Enhanced $b \to sg$ Decay, Inclusive η' Production, and the Gluon Anomaly

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The experimental hint of large $B \to \eta' + X_s$ is linked to the $b \to s$ penguins via the gluon anomaly. Using running α_s in the η'-g-g coupling, the standard $b \to sg^*$ penguin alone seems insufficient, calling for the need of dipole $b \to sg$ at the 10% level from new physics, which could also resolve the semileptonic branching ratio and charm counting problems. The interference of standard and new physics contributions may result in *direct* CP asymmetries at the 10% level, which could be observed soon at B factories. [S0031-9007(97)05041-2]

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In this paper we explore the possible connections between several fascinating topics in B physics and QCD: the possibility of enhanced $b \to sg$ decay at the 10% level [1–3], the recent experimental hint [4–6] of large inclusive $B \to \eta' + X_s$, and the gluon anomaly. It has been suggested [7] that the standard QCD penguin could account for inclusive η' production through the latter. We point out that with running α_s in the anomaly coupling, however, the standard model (SM) alone may not be sufficient, suggesting the need for dipole $b \to sg$ transitions from new physics. If so, CP violating rate asymmetries between $B \to \eta' + X_s$ and $\bar{B} \to \eta' + \bar{X}_s$ could be at the 10% level and easily observable at B factories.

As noted some time ago, the low semileptonic branching ratio ($\beta_{\rm s.l.}$) and charm deficit (n_C) problems could be explained by some hidden B decay mode $\sim$10%–15% [1,2], such as $b \to sg$ with g on shell. The recent analyses [3,8] argue for the existence of additional charmless B decays at the 10% level, but differ in the interpretations. Against the possibility of [3] $b \to sg \approx 10\%$ from new physics, the authors of Ref. [8] argue for nonperturbative effects from $b \to sc\bar{c}$ transitions. Since the QCD penguin, known to be around 1% [9], contains $b \to sc\bar{c} \to sg^* \to sq\bar{q}$ as a subprocess, one needs to involve [8] some intermediate $c\bar{c}$ state, such as a $c\bar{c}g$ "hybrid" meson. The "hybrid" state, however, must satisfy the following: (1) Sizable production fraction in $b \to sc\bar{c}$; (2) narrow width to allow more time for $(c\bar{c})_8 \to g^*$ annihilation; (3) decays via $D\bar{D} + X$ or $(c\bar{c})_{\rm onia} + X$ are suppressed; (4) evasive so far in usual e^+e^- or $p\tilde{p}$ annihilation studies. Hence, though possible in principle, the hybrid (or any non-onia $c\bar{c}$ state) scenario is no less exotic than the $b \to sg$ picture.

Several rare B decays have just been reported [4,6] for the first time. The penguin dominant $K\pi$ mode is at the 1.5×10^{-5} level, while the tree dominant $\pi\pi$ mode has yet to be seen. This agrees with theory expectations [10] if one takes into account the smallness of V_{ub}. The ωK, $\omega\pi$ modes are comparable to $K\pi$ and larger than expected. No $\eta h^{\pm}$ events are seen, but $\eta' K \simeq 7.1 \times 10^{-5}$ is quite sizeable. Together with $\phi K^* \sim K\pi$ [6], penguin effects are clearly rather strong. Though interesting, this handful of modes does not yet seriously challenge models of exclusive decay. Perhaps more intriguing is the hint [4–6] of

$$\beta(B \to \eta' + X_s) = (62 \pm 16 \pm 13) \times 10^{-5} \times (2.0 < p_{\eta'} < 2.7\ \text{GeV}), \quad (1)$$

where $X_s \equiv K + n(\leq 4)\pi$ with at most one π^0. Some $\eta' K$ events are captured, but the $\eta' K^*$ mode is conspicuously absent, and most events are at larger m_{X_s}. Though $\eta' D^{(*)}$, $\eta' D^{**}$ backgrounds are yet to be fully ruled out [5], if large inclusive charmless *fast* η' production becomes established soon, it would be one of the most exciting pieces of B physics ever.

As η' is mainly an SU$_F$ (3) singlet, it is naturally related to gluons, motivating Atwood and Soni [7] (AS) to connect inclusive η' production to the QCD penguin via the gluon anomaly. Denoting η'-g-g coupling as $H(q^2, k^2, m_{\eta'}^2)\epsilon_{\mu\nu\alpha\beta}q^\mu k^\nu \epsilon^\alpha(q)\epsilon^\beta(k)$, they extract $H(0, 0, m_{\eta'}^2) \simeq 1.8\ \text{GeV}^{-1}$ from $J/\psi \to \eta'\gamma$ decay. Assuming *constant* $H(q^2, 0, m_{\eta'}^2) \approx H(0, 0, m_{\eta'}^2)$, they find that the standard $b \to s$ penguin could account for the $B \to \eta' + X_s$ rate. We wish to explore the q^2 dependence of the anomaly coupling, starting with the running of α_s.

Let us give a more theoretical basis to the gluon anomaly coupling, which concerns the η^0-g-g effective vertex of the singlet field η_0. In the chiral limit $m_q \to 0$ with $N_F = 3$ chiral quarks, the singlet current has an anomaly $\partial^\mu J_\mu^0 = (2N_F\alpha_s/4\pi)\text{tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$, which breaks the U$_A$ (1) symmetry, and through the topological charge $\langle 0|(2N_F\alpha_s/4\pi)\text{tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})|\eta'\rangle$, etc., m_η and $m_{\eta'}$ are elevated by their "gluon content." Deriving from QCD the low energy effective theory of η and η' mesons continues to be an active research field [11]. The η_0-g-g coupling can be formulated *without assuming* PCAC, as the U_A (1) symmetry is already broken. We find [11] the low energy effective coupling $(N_F\alpha_s/4\pi)\theta\text{tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$ which arises from the Wess-Zumino term, where $\theta = \eta_0/\sqrt{N_F}f_0$ is the collective "chiral rotation." Both η_0 and the "decay constant" f_0 are very complicated objects, and the connection of η_0 to physical mesons is highly nontrivial. We saturate η_0/f_0 by $c_P\eta'/f_{\eta'} + s_P\eta/f_\eta$, where $s_P \equiv \sin\theta_P$ is the pseudoscalar mixing angle, and sweep theoretical uncertainties such as form factor dependence into $f_{\eta'}$. We shall, however, assume constant $f_{\eta'} \simeq f_\pi \simeq 131$ MeV [12] in the following, which is still a rather strong assumption.

We arrive at the effective η'-g-g vertex

$$-ia_g c_P \eta' \epsilon_{\mu\nu\alpha\beta}\epsilon^\mu(q)\epsilon^\nu(k)q^\alpha k^\beta, \tag{2}$$

where $a_g(\mu^2) = \sqrt{N_F}\alpha_s(\mu^2)/\pi f_{\eta'}$ is the effective gluon anomaly coupling and is nothing but $H(q^2, k^2, m_{\eta'}^2)$ of AS. The explicit α_s factor suggests running coupling as commonly seen in QCD, a point which is ignored by AS. As a check, we find $a_g(m_{\eta'}^2) \simeq 1.9$ GeV^{-1}, agreeing well with $H(0, 0, m_{\eta'}^2)$ found by AS, which confirms the validity of Eq. (2). With $q^2 \neq 0$ and $k^2 = 0$ but keeping η' on shell, however, it is plausible that $\mu^2 = q^2$ for $q^2 > m_{\eta'}^2$.

To compute the $b \to n'sg$ rate, let us define $v_i \equiv V_{is}^* V_{ib}$ and ignore v_u (hence $v_t \cong V_{ts} \cong -V_{cb}$). The loop induced [see Fig. 1(a)] $b \to s$ current [9] in SM is

$$\frac{G_F}{\sqrt{2}}\frac{g_s}{4\pi^2}v_t \bar{s}t^a\{\Delta F_1(q^2\gamma_\mu - q_\mu)L - F_2 i\sigma_{\mu\nu}q^\nu m_b R\}^b, \tag{3}$$

where $\Delta F_1 \equiv F_1^t - F_1^c \simeq 0.25 - [-2/3\log(m_c^3/M_W^2)] \simeq -5$, and $F_2 \cong F_2^t \simeq 0.2$. Only the F_2 term contributes to on-shell $b \to sg$, but since $F_2 \ll |\Delta F_1|$, $b \to sg^* \to sq\bar{q}$ dominates over $b \to sg$ [9]. Representing Fig. 1(a)] as a box and Eq. (2) as a blob, the $b \to \eta' sg$ process [7] is shown in Fig. 1(b). With $q^2 = (k + k')^2$ (g^* mass) and $m^2 = (p' + k)^2$, the $sg\bar{q}$ system evolves into X_s, and $m^2 \equiv m_X^2$, is the *physical* recoil mass against the η' meson. Because of the anomaly coupling, a *parton level calculation gives us a handle on physical distributions.* Defining $x \equiv m^2/m_b^2$, $y \equiv q^2/m_b^2$, and $x' \equiv m_{\eta'}^2/m_b^2$, we find

$$\frac{d^2\beta(b \to \eta' sg)}{dx\,dy} \cong 0.2\left(\frac{g_s(m_b)}{4\pi^2}\right)^2 \frac{a_g^2 m_b^2}{4} \times \left\{|\Delta F_1|^2 c_0 + \mathrm{Re}(\Delta F_1 F_2^*)\frac{c_1}{y} + |F_2|^2\frac{c_2}{y^2}\right\}, \tag{4}$$

where $c_0 = [-2x^2y + (1 - y)(y - x')(2x + y - x')]/2$, $c_1 = (1 - y)(y - x')^2$, $c_2 = [2x^2y^2 - (1 - y) \times (y - x')(2xy - y + x')]/2$, and the factor $0.2 \simeq V_{cb}^2 G_F^2 m_b^5/192\pi^3\Gamma_B$ comes from normalizing against $\beta_{\mathrm{s.l.}}$ (see, e.g., Ref. [7]). We confirm the formulas of AS, but there are some subtle differences in defining ΔF_1 and F_2, to which we now turn.

AS adapt from leading order results from operator analysis. They adopt the convention of Buras [13] for the $c_8(\mu)$ coefficient and absorb a factor of $1/2$ into their definition of F_2. In our notation, we find $F_2(\mu) \simeq 0.286$ as compared to $F_2(m_t) \simeq 0.2$, bringing $\beta(b \to sg)$ from 0.1% [9] to 0.2%. This is agreeable since the dipole

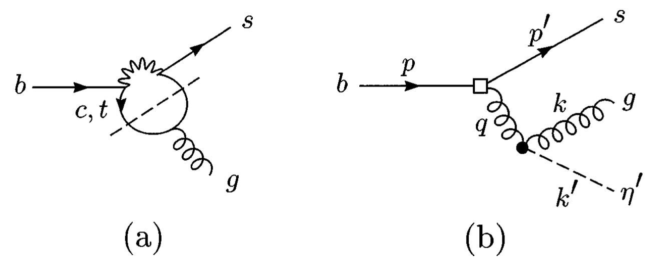

FIG. 1. (a) Sample diagram for loop induced $b \to sg^*$ with possible $c\bar{c}$ cut; (b) $b \to \eta' sg$ transition via effective b-s-g coupling (possibly from new physics) and η'-g-g anomaly vertex.

O_8 operator contains explicitly the gluon field. The AS treatment of F_1 is more dubious. They identify $4(c_4 + c_6)/g_s \equiv F_1^{\mathrm{AS}}(\mu)$ [which is our $(g_s/4\pi^2)\Delta F_1$] and find a value of -0.168 at LO [13]. In effect, they take the $(\bar{s}t^a\gamma_\mu Lb)(\bar{q}t^a\gamma_\mu q)$ part of $c_4(\mu)O_4 + c_6(\mu)O_6$, and replace $\bar{q}t^a\gamma_\mu q$ by a gluon. This is, however, not appropriate since the $c_4(\mu)$ and $c_6(\mu)$ coefficients contain resummed leading logs. The final $\bar{s}t^a\gamma_\mu Lb$ current does not simply couple to an effective gluon. The correct approach is to insert η' in every step of the operator analysis, which is nontrivial and not yet done.

We will thus use the simple one loop results for F_1 and F_2 as outlined earlier, with $g_s = g_s(m_b)$ in Eq. (3). The operator analysis confirms that the correction is only of $\mathcal{O}(\alpha_s)$, but we now have the advantage of proceeding consistently from Fig. 1(a) to Fig. 1(b). In addition, whereas the operator approach usually stops at a set of effective operators at $\mu = m_b$, our formalism automatically includes perturbative final state rescattering effects such as $b \to sc\bar{c} \to sg^*$, which is very useful when we turn to *CP* violating asymmetries.

Let us check against the results of AS numerically. Using m_b, $m_s = 4.8$, 0.15 GeV, $\alpha_s(m_b) \simeq 0.21$, and constant $a_g c_P \simeq 1.7$ GeV^{-1}, we find that $(g_s/4\pi^2)\Delta F_1(\mu) = -0.168$ alone gives $\beta(b \to \eta' sg) \approx 1.6 \times 10^{-3}$, not far form the AS result of 1.9×10^{-3}. However, inclusion of the $F_2(\mu) = 0.286$ term leads to $\sim -20\%$ *reduction* rather than the $\sim +50\%$ increase claimed by AS. The formulas of AS in fact confirm our findings. Note that the F_2 effect alone is negligible but the interference effect is *destructive* [9]. The $d\beta/dm$ plot in Fig. 3 [7] of AS seems to be the dashed curve [14] for $d\beta/dq$ in our Fig. 2(b). The actual efficiency of an m_X, cut at 2.35 GeV (i.e., $p_{\eta'} > 2$ GeV) for our $d\beta/dm$ [Fig. 2(a)] is of order $1/2$, and is *not sensitive* to Fermi motion of the b quark. The $b \to \eta' sg$ rate for pure $|F_2| \cong 2$ (i.e., $b \to sg \sim 10\%$ from new physics) is slightly lower than the SM result. But if it interferes with ΔF_1^{SM} constructively, the resulting $\beta(b \to \eta' sg) \simeq 0.8\%$ would be way too large.

However, as argued earlier, the anomaly coupling $a_g \propto \alpha_s$ could be running. Since $(m_b - m_s)^2 \geq q^2 \geq m_{\eta'}^2$, the likely scale would be the q^2 of the virtual gluon. Using two-loop running $\alpha_s(q^2)$ in a_g, $\beta(b \to \eta' sg)$ drops by a

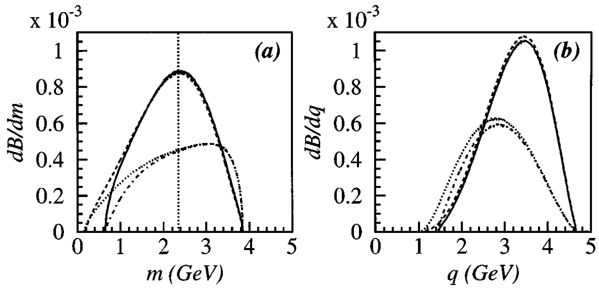

FIG. 2. (a) $d\beta/dm \equiv d\beta/dm_{X_s}$, and (b) $d\beta/dq$ for SM penguin induced $b \to \eta' sg$ (dashed and solid line: cut of $m_g = 0, 0.5$ GeV). The purely dipole (dot-dashed line) effect with $|F_2| \approx 2$ is also given. The vertical dotted line indicates the $m_{X_s} = 2.35$ GeV cut.

factor of more than 3. This is because $\alpha_s(m_b^2)/\alpha_s(m_{\eta'}^2) \sim 1/2$, and the derivative coupling nature of the anomaly favors large q^2 and m^2, as seen in Fig. 2. The anomaly is thus *uniquely suited for generating fast η' mesons.* The SM effect alone now drops to $\sim 0.43 \times 10^{-3}$, and, even without applying the m_{X_s} cut, it falls short of Eq. (1). Thus, Fig. 1(b) with running α_s in the anomaly coupling suggests that new physics is needed to account for the observed $B \to \eta' + X_s$ rate [15].

It is possible to enhance the chromodipole bsg coupling by new physics at the TeV scale (such as supersymmetry or techniscalars), without jeopardizing the electrodipole $bs\gamma$ coupling [2,16]. Explicit examples [16] with gluino loops favor large $F_2^{\rm New}$ with sign *opposite* to SM, which is just what is needed (see below). The chromodipole term may be linked to quark mass generation since both involve chirality flip [2]. This TeV scale connection and the appearance of the b_R field provide an exciting impetus to the problem, namely CP violation [17]. One is now *sensitive to CP violating phases which are in principle different from the standard CKM phase.* Note that within SM, the small effect of $v_u \neq 0$ leads to CP violating asymmetry $< 1\%$ in $b \to \eta' sg$, much like other inclusive $b \to s$ decays [18].

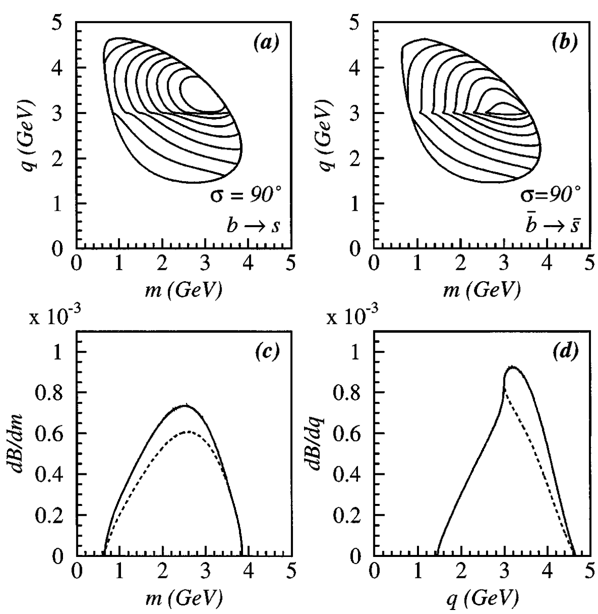

FIG. 3. (a),(b) Dalitz plot. (c) $d\beta/dm$ and (d) $d\beta/dq$ for $b \to \eta' sg$ (solid) vs $\bar{b} \to \eta' \bar{s} g$ (dashed), for $\sigma = \pi/2$.

The CP violation effect is precisely rooted in $\Delta F_1^{\rm SM}$-$F_2^{\rm New}$ interference. Parametrizing the new physics term as $F_2 \equiv F_2^{\rm SM} + F_2^{\rm New} \simeq -2e^{i\sigma}$ with v_t taken as real, the required absorptive part comes from [18,19] $c\bar{c}$ rescattering in ΔF_1 [see the cut in Fig. 1(a)]. This is facilitated by the peaking of $d\beta/dq$ at $q^2 \gtrsim (2m_c)^2$. The absorptive part is incorporated by making the change [18] $\Delta F_1 \to \Delta F_1 + 4\Pi(q^2/m_c^2)$, where Π is the familiar one-loop vacuum polarization from QED. For $\bar{b} \to \eta' \bar{s} g$ one simply replaces F_2^* by F_2 in Eq. (4). We thus easily arrive at the average branching ratio $\beta_{\rm av}$ an asymmetry $a_{\rm CP} = (\beta - \bar{B})/(\beta + \bar{\beta})$, and the results are given in Table I. The asymmetry is generally larger for $\cos\sigma < 0$ (except vanishing as $\sigma \to \pi$) because of destructive interference, but $\beta_{\rm av}$ often becomes too small in this region. To visualize the effect, we give in Fig. 3 the Dalitz plot (in q and m) and differential rates for both $b \to \eta' sg$ and $\bar{b} \to \eta' sg$, for $\sigma = \pi/2$. The more visible difference in $d\beta/dq$ is not observable. However, since the shape for $d\beta/dm$ is largely unchanged, a 10% difference in rate below the m_X, cut of 2.35 GeV should be readily visible, at CLEO and at proposed B factories that would start operation in 1999. This is a *direct CP* violation effect independent of B^0-$\bar{B}^0$ mixing, and can be seen in both charged and neutral B decays, *in a mode which has already been observed.*

Some remarks are in order. First, $b \to sg \sim 10\%$ alone leads to $b \to \eta' sg$ only at $\sim 0.5 \times 10^{-3}$, comparable to the standard $b \to sg^*$ penguin which starts from 1%. This is because $\Delta F_1^{\rm SM} \sim 5$ is still larger than $|F_2^{\rm New}| \sim 2$. Second, in our numerical study, we took $m_g \sim 0.5$ MeV in phase space to remove soft gluons [14]. If one assumes the $sg\bar{q}$ system with a soft gluon [see Fig. 2(a)] is swept into the K meson, the removed 4%–5% matches the observed exclusive $\eta' K$ rate. Third, the $B \to \eta + X_S$ rate should be smaller by $\tan^2\theta_P \sim 0.1$ in rate. However, fast η from the $B \to \eta' + X_S$, $\eta' \to \eta\pi\pi$ cascade may be the source of the little "bump" at high p_η in fully inclusive $B \to \eta + X$ spectrum [20]. Four, the "hybrid $c\bar{c}g$" mechanism of Ref. [8] might also work, since the effective $b \to sc\bar{c} \to sg^*$ penguin is much larger than in perturbative applications of SM [15]. However, SM mechanisms alone would never bring about CP asymmetries beyond 1% in these modes [18]. Thus, *the large CP asymmetries discussed*

TABLE I. $\beta_{\rm av}$ and a_{CP} for $b \to \eta' sg$ vs $\bar{b} \to \eta' \bar{s} g$ transitions, with $F_2^{\rm New} = -2e^{i\sigma}$. The latter alone gives branching ratio $\simeq 0.45 \times 10^{-3}$, comparable to SM effect without $c\bar{c}$ rescattering.

$\sigma =$	0	30°	60°	90°	120°	150°	180°
$\beta_{\rm av}$ ($\times 10^{-3}$)	2.5	2.4	2.0	1.5	0.91	0.52	0.4
$a_{\rm CP}$ (%)	0.0	2.9	6.0	9.5	13.1	13.3	0.0

here could serve as a unique signature for the presence of new physics from dipole $b \to sg$ transition [17]. Five, the existence of large $b \to sg$ and associated *CP* asymmetries would have implications on the responsible new physics at TeV scale. For example, the lightest squark could still be around 100 GeV and gluino mass of order 200 GeV. Existing bounds are evaded by large nondegeneracies in squark masses, but such masses can certainly be probed at the Tevatron. However, there are solutions where $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are much higher [2,16]. Finally, we stress that the anomaly induced $b \to \eta' sg$ of Fig. 1(b) is a new diagram in *addition* to the usual $b \to sg^* \to sq\bar{q}$, and shows very different q^2 and m^2 dependence. It is worthwhile to pursue effects of the gluon anomaly in more conventional processes, in particular, to measure η'-g-g from factor effects. An example would be $e^+e^- \to \eta' + q\bar{q}g$, to see if gluon fragmentation into η' differs from, say, into pions. The study of these processes would be reported elsewhere.

In summary, applying the η'-g-g anomaly with running α_s, we find that $\beta(b \to \eta'_{\rm fast} + X_s) \sim 0.6 \times 10^{-3}$ perhaps cannot be sustained by the standard $b \to sg^*$ penguin alone, but calls for new physics from $b \to sg$ at the 10% level, which would also help alleviate the $\beta_{\rm s.l.}$ and n_C problems. *Direct CP* violating rate asymmetries could then be as large as 10% and easily observable, perhaps even before the advent of asymmetric *B* factories.

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Note added.—After our work was submitted, new experimental [6] and theoretical results [21–23] have appeared. We thank A. L. Kagan for correcting us for the *destructive* nature of the $\Delta F_1 F_2$ term in SM [9,22], which strengthens the need for $F_2^{\rm New}$. Our work has aroused interest in the off-shell (form factor) behavior of the g^*-g-η' vertex. Reference [22] argues for $m_{\eta'}^2/(m_{\eta'}^2 - q^2)$ form factor suppression in analogy to the quark triangle loop for γ^*-γ-π^0. However, while asymptotically $1/q^2$ suppression must set in, the gluon anomaly differs from the QED case in the gluon self-couplings. Indeed, Refs. [21] and [23] stress that nonperturbative effect could make the g^*-g-η' vertex unpredictable (Ref. [21] extends our new physics CP violation effect to channels beyond η'). The $\sqrt{q^2} \sim 2$–4 GeV range of interest coincides with the glueball mass range, which might well delay the onset of form factor suppression, e.g., in the form of $m_G^2/(m_G^2 \pm q^2)$ where m_G is the relevant glueball mass. On the other hand, the anomaly coupling is fixed at the (low energy) $m_{\eta'}$ scale, and it seems unlikely that one would hit a resonance pole in q^2. In any case, the g^*-g-η' form factor at intermediate q^2 is an extremely interesting subject in QCD itself, and has yet to be studied. However, even with nonperturbative g-g binding effects, running α_s should still be taken into account since it enters multiplicatively. Our criticism of AS is that, taking $H(q^2, 0, m_{\eta'}^2) = H(0, 0, m_{\eta'}^2) = a_g(m_{\eta'}^2)$ to be constant and equal to the largest possible coupling, they likely overestimate the SM effect. At the least, our work can be viewed as an illustration of how a consistent picture of semi-inclusive $B \to \eta'_{\rm fast} + X_s$ and the $\beta_{\rm s.l.}$ and n_C problems together suggest a common $b \to sg \sim 10\%$ new physics solution, and the dramatic consequence of $\sim$10% *inclusive direct CP* asymmetries that might follow.

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