-\mu^+$, e^+e^-, $\mu^\pm e^\mp$; $K_S \to e^-e^+$, $\mu^+\mu^-$), neutral $B_{(s)}$ meson decays ($B_{d(s)} \to \ell^-\ell'^+$, $\ell^{(\prime)} = e, \mu, \tau$), inclusive $B \to X_s \ell^+\ell^-$, exclusive semileptonic $B \to \pi\ell^+\ell'^-$ and $B \to K\ell^+\ell'^-$, semileptonic tau decays ($\tau \to \mu\eta, \mu K_S, eK_S, \mu\pi^0, e\pi^0$) and $\mu - e$ conversion on nuclei. For more details about these constraints we refer reader to [13].

Next we turn our attention to observables which are affected by leptoquark couplings of Δ at the one-loop level. These are $K - \bar{K}$ and $B - \bar{B}$ mixing amplitudes, LFV neutral current processes like the radiative μ and τ decays ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$), as well as flavor diagonal observables, such as the anomalous magnetic moments of leptons or the decay width of the Z to $b\bar{b}$ pairs. The most interesting observable in 1-loop category is the muon anomalous magnetic moment $(g-2)_\mu$. In the recent years, the experimental result on the anomalous magnetic moment of the muon $a_\mu \equiv (g-2)_\mu/2$ from BNL [4] has been about 3σ above the SM predictions [5]

$$a_\mu^{\text{exp}} = 1.16592080(63) \times 10^{-3}\,, \tag{3.2a}$$

$$a_\mu^{\text{SM}} = 1.16591793(68) \times 10^{-3}\,. \tag{3.2b}$$

Treating both experimental and theoretical uncertainties as Gaussian, we may identify the missing contribution to a_μ

$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.87 \pm 0.93) \times 10^{-9}\,, \tag{3.3}$$

with the presence of NP. On top of the a_μ^{SM} we get a new contribution

$$a_\mu = \frac{1}{16\pi^2}\frac{m_\mu^2}{m_\Delta^2}\sum_{i=d,s,b}|Y_{\mu i}|^2\,, \tag{3.4}$$

which comes from a diagram on Fig. 2. Thus a finite magnitude is preferred for a combination of the second row elements of Y

$$\sum_{i=d,s,b}|Y_{\mu i}|^2 = (4.53 \pm 1.47) \times 10^{-7} \times \frac{m_\Delta^2}{m_\mu^2} = (6.45 \pm 2.09) \times \frac{m_\Delta^2}{(400\text{ GeV})^2}\,. \tag{3.5}$$

Figure 2: Diagrams with Δ and down-quarks contributing to the lepton anomalous magnetic moments.

To see how the observed a_μ is generated while the FCNC and LFV constraints are evaded we determine matrix Y in a fit to all abovementioned observables [13] at a representative mass $m_\Delta = 400$ GeV. In a trivial case, when we set $Y = 0$ to recover the SM, we find $\chi^2_{\rm min} = 12.5 = 9.5_{a_\mu} + 1.5_{\rm CKM} + 0.8_{\Delta m_s} + 0.3 + \cdots$ with a dominant contribution from the a_μ anomaly. Finally we let Y take any value and we find a global minimum $\chi^2_{\rm min} = 2.5 = 1.8_{\rm CKM} + 0.4_{\Delta m_s} + 0.14_{\sin 2\beta} \cdots$ for 15 degrees of freedom, which signals a very good agreement of all predictions with the considered observables. In particular, the best point perfectly resolves the anomalous magnetic moment constraint a_μ and slightly improves the quark flavor constraints. The allowed $1\,\sigma$ ranges of Y matrix elements are shown below

$$|Y^{(1\sigma)}| \in \begin{pmatrix} < 1.4\times 10^{-6} & < 8.7\times 10^{-5} & < 4.2\times 10^{-4} \\ < 3.6\times 10^{-3} \cup [2.1, 2.9] & < 3.6\times 10^{-3} \cup [2.1, 2.9] & < 6.2\times 10^{-4} \cup [2.3, 2.7] \\ < 5.6\times 10^{-3} & < 8.1\times 10^{-3} & < 9.6\times 10^{-3} \end{pmatrix}. \quad (3.6)$$

Couplings to the electron are strongly suppressed, while couplings to the muon (the second row of Y) can take values of order 1, in order to satisfy the a_μ constraint. In the last row, elements $Y_{\tau s}$ and $Y_{\tau b}$ can also be of order 0.01 at $1\,\sigma$. Three possible regimes emerge in the second and the third row, depending on which element in the second row is large. These are

$$\begin{pmatrix} & & \\ \blacksquare & & \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} & & \\ & \blacksquare & \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} & & \\ & & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix}. \quad (3.7)$$

Here $\blacksquare$ stands for order 1 element, $\bullet$ for (at most) order 0.01 element, and we neglect elements which are $\lesssim 10^{-3}$.

4. Conclusions

Scalar Δ couplings to diquarks or to leptons and quarks exhibit hierarchy, with g_{ut} and $Y_{\mu i}$ sizable to explain the large forward-backward asymmetry in $t\bar{t}$ production and anomalous magnetic moment of the muon, respectively. Remaining couplings are suppressed by $D - \bar{D}$ mixing (g_{ct}), dijet and single t production (g_{uc}) or a combination of low-energy LFV and FCNC bounds (all but one element $Y_{\mu i}$). For a leptoquark couplings we also found that LFV B and τ decay constraints lead to strong limits on the tau lepton couplings to down quarks which in turn exclude the possibility of sizable effects in the B_s system [13].

The requirement of one large element $Y_{\mu i}$ puts Δ in the so-called second generation leptoquark category. Moreover, as it does not couple to neutrinos, the bound extracted from the recent LHC data for the second-generation leptoquarks [14] is truly applicable in this case and reads $m_\Delta \gtrsim$

380 GeV, accounting for the reduced $\Delta \to \mu j$ branching ratio of order $\mathscr{B} \gtrsim 0.7$ due to the presence of the $\Delta \to tj$ decay channel [2]. This and the upper bound on its mass—$m_\Delta < 560$ GeV—that originates from simple perturbativity arguments [13] thus place it in a very narrow window of discovery.

We have also systematically implemented [13] all the phenomenological constraints in a class of $SU(5)$ models where all the fermion masses are generated at the tree-level to find out that the explanation of the a_μ anomaly requires the vacuum expectation value of the 45-dimensional representation to be of the order of 10^{-1} GeV. This result implies that the up-quark couplings, in this setup, are symmetric in nature. We have also shown that the symmetric scenario for the Yukawa couplings in the down-quark and charged lepton case is not compatible with the constraints due to the presence of light Δ and discussed implications for the $SO(10)$ type of unification. The simplest of possible realizations of both $SO(10)$ and $SU(5)$ with the symmetric Yukawa sector, that could accommodate observed fermion masses, are shown not to be viable unless Δ is heavy enough not to play any role in low-energy phenomenology.

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