Beautiful mirrors at the LHC

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ABSTRACT: We explore the "Beautiful Mirrors" model, which aims to explain the measured value of A_{FB}^b, discrepant at the 2.9σ level. This scenario introduces vector-like quarks which mix with the bottom, subtly affecting its coupling to the Z. The spectrum of the new particles consists of two bottom-like quarks and a charge $-4/3$ quark, all of which have electroweak interactions with the third generation. We explore the phenomenology and discovery reach for these new particles at the LHC, exploring single mirror quark production modes whose rates are proportional to the same mixing parameters which resolve the A_{FB}^b anomaly. We find that for mirror quark masses $\lesssim 500$ GeV, a 14 TeV LHC with 300 fb^{-1} is required to reasonably establish the scenario and extract the relevant mixing parameters.

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Contents

1 Introduction

The primary mission of the Large Hadron Collider (LHC) is to seek evidence for the breakdown of the Standard Model (SM) [1]. For the most part, the SM with a light Higgs provides a very accurate description of the observed data coming from a wide variety of experiments. While deviations from the SM have come (and mostly gone), most disappear as statistics and experimental precision increases and theoretical inputs improve. The agreement between the SM predictions and experiment is unprecedented, particularly in the arena of precision electroweak measurements, many of which have per mil level uncertainties [2].

However, there is one notable exception. The forward-backward asymmetry of the bottom quark (A_{FB}^b) shows roughly a 2.9σ deviation[1] from the value predicted by a best fit to precision data within the SM [2]. While not in itself very significant, this deviation has persisted for more than a decade and may be a guide to what the LHC could find. A_{FB}^b further plays an interesting role in the global fit to precision data, which in the context of the SM provides the indirect constraints on the Higgs mass [3, 4]. Indeed, the poor fit to A_{FB}^b can be understood as a tension in the preferred value of m_h between the leptonic observables, which prefer $m_h \sim 50$ GeV and A_{FB}^b which prefers values closer to ~ 1 TeV.

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[1]It is interesting that recent Tevatron measurements also show an unexpected asymmetry in top quark pair production [5–7], though existing proposed new physics explanations do not typically correlate this with any particular effect on A_{FB}^b [8–19].

The fit has settled into an "unhappy" middle ground between the two, favoring the other measurements at the cost of disagreeing with the observed A^b_{FB}. As a result, if one simply ignores A^b_{FB}, one gets a fit to m_h which is marginally at odds with the direct search bound from LEP-II [20].

Broadly defined, there are three attitudes one can take toward A^b_{FB} and the precision data:

- One can assume A^b_{FB} is a statistical (or unaccounted for systematic) effect and that reasonable variations of the other measured precision observables explain the tension between the SM fit to the Higgs mass and direct searches.

- One can consider the possibility that A^b_{FB} itself does not reflect the presence of new physics, but accidently makes the SM fit to m_h more palatable than it would otherwise have been. In this case, one can invoke new physics contributions to the Peskin and Takeuchi T parameter [21] which may reconcile the indirect bounds on m_h with the direct search limits (for a few examples, see [22–24]).

- One can take the attitude that the bottom quark couplings to the Z boson may themselves reflect the presence of new physics [25–29].

In this article, we will take the last approach, and explore the consequences of one particular model of this kind, the "Beautiful Mirrors" model [27], which introduces new physics to produce the observed anomaly in A^b_{FB}.

The Beautiful Mirrors model works by introducing a new set of vector-like (or "mirror") quarks, which mix with the bottom quark, adjusting its coupling to the Z. Vector-like quarks are chosen so that gauge anomalies are trivially evaded, and the requirement that there be no source of EWSB other than the SM Higgs (motivated to avoid tree-level contributions to the oblique electroweak parameters) restricts the $SU(2)$ representations of the mirror quarks to singlets, triplets, and doublets. In [27], two versions of the doublet model were explored. The desired shift in the Z couplings to bottom quarks may be effected for mirror quark quantum numbers under $(SU(3), SU(2), U(1))$ given by $(3, 2, 1/6)$ or $(3, 2, -5/6)$. The first option looks like a vector-like fourth SM generation, and requires mirror quark masses $\lesssim 400$ GeV and SM Higgs mass $m_h \gtrsim 300$ GeV in order to fit the LEP data. Its detailed phenomenology was explored in ref. [28, 29]. The null results for direct searches for the mirror quarks [30] have severely restricted the parameter space of this model, leading us to consider the more exotic representation $(3, 2, -5/6)$, which contains a bottom-like mirror quark ω and its electroweak partner, an electrically charged $-4/3$ quark, χ. The precision data favors the masses for these "exotic mirrors" to be $\gtrsim 500$ GeV [27], making them perfect targets for a discovery at the LHC.

In this paper we explore the phenomenological consequences of the Exotic Mirrors model at the LHC. We begin in section 2 by revisiting the target Z-b-$\bar{b}$ couplings, which helps pin down the amount of mixing required when we discuss the beautiful mirrors model itself in section 3. LHC signals and strategies to establish a given signal as arising from the mirror quark solution to the A^b_{FB} puzzle are presented in section 4. We conclude in section 5.
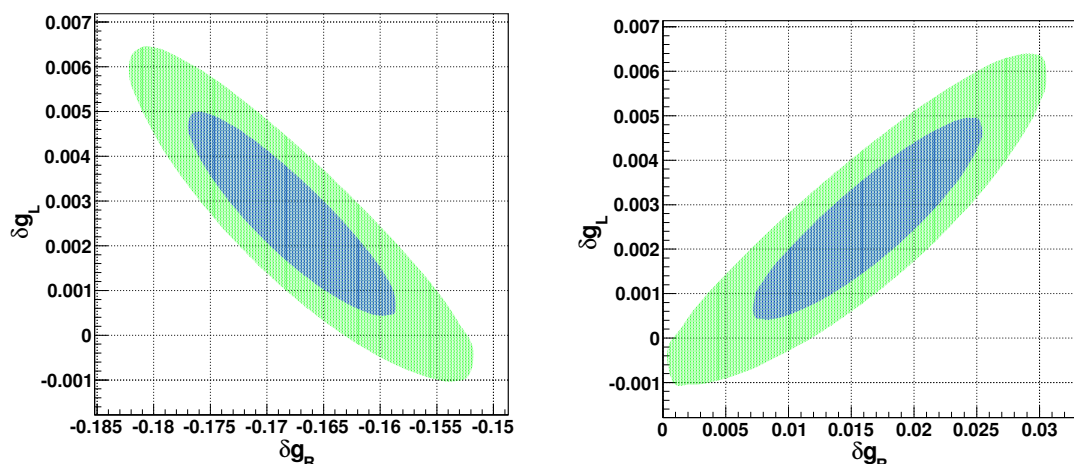
Figure 1. The regions in the Z-b-$\overline{b}$ coupling parameter space favored by EW precision data. The inner (outer) shaded regions correspond to 1σ (2σ) agreement with the best fit shifts in the left- and right-handed couplings.

2 Z boson couplings to bottom quarks

In this section, we examine the ranges of values of the Z-b-$\overline{b}$ couplings consistent with precision electroweak data. Modifications to bottom couplings must be applied subtly. While A_{FB}^b is discrepant as described above, the branching ratio of Z bosons decaying into $b\overline{b}$ (which is usually reported as a ratio between the decay to bottom quarks and into all hadrons, $R_b \equiv \Gamma(Z \to b\overline{b})/\Gamma(Z \to \text{hadrons})$) shows no large deviation [2]. In addition, as discussed in [27], there is data from off of the Z-pole which, while less precise than the Z-pole measurements, implies important constraints on the signs of the couplings. In particular, the off-pole data requires that the left-handed interaction be close to the SM value, but does not restrict the sign of the right-handed value. Since together A_{FB}^b and R_b restrict the magnitude of the couplings, the allowed space of couplings lies within two disjoint regions of parameter space.

To explore the allowed regions of coupling space, we allow shifts in the left- and right-handed Z-b-$\overline{b}$ interactions by δg_L and δg_R, respectively. We include these parameters in a global fit to the precision data, including the Tevatron measurements of the top and W masses [31, 32]. We marginalize over α_{EM}, α_S, m_t, m_Z, and m_h, in particular allowing m_h to take any value consistent with the direct search limit from LEP-II [20]. We assume there are no large additional contributions to the oblique parameters S and T beyond those which result from varying the top and Higgs masses.[2] The results of the fit are presented in figure 1, which indicates that the data favors small ($\sim 10^{-3}$) corrections to the left-handed coupling and more large (either $\sim +10^{-2}$ or ~ -0.2) shifts in δg_R. The values of δg_R and δg_L should be highly correlated with one another, in order to result in the necessary correction to A_{FB}^b, while the maximum and minimum changes are set by R_b.

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[2]Note that the assumption of no large additional contributions to the S and T parameters is consistent with the exotic mirror scenario, but *not* with standard mirror quarks.

3 Beautiful mirrors

The exotic beautiful mirrors model extends the Standard Model by introducing two sets of vector-like quarks, $\Psi_{L,R}$ with quantum numbers $(3, 2, -5/6)$ and $\xi_{L,R}$ with quantum numbers $(3, 1, -1/3)$. In terms of its $SU(2)$ components, Ψ decomposes as,

$$\Psi_{L,R} = \begin{pmatrix} \omega_{L,R} \\ \chi_{L,R} \end{pmatrix} \tag{3.1}$$

where ω is a charge $-1/3$ quark and χ has charge $-4/3$. Introducing vector-like quarks allows for new flavor mixing, which we will ultimately invoke to explain the measured value of A_{FB}^b. Among other effects, this mixing can lead to right handed W couplings and tree level flavor changing interactions with the Z and Higgs.

We assume for simplicity that the exotic quarks only couple to the third generation SM quarks, as Z couplings to the two light generations appear to agree with SM predictions and any corrections are thus constrained to be small. Allowing for substantial mixing between the mirror quarks and the two lighter SM generations will generate tree level FCNC interactions which can contribute to $b \to s\gamma$ [44–47] which is highly constrained.

In addition, mixing with the light quarks leads to interactions of the type Z-b-s, Z-b-d, and Z-s-d, as well as one loop box diagrams (with the mirror quark running in the loop), contributing to B-$\overline{B}$ [33–42] and possibly K-$\overline{K}$ and D-$\overline{D}$ mixing [43], all of which lead to tight constraints. These interactions are additionally constrained by rare decay processes of the strange and bottom mesons [48–51], as well as B and K meson decays such as $B \to \ell^+\ell^- X$, $B \to J/\psi K_s$ and $K \to \pi\nu\overline{\nu}$ [52–54].

That said, provided the mixing is small enough, the presence of such mixing between the mirror quarks and the first- and second-generation fermions (perhaps motivated by minimal flavor violation [55–59]) would not much affect the parameter space or resulting phenomenology. The choice of exotic mirrors (as opposed to the Standard Mirror gauge assignment) induces no right-handed W-t-b interaction, evading potentially strong bounds again coming from $b \to s\gamma$ [60].

3.1 Mixing and the mass eigenstates

Electroweak symmetry breaking (EWSB) occurs as in the SM through the vacuum expectation value of a Higgs scalar, Φ. We assume that the SM Higgs is the only source of EWSB, and write down the complete set of interactions between the mirror quarks and the third generation SM quarks, as allowed by $SU(3) \times SU(2) \times U(1)$ gauge invariance. In addition, the vector quarks have Dirac masses, whose magnitudes are not dictated by EWSB, but we will assume are at the $\sim$ TeV scale. Such mass terms are protected by chiral symmetries, and thus technically natural in the sense of 't Hooft [61]. The complete set of Yukawa interactions and masses involving the mirror quarks are,

$$\mathcal{L}_{\text{mass}} = -y_1\overline{Q}'_L \Phi b'_R - y_R \overline{\Psi}'_L \tilde{\Phi} b'_R - y_L \overline{Q}'_L \Phi \xi'_R - y_5 \overline{\Psi}'_L \tilde{\Phi} \xi'_R - M_2 \overline{\Psi}'_L \Psi'_R - M_3 \overline{\xi}'_L \xi'_R + h.c. \tag{3.2}$$

where the primed fields refer to gauge (as opposed to mass) eigenstates and Q'_L refers to the third generation quark doublet and b'_R is the third generation down-type singlet.

After symmetry breaking, the couplings are most transparent in the unitary gauge, $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & v+h \end{pmatrix}^T$, where $v \sim 174$ GeV is the EWSB vacuum expectation value and h is the Higgs boson. The mass and mixing terms of the Lagrangian may be written in matrix form,

$$\mathcal{L}_{\text{mass}} = -\overline{\mathbf{d}}'_{\mathbf{L}} \left(\mathbf{M_d} + \frac{h}{v} \, \mathbf{N_d} \right) \mathbf{d}'_{\mathbf{R}} + h.c. \tag{3.3}$$

where $\mathbf{d}'_{\mathbf{L,R}} = (b_{L,R}, \omega_{L,R}, \xi_{L,R})$ are vectors in flavor space. $\mathbf{M_d}$ is the bottom sector mass matrix,

$$\mathbf{M_d} = \begin{pmatrix} Y_1 & 0 & Y_L \\ Y_R & M_2 & Y_5 \\ 0 & 0 & M_3 \end{pmatrix} \tag{3.4}$$

where $Y_i = y_i v / \sqrt{2}$. $\mathbf{N_d}/v$ is the coupling matrix between the real Higgs and the down type quarks,

$$\mathbf{N_d} = \begin{pmatrix} Y_1 & 0 & Y_L \\ Y_R & 0 & Y_5 \\ 0 & 0 & 0 \end{pmatrix} . \tag{3.5}$$

To diagonalize the mass matrix we rotate by unitary matrices $\mathbf{U_d}$ and $\mathbf{W_d}$ which transform the left- and right-handed gauge eigenstates into the corresponding mass eigenstates (denoted by unprimed vectors in flavor space, $\mathbf{d_{L,R}}$). We parametrize these matrices

$$\mathbf{U_d} = \begin{pmatrix} c_{12}^L c_{13}^L & s_{12}^L c_{13}^L & s_{13}^L \\ -s_{12}^L c_{23}^L - c_{12}^L s_{23}^L s_{13}^L & c_{12}^L c_{23}^L - s_{12}^L s_{23}^L s_{13}^L & s_{23}^L c_{13}^L \\ s_{12}^L s_{23}^L - c_{12}^L c_{23}^L s_{13}^L & -c_{12}^L s_{23}^L - s_{12}^L c_{23}^L s_{13}^L & c_{23}^L c_{13}^L \end{pmatrix} \tag{3.6}$$

where $c_{12}^L \equiv \cos\theta_{12}^L$ and so on, and with an analogous expression for $\mathbf{W_d}$ with $\theta_{ij}^L \to \theta_{ij}^R$. We have set potential phases to zero for simplicity; their inclusion will complicate the analysis slightly but are not expected to shed much light on the A_{FB}^b puzzle. These matrices transform the gauge eigenstates to mass eigenstates,

$$\mathbf{d}'_{\mathbf{L}} = \mathbf{U_d} \, \mathbf{d_L} \, ,$$
$$\mathbf{d}'_{\mathbf{R}} = \mathbf{W_d} \, \mathbf{d_R} \, . \tag{3.7}$$

The requirement that these transformations produce the mass eigenbasis requires

$$\mathbf{U_d}^\dagger \mathbf{M_d W_d} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}. \tag{3.8}$$

For values of the mixing which are phenomenologically viable, b_1 is predominantly the original SM bottom quark fields, b_2 is mostly ω and b_3 is mostly ξ. The eigenvalues $m_1 \equiv m_b$, m_2, and m_3 are the bottom quark mass, and two exotic quark masses, respectively. Note that we do not necessarily order the exotic quarks $b_{2,3}$ by mass.

3.2 Higgs couplings

The Higgs couplings are complicated by the fact that the mass matrix receives contributions from the vector-like masses M_2 and M_3, resulting in flavor-violating Higgs couplings between the three mass eigenstate quarks,

$$\mathcal{L}_{hq} = -\frac{h}{v}\, \overline{\mathbf{d}}\, \mathbf{V_d} P_R\, \mathbf{d} + h.c. \tag{3.9}$$

where $\mathbf{V_d} = \mathbf{U_d^\dagger N_d W_d}$. The off diagonal entries of $\mathbf{V_d}$ will lead to tree level flavor changing couplings between the Higgs of the form h-$\overline{b}_1$-b_2, etc. Such couplings allow for decays of the heavy quarks into a bottom quark and a Higgs, as discussed below.

3.3 W and Z couplings

We now examine the modifications to the W and Z couplings coming from the mixing of the bottom quark with the exotics. In the mass basis there are W couplings of the form

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu^- \left[\overline{\chi}\gamma^\mu \left(\mathbf{U_d^{2j}} P_L + \mathbf{W_d^{2j}} P_R \right) \mathbf{d^j} + \overline{\mathbf{d}}^{\mathbf{i}} \gamma^\mu \mathbf{U_d^{1i*}} P_L t \right] + h.c. \tag{3.10}$$

where $g = e/\cos\theta_w$ as usual.

The couplings between the Z and the down-type quarks may be written in matrix form,

$$\mathcal{L}_Z = \frac{g}{\cos\theta_w} Z_\mu \overline{\mathbf{d}} \gamma^\mu \left(\mathbf{L} P_L + \mathbf{R} P_R \right) \mathbf{d} + h.c. \tag{3.11}$$

where

$$\mathbf{L} = \mathbf{U_d^\dagger\, g_L\, U_d}, \tag{3.12}$$
$$\mathbf{R} = \mathbf{W_d^\dagger\, g_R\, W_d}, \tag{3.13}$$

and the $\mathbf{g_{L,R}}$ are diagonal matrices in the gauge basis with left and right-handed couplings of the down-type quarks to the Z boson as their entries,

$$\mathbf{g_L} = \mathrm{Diag}\left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_w, \quad \frac{1}{2} + \frac{1}{3}\sin^2\theta_w, \quad \frac{1}{3}\sin^2\theta_w \right), \tag{3.14}$$

$$\mathbf{g_R} = \mathrm{Diag}\left(\frac{1}{3}\sin^2\theta_w, \quad \frac{1}{2} + \frac{1}{3}\sin^2\theta_w, \quad \frac{1}{3}\sin^2\theta_w \right). \tag{3.15}$$

Our primary concern is to modify the b-quark couplings wth the Z, in order to explain the measured A_{FB}^b while remaining consistent with R_b. These couplings are determined by the 11 entries of the $\mathbf{L}$ and $\mathbf{R}$ matrices. In terms of the parameterization, eq. (3.6), these entries are,

$$\mathbf{L}^{11} = \mathbf{g_L}^{11} \left(c_{12}^L c_{13}^L\right)^2 + \mathbf{g_L}^{22} \left(-s_{12}^L c_{23}^L - s_{13}^L s_{23}^L c_{12}^L\right)^2 + \mathbf{g_L}^{33} \left(s_{12}^L s_{23}^L - s_{13}^L c_{23}^L c_{12}^L\right)^2,$$
$$\mathbf{R}^{11} = \mathbf{g_R}^{11} \left(c_{12}^R c_{13}^R\right)^2 + \mathbf{g_R}^{22} \left(-s_{12}^R c_{23}^R - s_{13}^R s_{23}^R c_{12}^R\right)^2 + \mathbf{g_R}^{33} \left(s_{12}^R s_{23}^R - s_{13}^R c_{23}^R c_{12}^R\right)^2 \quad (3.16)$$

These expressions may be simplified by noting that the term proportional to the electric charge is common to all of the diagonal entries of $\mathbf{g_{L,R}}$ and thus cancels out of shifts in the coupling, leaving behind only the non-universal terms proportional to T_3. In terms of the mixing angles, these shifts become,

$$\delta g_L^b = \frac{g}{2\cos\theta_w} \left[1 - (c_{12}^L c_{13}^L)^2 + (s_{12}^L c_{23}^L + s_{13}^L s_{23}^L c_{12}^L)^2\right],$$
$$\delta g_R^b = \frac{g}{2\cos\theta_w} \left(s_{12}^R c_{23}^R + s_{13}^R s_{23}^R c_{12}^R\right)^2. \quad (3.17)$$

3.4 Sample parameters

Comparing the expressions for the shifts in the Z-b-$\bar{b}$ interactions in Equation (3.17) with the results in figure 1, we can determine relations among the input parameters which will improve the agreement of A_{FB}^b with its measured value.

We will analyze a specific point within this parameter space and examine the collider phenomenology. For simplicity we assume negligible mixing between ω and ξ with $s_{12}^R = 0.21$ and $s_{13}^L = 0.078$ and all other mixing angles set to zero. For greater clarity of notation, therefore, we denote these angles simply by s_R and s_L henceforth. The negligible mixing between ω and ξ means we have chosen $Y_5 = 0$. The Yukawa couplings in the bottom sector mass matrix can be related to the mixing angles in the limit of negligible m_b as follows

$$y_L \simeq \frac{M_3 s_L}{v} \qquad y_R \simeq \frac{M_2 s_R}{v} \quad (3.18)$$

The mixings which are postulated here yield couplings shifts through equation (3.17) of

$$\delta g_L^b = 2.27 \times 10^{-3} \qquad \delta g_R^b = 1.64 \times 10^{-2} \quad (3.19)$$

and were chosen with the intent of simplifying our discussion by removing the mixings not relevant to the measured asymmetry while giving coupling shifts near the center of the favored region.

These assumptions leave us with only three free parameters in our system, m_{b_2}, m_{b_3}, and m_h. The relation between m_{b_2} and m_χ is

$$m_\chi^2 = m_{b_2}^2 - Y_R^2 = m_{b_2} c_R^2 \quad (3.20)$$

As mentioned in [27] the fit to data is not very sensitive to m_{b_3} as long as it is below a few TeV. Looking at the $m_h - m_\chi$ parameter space plot, in the study just mentioned, we choose $m_h = 120$ GeV and let the masses m_{b_2}(or equivalently m_χ) and m_{b_3} vary between 500 GeV and 2 TeV. These points lie within 1σ of the best fit point. We study the detailed phenomenology at this point in parameter space, but will note where interesting deviations are possible.
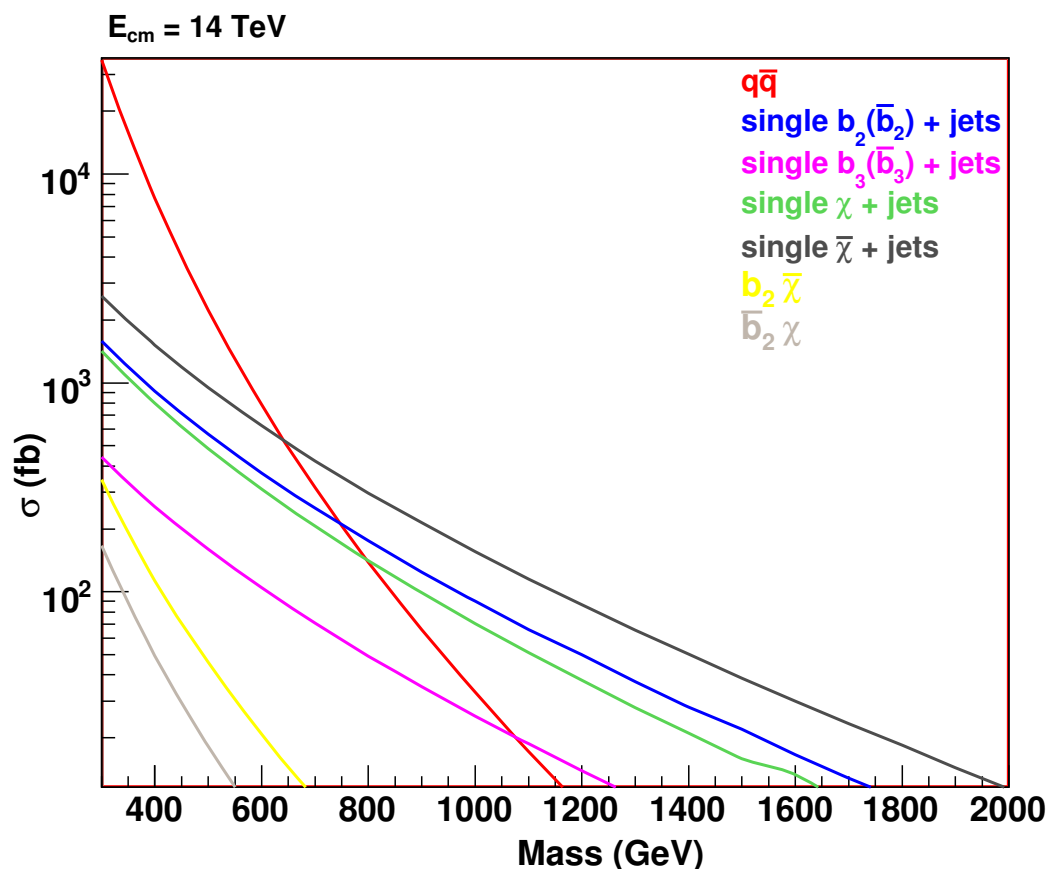
Figure 2. Production cross sections for both single and pair production of mirror quarks, as a function of their masses and for the mixing angles specified in the text. The single $b_{2,3}$ + jets rates sum both production of $b_{2,3}$ + jets and $\bar{b}_{2,3}$ + jets. For this plot we have chosen $m_h = 120$ GeV

4 Mirror quark phenomenology at the LHC

The key question for the LHC is whether or not the mirror quarks can be discovered, and their $SU(2) \times U(1)$ gauge representations and mixing angles understood well enough to experimentally connect them to the measured value of A_{FB}^b. This task is complicated by the fact that the mixing through EWSB itself obscures the original representations of b_2 and b_3, and the χ, while unusual in that it has charge $-4/3$, decays into W^-b, looking much like a t' which produces a "wrong sign" bottom quark in its decay; measuring the charge of the final state b quark is extremely subtle, though perhaps not impossible [62, 63].

4.1 Mirror quark production and decay

The mirror quarks χ, b_2, and b_3 can be produced either in pairs through QCD, or singly, through the electroweak interaction. Single χ quarks are produced through a bq initial state with a t-channel W boson exchanged whereas single b_2 and b_3 arise from a bq initial state with a t-channel Z boson (or, to a much smaller degree, Higgs boson) exchanged. The

resulting cross sections as a function of the mass of the exotic quark in question are plotted in figure 2, where we have used the mixing angles appropriate for the sample solution to the A_{FB}^b puzzle discussed in section 3.4 and a Higgs mass of 120 GeV (although the results are quite robust for larger Higgs masses as well). The cross sections have been computed at tree level with the MadEvent code [64], using the CTEQ6L parton distribution functions (PDFs) [65]. As can be seen, for the modest mixing angles favored by A_{FB}^b, pair production is the dominant mechanism for exotic quark masses below ~ 700 GeV. The difference in rates between single χ ($Q = -\frac{4}{3}$) and single $\overline{\chi}$ ($Q = +\frac{4}{3}$) production can be understood from the difference in PDFs of the initial state quarks. The $\overline{\chi}$, which is primarily produced from an initial state u-quark, is expected to have a higher electroweak production rate than χ which which comes primarily from an initial d-quark. The same trend is familiar from single top production in the Standard Model.

Pair production cross sections are not affected by the choice of mixing angles at all, and thus the prediction of that cross section is robust for any point in the parameter space of the exotic mirrors model. Single production cross sections are proportional to the square of the relevant mixing angle or combination of mixing angles, and thus those cross sections will be shifted by changes in mixing angles.

The χ quark decays with 100% branching ratio into W^-b for our parameter point, appearing as a a $\overline{t}'$ which produces b instead of a $\overline{b}$ when it decays. As such, it is sensitive to the usual fourth generation t' searches at the LHC, with an expected reach through pair production of roughly 800 GeV [66] for 100 fb^{-1} of integrated luminosity at 14 TeV. Searches for t' quarks at the Tevatron provide bounds of $m_\chi \geq 335$ GeV [67]. Allowing $\omega - \xi$ mixing can open additional channels for χ decay such as $\chi \to W^-b_3$, subject to kinematic constraints. Depending on the size of the mixing this can become comparable in magnitude to the direct decay to purely SM final states.

The bottom-like quarks b_2 and b_3 can decay into Zb_i, hb_i (provided the Higgs is light enough), Wt, and $W\chi$. For our example parameter point, the χ is too heavy to be produced on-shell in decays of b_2, and b_3 does not have a charged-current coupling to χ due to our choice of no $\omega - \xi$ mixing. Heavy quark decays into Wt are rendered negligible by this assumption as well. Thus, these quarks decay only through the FCNC modes,

$$b_{2,3} \to hb,$$
$$b_{2,3} \to Zb.$$

For Higgs mass of 120 GeV and exotic quark mass of 500 GeV, the branching ratios for both b_2 and b_3 are 52% $b_{2,3} \to Zb$ and 48% $b_{2,3} \to hb$. Note that these branching ratios are insensitive to changes in the mixing angles $s_{L,R}$, and are not strongly sensitive to increases in exotic quark mass. The Z decay mode offers the possibility of lepton pairs in the final state (with modest branching ratio) whereas the h decay mode leads to a $b_{2,3} \to b\overline{b}b$ final state a large fraction of the time.

Branching ratios of b_i decays are independent of shifts in s_L and s_R in absence of $\omega - \xi$ mixing. This is because in that limit the flavor changing couplings of the higgs and the Z both have identical dependence on the mixing angles. If mixing between the new vector-like quarks is allowed it can lead to shifts in the relative branching fractions to Z and h

final states, and also opens additional decay channels, such as $b_3 \to W + \chi$ or $b_2 \to Z b_3$, dependent on kinematic constraints. These will in general lead to more spectacular cascade decays, as the decay product vector quark then further decays to SM fields.

While the LHC cannot hope to exclude the entire range of mirror quark masses favored by the electroweak fit, it is sensitive to much of the parameter space. For masses $\lesssim 1$ TeV, we can expect based on earlier studies [66] that by the end-running of the LHC (which we take to be at center-of-mass running of 14 TeV and data sets on the order of 300 fb^{-1}), the LHC will have observed the mirror quarks through pair production in the decay modes $\chi \to W^- b$ and $b_{2,3} \to Z b \to \ell^+ \ell^- b$. We explore several subdominant production processes which can help differentiate the beautiful mirrors model from other models with additional vector-like quarks, and establish the mixing parameters as consistent with a solution to A_{FB}^b. We choose as a reference value for our studies mirror quark masses $M_2 (= m_\chi) = 500$ GeV. Such masses are consistent with Tevatron bounds and within the 1σ fit to the precision data [27], and represent a cautiously optimistic region of parameter space. We assume M_3, which is not well constrained by the fit, is ≥ 1 TeV, and thus do not assume b_3 will be observable.

4.2 $\overline{\chi}$ production

The process $u\overline{b} \to d\overline{\chi}$ is the largest of the single production modes in the model, and under our assumption that $M_3 \gg M_2$, its rate is proportional to s_R^2, thus providing a measure of the key mixing which is responsible for δg_R. There is also a contribution from the left-handed mixing, but this is constrained to be small by precision data. We attempt to extract the signal (and thus measure s_R) by looking at the semi-leptonic χ decay: $pp \to j\overline{\chi} \to jb\ell\nu$ where j is a light-quark initiated jet and $\ell = e$ or μ. To improve background rejection, we do not attept to reconstruct single χ production here, focusing on the dominant single $\overline{\chi}$ signal. For our sample parameter point, the signal inclusive cross section, including branching ratios, is 949 fb. The SM background (with very mild acceptance cuts on the jets) is 12.7 nb, dominantly Wjj production, with smaller contributions from $t\overline{t}$ and single top production. Events are showered and hadronized with PYTHIA [68], and we estimate detector effects with PGS [69] using the default LHC detector model of MadEvent.

To separate the signal from the background efficiently, we require that the event contain exactly one b-tagged jet with transverse momentum $P_T \geq 100$ GeV, one positively-charged lepton with $P_T \geq 50$ GeV (which is sufficient to trigger on the events even in high luminosity running), no more than two jets with $P_T \geq 30$ GeV, and missing momentum $\not{E}_T \geq 50$ GeV. We further require that the invariant mass of the two highest P_T jets M_{jj} be ≥ 100 GeV. We assume the $\not{E}_T$ arises from a neutrino present in a on-shell W decay, and use the W mass to reconstruct the longitudinal neutrino momentum. Armed with that information, we can reconstruct the four-momentum for the W boson, which we combine with the b-tagged jet to form the invariant mass which in a signal event would reconstruct the χ mass of 500 GeV. We apply a wide cut to this quantity, requiring it to be in the range 400–600 GeV.

We found a signal acceptance of about 1% and a background suppression factor of 2.6×10^{-5} using these cuts. While the signal-to-background ratio remains small, sufficient statistics can be generated for a significant observation of the process and a measurement of the signal cross section. With 100 fb^{-1} of data the total number of expected events

exceeds the SM prediction by 950, equivalent to 5.2σ, constituting a discovery of the single production process for $\overline{\chi}$, and with 300 fb^{-1} the cross section can be measured to be 949 ± 147 fb, where systematic uncertainties in determining the acceptances are assumed to be small in comparison to the large statistical uncertainties. This measurement corresponds to 2,800 expected signal events over 99,000 expected background events. Extracting s_R from the cross section is straightforward, as all other quantities entering the conversion are known with effectively zero error compared to the measured cross section. We end up with a measurement of $s_R^2 = 0.044 \pm 0.007$.

The discovery potential in this channel extends well beyond the mass studied here. Azuelos *et al* [71] found that a vector like t' was discoverable through the $t' \to Wb$ channel up to $m_{t'} \simeq 2.5$ TeV. Our model predicts an identical signal, with comparable production cross section and more favorable branching ratio for this measurement.

The fact that χ has charge $-4/3$ is a very distinctive feature compared to other models of vector-like quarks, but difficult to establish experimentally. One could attempt to measure the charge of the b quark produced in a χ decay; this has been successfully employed by Tevatron experiments to establish the top quark charge [62, 63], but depends sensitively on modeling the detector response correctly, and thus is beyond the scope of this work. Additional strategies could be to examine processes such as $\chi\overline{\chi}\gamma$, which is expected to lead to a successful LHC measurement of the top quark charge [70]. We have performed simulations of $\chi\overline{\chi}\gamma$ production, but find that the contribution induced by photon radiation from the parent quark becomes lost in radiation from the W or lepton in its decay. The large χ mass has the unfortunate effect of both reducing the over-all rate substantially compared to the $t\bar{t}\gamma$, and also collimates the χ decay products, making it more difficult to extract the cases where the photon is radiated by the final state lepton from that where it is radiated from the quark itself than was true for the well-spread out top quark decay products.

Ultimately, the most promising argument for the charge of the χ may be indirect by the failure to observe the decay mode $\chi \to Zt$, which would generically be present for a charge 2/3 vector quark, which would be allowed to mix with the top. This argument rests on the assumption that one has observed $b_2 \to Zb$, and thus knows that the newly discovered objects are in fact vector-like as opposed to chiral quarks. However, it is worth bearing in mind that even for a vector-like t', the Z-t'-t interaction is controlled by separate mixing angles from those in the b sector, and thus may turn out to be very small.[3]

4.3 Single $b_2/\overline{b_2}$ production

After single $\overline{\chi}$ production, the next largest single mirror quark production mode is single b_2 production (including single $\overline{b}_2$ production), which proceeds through an FCNC Z or h exchange in the t-channel. The rate for this process is proportional to $s_R^2 c_R^2$, and thus provides another measurement of the mixing angle s_R^2. We examine the feasibility of observing the process $pp \to jb_2 \to jb\ell^+\ell^-$ through an intermediate Z boson from the b_2 decay (and also the conjugate process for $\overline{b}_2$). The signal cross section (including branching ratios) for $m_{b_2} = 500$ GeV is 16.6 fb. The background is dominantly $Zb\overline{b}$ and $t\bar{t}$ and is 125 pb after acceptance cuts.

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[3]In fact, the reasonable agreement between the experimental measurements of $b \to s\gamma$ and SM predictions *requires* that the product of the t-t' and b-b' mixings be $\lesssim 10^{-2}$ [60].

We require at least one of the leptons in the event to have $P_T \geq 20$ GeV, sufficient for triggering. We select events with at least one b-tagged jet with $P_T \geq 70$ GeV. The main criteria to distinguish between the signal and background are the reconstructed mass of two leptons, which should be close to the Z mass and its combination with the b-jet to form an invariant mass close to m_2. In events with more than one b-tagged jet (as is often the case for the background processes), we combine the b-jet that has the largest P_T with the lepton pair to form the reconstructed b_2 mass. We require the reconstructed b_2 mass to be within a 25 GeV window of the reference value of $m_2 = 500$ GeV. This window contains 42.3% of the signal rate after jet smearing. In addition, we place a restriction on the angular separation of $\Delta R \leq 1$ between the pair of leptons, since the signal produces highly boosted Z bosons from the b_2 decay whose decay products are collimated.

At an integrated luminosity of 300 fb^{-1} the number of predicted signal events for our parameter point is 280, after applying the above mentioned cuts. The analysis efficiency is 5.6%. The number of expected background events is 1260 after background suppression by a factor of 3.4×10^{-5}. The resulting significance is 7.9σ, and the measurement of the mixing angle is $s_R^2 = 0.044 \pm 0.008$, which is comparable to the precision offered by single $\overline{\chi}$ production. While not a direct reconstruction of the vector-like quarks, these two measurements together provide evidence that the primary mixing with the third generation SM quarks is through the bottom sector, with no apparent mixing involving the top (which is forbidden in our construction by $U(1)_{EM}$ but could be allowed in generic models of mirror quarks containing top-like objects).

4.4 Electroweak $b_2 - \chi$ production

Another process which allows us to extract information about the mixing angle is electroweak production of a pair of mirror quarks, χb_2 through an s-channel W boson. The cross section, which is proportional to c_R^2, turns out to be quite small due to the fact that on top of being governed by weak couplings, two heavy quarks are being produced. To analyze this signal we look at the process $pp \to \chi b_2 \to \ell^\pm \ell^\mp b \bar{b} \ell' \nu$ (and its charge-conjugate version). This particular signature has the b_2 decaying through a Z into $\ell^+ \ell^-$ whereas χ decays as usual into Wb. After acceptance cuts, the cross section for this signal is 0.359 fb. The background was generated using MadEvent and the relevant decays were obtained with BRIDGE [72] before showering and hadronizing with PYTHIA. Again detector effects were estimated with PGS using the default LHC detector model of MadEvent. This resulted in a background cross section of 3.8 fb.

Due to the small number of events, distinguishing signal from background is difficult. In order to retain enough events to obtain sufficient statistics one must be conservative in applying cuts. We first require that the event contain two b-tagged jets with $P_T \geq 60$ GeV. Since we expect the charged lepton pair decaying from the highly boosted Z to be collimated we first find the $\ell^\pm \ell^\mp$ pair with the smallest ΔR and combine it with one of the b jets to form an invariant mass (in a signal event this would reconstruct the b_2 mass) which we require to be greater than 50 GeV.

To determine which lepton is associated with the neutrino we again assume the $\not{E}_T$ arises from a neutrino present in an on-shell W decay. We then find any charged leptons not

belonging to the pair which decay from the Z and out of those find the one with the smallest $\Delta\phi$ relative to the missing E_T. We use the W mass to reconstruct the longitudinal neutrino momentum, and from that we reconstruct the four-momentum for the W boson and combine it with the other b-tagged jet with $P_T \geq 60$ GeV to obtain the invariant mass (in a signal event this would reconstruct the χ mass) which we require to be greater than 200 GeV.

With a signal acceptance of 6.25% these selection criteria lead to an expected 10 signal events at 300 fb^{-1}. We expect 3 background events after a suppression factor of 2.4×10^{-3} leading to a significance of 4σ for the signal over background. While this does not constitute a discovery, when combined with the information obtained from other signals, it provides evidence that the χ and b_2 quarks form an $SU(2)$ doublet, and thus does help to verify the structure of the Beautiful mirrors model.

5 Conclusions

While the possibilities for discovery at the LHC are vast, it may be that there are clues as to what could be discovered in the form of modest deviations already present in lower energy data. In this article, we have discussed one such deviation, the forward-backward asymmetry of the bottom quark, which has persisted for more than a decade and appears to play a key role in the SM fit to the Higgs mass. We have explored one particular model which addresses the discrepancy by adding additional vector-like quarks which mix with the b, subtly affecting its coupling to the Z boson.

These quarks are perfect targets for discovery at the LHC, which is likely to initially observe them through pair production. We have examined the prospects for observing single production as well. While single production has smaller rates, being suppressed by electroweak strength couplings and mixing angles, it probes the basic phenomena responsible for the solution to the mystery of A_{FB}^b. In particular, we have studied single $\overline{\chi}$ production followed by the dominant decay $\overline{\chi} \to W^+ \overline{b}$, single b_2 production followed by the decay $b_2 \to Zb \to \ell^+\ell^- b$, and pair production of $\chi \overline{b}_2$ (with the same decay chains as above). These processes are expected to be visible for quark masses up to about 500 GeV at a 14 TeV LHC with hundreds of fb^{-1}, and provide evidence that the χ and b_2 quarks form a vector-like electroweak doublet which mixes primarily with the bottom quark. The primary mixing parameter, s_R^2, responsible for explaining the value of A_{FB}^b, can be measured at the 20% level.

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