A New Light Particle in B Decays?

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We investigate the possibility whether the tensions with SM expectations observed in several $b \to s\ell\ell$ transitions, including hints for lepton flavour non-universality, could be due to the decay of B into a new *light* resonance. We find that qualitative agreement with the data can be obtained with a light vector resonance dominantly decaying invisibly. This scenario predicts a shift in the muon anomalous magnetic moment that could explain the long-standing discrepancy. The most stringent constraint comes from searches for B decays with missing energy. A striking prediction is a strong q^2 dependence of the lepton flavour universality ratios R_K and R_{K^*} that should allow to clearly confirm or rule out this possibility experimentally. We also comment on the possible connection of the invisible decay product with Dark Matter.

INTRODUCTION

Rare semi-leptonic B decays based on the $b \to s\ell\ell$ transition are sensitive probes of physics beyond the Standard Model (SM). In recent years, several tensions between SM expectations and experiments have been observed, including in particular an apparent enhancement of the angular observable S_5 (or P_5')[1] in $B^0 \to K^{*0}\mu^+\mu^-$ [3–5], a suppression of the branching ratios of $B_s \to \phi\mu^+\mu^-$ [6], $B^+ \to K^{(*)+}\mu^+\mu^-$ [7], $B^0 \to K^{(*)0}\mu^+\mu^-$ [7, 8], and a suppression of the ratio R_K of dimuon to dielectron rates in $B^+ \to K^+\ell^+\ell^-$ [9]. Very recently, the LHCb collaboration has also revealed an apparent suppression of the analogous ratio R_{K^*} in $B^0 \to K^{*0}\ell^+\ell^-$ decays [10].

The tensions in branching ratios and angular observables could be due to underestimated theoretical uncertainties, e.g. in form factors or from unexpectedly large non-factorisable hadronic effects. Barring statistical fluctuations or experimental systematics, deviations from lepton flavour universality are instead clear indications of physics beyond the SM. The most straightforward new physics (NP) explanation of these anomalies makes use of a suppression of the semi-leptonic vector operator $O_9 \propto (\bar{s}_L\gamma^\mu b_L)(\mu\gamma_\mu\mu)$ caused by destructive interference of the SM loop contribution and a tree- or loop-level exchange of new heavy particles (see e.g. [11] for a recent global fit to $b \to s\mu\mu$ data). A second possibility is to have NP generate a local operator with the quark content $\bar{s}b\bar{c}c$ [12]; such an effect would however be lepton flavour universal and thus it would not explain R_K nor R_{K^*}. In this letter, we consider a third possiblity: a NP effect due to new *light* particles produced on shell in the B decay.

Our letter is organized as follows. We first define our phenomenological setup and discuss the constraints on its parameters. We then show how a light new particle could solve the aforementioned tensions in $b \to s\ell\ell$ transitions, first all of them, and then only some selected ones. Finally, we briefly explore a possible connection with Dark Matter, and conclude.

SETUP

Since several tensions have been observed in decays based on the $b \to s\mu^+\mu^-$ transition, the deviations from lepton flavour universality (LFU), R_K and R_{K^*}, are explained much better by models that suppress the $b \to s\mu^+\mu^-$ transition rather than enhance the $b \to se^+e^-$ transition. We thus require the SM amplitude to interfere destructively with the on-shell production of the new state, in the region of dimuon invariant mass q^2 relevant for the R_K and R_{K^*} measurements. We are then led to consider a new vector boson V with mass below the B meson mass, since a new scalar would induce a negligible interference. We anticipate that a sizeable width will be needed, since no clear peaks (besides the known QCD resonances) have been observed in $b \to s\mu\mu$ decays.

We consider a simplified model valid at energy scales of the order of a few GeV which, in addition to the SM states, contains a single uncoloured vector particle V with mass m_V and a SM singlet lighter than $m_V/2$, either fermion or scalar. The latter escapes the detector unmeasured and is required to allow V to have a sizable decay width without violating existing bounds. The Lagrangian of this setup reads

$$\mathcal{L} = \big[(g_{bs}\,\bar{s}_L\gamma_\nu b_L + \text{h.c.}) + g_{\mu V}\,\bar{\mu}\gamma_\nu\mu + g_{\mu A}\,\bar{\mu}\gamma_\nu\gamma_5\mu \\ + g_\chi\,\bar{\chi}\gamma_\nu\chi\big]V^\nu + \frac{m_V^2}{2}V^\nu V_\nu, \tag{1}$$

where we only allow the couplings we require, and we assume them to be real for simplicity. For definiteness we have chosen the light SM singlet to be a Dirac fermion χ. We further require $g_\chi \gg g_{\mu V,A}$ such that $\text{BR}(V \to \chi\chi) \simeq 1$. In this case, the decay width of V is given by

$$\Gamma_V \simeq \frac{m_V}{12\pi}\,g_\chi^2\,. \tag{2}$$

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[1] See [1, 2] for definitions of these observables.

A large relative width requires a strong coupling $g_\chi \gtrsim 1$; alternatively, the single field χ could be replaced by a sizeable number of more weakly coupled χ_i.

The flavour-changing V coupling could arise for instance from a tree-level $\bar{t}tV$ coupling permitting a penguin diagram similar to the SM W-top loop; this case would also predict $b \to d$ and $s \to d$ transitions, which would however not change our discussion. A kinetic mixing between the photon and V would generically be generated at loop level, but with a size that would again not change the phenomenology we discuss. The couplings of V to SM particles could arise from a portal to a dark sector, possibly justifying the large invisible V width, and/or from a low energy remnant of larger flavour symmetries at high energy. The couplings in eq. (1) could also be understood within an "effective Z'" framework [13], where V is the gauge boson of a $U(1)'$ under which the SM is neutral: new vector-like fermions, charged under $U(1)'$, mix with the SM ones and induce their couplings to V. However, for the remainder of this letter, we will not specify a UV completion but will instead simply work with (1). We will comment on the case of a light scalar (as opposed to the fermion χ) later on.

CONSTRAINTS

An important constraint comes from the process $B \to K\chi\chi$, which has the same experimental signature as the SM process $B \to K\nu\bar{\nu}$. We perform a combination of all such independent measurements by Belle and Babar [14–17], and find $\mathrm{BR}(B \to K\chi\chi) < 1.5 \times 10^{-5}$ at 95%CL. Since the SM prediction for $\mathrm{BR}(B \to K\nu\bar{\nu})$ is roughly 0.5×10^{-5} [18], we impose the upper bound $\mathrm{BR}(B \to K\chi\chi) < 10^{-5}$. Using the narrow width approximation (NWA) for V and using $\mathrm{BR}(V \to \chi\chi) \simeq 1$, the branching ratio reads

$$\mathrm{BR}(B \to K\chi\chi) \simeq \tau_B \, \frac{m_B^3}{64\pi m_V^2} \, \lambda^{3/2} \, [f_+(m_V^2)]^2 \, g_{bs}^2 \,, \quad (3)$$

where $f_+(q^2)$ is a $B \to K$ form factor that we take from [19] and $\lambda = 1 + \hat{m}_V^4 + \hat{m}_K^4 - 2(\hat{m}_K^2 + \hat{m}_V^2 + \hat{m}_K^2\hat{m}_V^2)$ with $\hat{m}_i = m_i/m_B$. This leads to a rough upper bound

$$g_{bs} \lesssim [m_V/\mathrm{GeV}] \times 0.7 \times 10^{-8} \,. \quad (4)$$

If V is broad enough for the NWA to break down, this bound becomes weaker.

Tree-level V exchange also contributes to the dispersive and absorptive parts of the B_s-$\bar{B}_s$ mixing amplitude. However, in view of the bound (4), the resulting contributions to the mass and width differences ΔM_s and $\Delta\Gamma_s$ are totally negligible.

A loop diagram with V also gives a contribution to the anomalous magnetic moment of the muon,

$$\delta a_\mu = \frac{g_{\mu V}^2 \, f_V\left(\frac{m_\mu^2}{m_V^2}\right) - 5g_{\mu A}^2 \, f_A\left(\frac{m_\mu^2}{m_V^2}\right)}{12\pi^2} \frac{m_\mu^2}{m_V^2}, \quad (5)$$

where $f_{V,A}(0) = 1$ and the full loop function can be found e.g. in [20][2]. Interestingly, for $|g_{\mu A}| < \sqrt{5}|g_{\mu V}|$, the contribution has the right sign to resolve the long-standing $(g-2)_\mu$ anomaly [21],

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (287 \pm 80) \times 10^{-11}. \quad (6)$$

For $m_V \gg m_\mu$ and $g_{\mu A} = 0$, bringing the measurement into agreement with the prediction at 2σ would require $0.004 \lesssim g_\mu/[m_V/\mathrm{GeV}] \lesssim 0.007$, while only requiring the contribution not to overshoot the measurement by more than 3σ implies $g_\mu/[m_V/\mathrm{GeV}] \lesssim 0.008$. As seen from (5), in principle the bound can be weakened or even removed by tuning $g_{\mu A}$ vs. $g_{\mu V}$.

If $g_{\mu A} \neq 0$, also a tree-level contribution to the $B_s \to \mu^+\mu^-$ decay is generated. It can be expressed in terms of shifts in the Wilson coefficients C_{10} and C_P (which we define as in [22])

$$C_{10}^V = \frac{g_{bs}g_{\mu A}/N}{m_{B_s}^2 - m_V^2 + im_V\Gamma_V}, \quad C_P^V = -\frac{2m_\mu}{m_V^2}C_{10}^V, \quad (7)$$

where $N = G_F V_{tb} V_{ts}^* \alpha/\sqrt{2}\pi \simeq -7.7 \times 10^{-10}$ GeV^{-2} in the usual CKM convention and we have neglected terms of $O(m_s/m_b)$. For an illustrative V mass of 3 GeV, the branching ratio of $B_s \to \mu^+\mu^-$ is modified by less than 20% with respect to the SM if $|g_{bs}g_{\mu A}| < 3 \times 10^{-9}$, i.e. $g_{\mu A}$ could be as large as 0.1 if g_{bs} saturates (4).

If V would couple also to muon neutrinos, a strong bound would be obtained from neutrino trident production [23][3]. This constitutes a model-building challenge to constructions that yield the couplings in (1), but since we work in a simplified model well below the electroweak scale we take the freedom to neglect this possibility.

At one-loop level also the coupling of the Z to muons, constrained by Z pole mesurements at LEP and SLD [24], is modified by a V loop. One finds [25]

$$\frac{g_{Z\mu\mu}}{g_{Z\mu\mu}^{\mathrm{SM}}} = 1 + \frac{g_{\mu V}^2 + g_{\mu A}^2}{16\pi^2}K_F\left(\frac{m_Z^2}{m_V^2}\right), \quad (8)$$

where $K_F(x) \approx -7/2 + \pi^2/3 + 3\ln x - \ln^2 x$ for large x [26]. With our choice of vector-like $V\mu\mu$ coupling, this bound turns out to be weak due to the accidentally suppressed vector coupling of the Z to charged leptons in the SM,

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[2] In the notation of that paper, $f_V(x) = \frac{3}{8}(2\,F_Z(x) + G_Z(x))$, $f_A(x) = \frac{3}{40}(G_Z(x) - 2\,F_Z(x))$.

[3] An EW-symmetric coupling to muon neutrinos would yield, for $g_{\mu A} = 0$, to $g_{\mu V} \lesssim 5 \times 10^{-3}$ at $m_V = 2.5$ GeV [23].

$\frac{1}{2} - 2s_w^2 \approx 0.04$, such that the bound only reaches $g_{\mu V,A} \lesssim 0.5$ even for V masses as low as 0.5 GeV, and is thus irrelevant for the further discussion.

Finally, the process $Z \to \mu^+\mu^- V$ does not lead to constraints from $Z \to 4\mu$ searches, since those have so far been performed only for $m_{\mu\mu} > 4$ GeV [27, 28]. It motivates searches for $Z \to \mu^+\mu^- +$ missing energy which, to our knowledge [29], have not been performed so far.

RESONANCES IN B DECAYS

Having obtained the most important constraints on the couplings of the light vector V to quarks and leptons, we can now proceed to discuss the impact on rare exclusive semi-leptonic B decays such as $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$. Tree-level exchange of the resonance V leads to a contribution to the amplitudes of these processes that can be most simply expressed as a q^2 dependent shift of the Wilson coefficients C_9 and C_{10},

$$C_{9,10}^V = \frac{g_{bs}\,g_{\mu V,A}/N}{q^2 - m_V^2 + im_V\Gamma_V}. \tag{9}$$

We are mainly interested in addressing three anomalies: the suppression of R_K as well as R_K^* for q^2 between 1 and 6 GeV^2 and the enhancement of P_5' for q^2 between 4 and 6 GeV^2 as seen by ATLAS and LHCb. If the resonance is fully contained in the q^2 bin to be integrated over, no significant suppression of the rate can be expected. Thus to explain R_K and R_K^* in the region from 1 to 6 GeV^2, a resonance with mass below 1 GeV or above 2.5 GeV is preferable. If the resonance is sufficiently close in mass to the J/ψ at 3.1 GeV, it would be very hard to detect directly. Indeed, due to the $B \to K\chi\chi$ constraint, the branching ratio $B \to KV$ is guaranteed to always be well below the $B \to J/\psi K$ one. If the mass instead lies between 2.5 and 3 GeV, a broad resonance could not be excluded at present in view of the sizeable hadronic uncertainties of the SM prediction in this region (cf. [30, 31]) and the unknown phase of the interference between the J/ψ and the SM short-distance contribution, leaving even the sign of the SM effect undetermined. We refrain here from a precise quantification of the constraints on the resonance width, and we simply work with $\Gamma/m_V \gtrsim 10\%$. This choice allows, for *any* $q^2 > 6$ GeV^2 and for the values of the parameters preferred by the flavour anomalies, to contain the deviation from the SM to less than 30% or so (see e.g. Fig. 1, analogous results hold for the other $b \to s\mu\mu$ observables).

Having identified the potentially interesting mass and width region, we next proceed to evaluate the effect on the observables of interest while taking into account the constraints discussed above. Saturating the bound (4) on the flavour-changing coupling and taking $g_{\mu A} = 0$, it turns out that the effects in the $b \to s\mu\mu$ transitions are rather small. Thus we require a mild tuning between
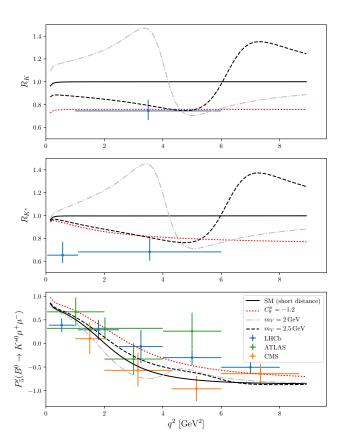

FIG. 1. R_K, R_{K^*}, and P_5' as functions of q^2 for the SM, for a heavy NP contribution to C_9^μ, and for two different scenarios with a light vector resonance, compared to experimental results. In both light NP scenarios, the relative width of V is 20%, the bound (4) is saturated, $g_{\mu V} = 0.1$ and $g_{\mu A} \simeq -0.44\,g_{\mu V}$ to reproduce the experimentally observed central value of $(g-2)_\mu$. A marked difference between the C_9^μ and the light vector contributions persists also at values of q^2 higher than those shown here.

$g_{\mu A}$ and $g_{\mu V}$ to obtain a suppression of $(g-2)_\mu$ by a factor of 3–5. This tuning is apparent in Fig. 2 left, where we also show the regions preferred at 2σ[4] by R_K, R_{K^*} and P_5', and where we have saturated the upper bound on g_{bs} in eq. (4) for definiteness. We find that an explanation of the flavour anomalies and $(g-2)_\mu$ is possible[5], compatibly with all the other constraints, for axial and vector coupling of V to muons both different from zero and of the order of a few times 10^{-2}. In the

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[4] To determine these regions, we have performed a fit to the experimental data on R_K and R_{K^*} by LHCb and to P_5' in the bins between 1 and 6 GeV^2 by ATLAS, CMS, and LHCb, using the `flavio` code [32] and the SM P_5' prediction from [33]. By "2σ" we mean that the χ^2 is improved with respect to the SM by 4.

[5] The LHCb and $(g-2)_\mu$ anomalies can be both addressed also in models with a heavy Z' if new leptons are added, see e.g. [34–36].

"funnel" region[6] $g_{\mu A} \simeq -0.44 g_{\mu V}$ the interval

$$10^{-9} \lesssim |g_{bs}\, g_{\mu V}| \lesssim 3 \times 10^{-9} \qquad (10)$$

can improve all three sets of flavour observables – R_K, R_{K^*} and P_5' – by more than 2σ each, as shown in Fig. 2 right, together with the region preferred $(g-2)_\mu$, and with the limit $B \to K+$invisible.

To explain the enhancement of P_5', but not R_K and R_{K^*}, a possibility is a resonance with mass just below the bin of interest, i.e. below 2 GeV. While the measurement of $B \to K^* \mu^+ \mu^-$ angular observables have been performed in relatively wide bins, a measurement of the differential decay rate of $B^+ \to K^+ \mu^+ \mu^-$ in fine q^2 bins has been performed in [37]. A detailed analysis of the compatibility of our scenarios with this measurement is beyond the scope of our analysis, here we just note that the inclusion of a resonance with mass around 1.8 GeV was found in [37] to "marginally improve the fit quality", while its mean and width do not correspond to a known state. The sign of the interference of the apparent resonance corresponds to the one of our $m_V = 2$ GeV scenario in Fig. 1.

Finally, one could wonder whether an analogous explanation could be the reason for the downward fluctuation in the lower q^2 bin of R_{K^*}, for example with a resonance with couplings like in (1) and mass $\gtrsim \sqrt{1.1}$ GeV. Such explanation would in principle be possible, at the price of an upward fluctuation in the second q^2 bin of R_{K^*} (where instead a downward fluctuation is observed), and would be generically disfavoured by the various constraints, that become stronger for smaller V masses. Therefore we do not explore this possibility further here[7].

COMMENTS ON DARK MATTER

It is natural to speculate whether the light new particle, responsible for the invisible V decay, could be a good Dark Matter (DM) candidate for the values of the parameters that explain the flavour anomalies. If this new particle is stable on cosmological scales, for fundamental or accidental reasons, a straightforward possibility to avoid overclosure of the universe is that its mass be larger than m_μ. The related annihilation cross section, in the limited mass range $m_\mu < m_{\rm DM} < m_V/2$, is then univocally determined by the requirement to alleviate the $b \to s\mu\mu$

tensions, and its value can for example be compared with the one needed to obtain the DM abundance via thermal freeze-out [40].

The average annihilation cross section of $\chi\bar\chi \to \mu^+\mu^-$ times relative velocity reads

$$\langle \sigma v \rangle \simeq \frac{g_\chi^2}{\pi} \frac{g_{\mu V}^2 \left(m_\chi^2 + \frac{m_\mu^2}{2}\right) + g_{\mu A}^2 \left(m_\chi^2 - m_\mu^2\right)}{(m_V^2 - 4m_\chi^2)^2} \sqrt{1 - \frac{m_\mu^2}{m_\chi^2}} \qquad (11)$$

and yields to values in the ballpark of $10^{-(22-21)}\mathrm{cm}^3/\mathrm{sec}$ for the preferred values of g_χ and $g_{\mu V,A}$. The annihilation of χ with $\bar\chi$ is then efficient in depleting the symmetric DM population, so that either χ or $\bar\chi$ could be a viable DM candidate in the presence of an initial asymmetry. Here we limit ourselves to notice this interesting property, whose further exploration goes beyond the scopes of this letter. The invisible stable state could also be a new light complex scalar particle ϕ (for a first exploration of sub-GeV scalar DM see [41]). Its interaction with V, $\mathcal{L} \supset i\, g_\phi V^\nu \phi^* \partial_\nu \phi + \text{h.c.}$, could for example arise if the ϕ potential spontaneously breaks the gauge group of V, thus also providing an origin for m_V. The $\phi\bar\phi$ annihilation cross section into muons times relative velocity then reads

$$\langle \sigma v \rangle \simeq v^2 \frac{g_\phi^2}{3\pi} \frac{g_{\mu V}^2 \left(m_\phi^2 + \frac{m_\mu^2}{2}\right) + g_{\mu A}^2 \left(m_\phi^2 - m_\mu^2\right)}{(m_V^2 - 4m_\phi^2)^2} \sqrt{1 - \frac{m_\mu^2}{m_\phi^2}}. \qquad (12)$$

Like in the fermion case, and despite the p-wave suppression, this cross section is large $(\langle \sigma v \rangle \approx 10^{-(24-23)}\mathrm{cm}^3/\mathrm{sec}$ at freeze-out) for the values of the couplings preferred by the flavour anomalies and efficiently depletes the symmetric DM population.

SUMMARY & OUTLOOK

In view of various deviations from SM predictions in rare B decays, we have speculated on the logical possibility of new *light* particles being responsible for these effects. Considering the case of a new light spin-1 boson, we have demonstrated that the effects can be qualitatively reproduced if

- ⋄ the resonance has a mass between about 2 and 3 GeV, in particular a mass $\gtrsim 2.5$ GeV allows for a common explanation of R_K, R_{K^*} and P_5';

- ⋄ the resonance dominantly decays invisibly with a partial width that is of order 10–20% of its mass.

The latter property has lead us to speculate about the invisible state as Dark Matter. The values of the parameters that explain the flavour anomalies predict that, if the new invisible state is heavier than m_μ, it has a large pair annihilation cross section, which is a necessary propriety of a would-be asymmetric DM candidate.

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[6] While $(g-2)_\mu$ is insensitive to the signs of $g_{\mu A}$ and $g_{\mu V}$, we do not show their other possible relative sign since it leads to a slightly worse fit of the $b \to s\ell\ell$ anomalies.

[7] A very light, narrow vector boson has been considered in [38] and found not be able to reconcile the R_K and $(g-2)_\mu$ anomalies. A narrow boson even lighter than the muon was considered in [39] and found to be only viable by postulating a momentum-dependent coupling to quarks.
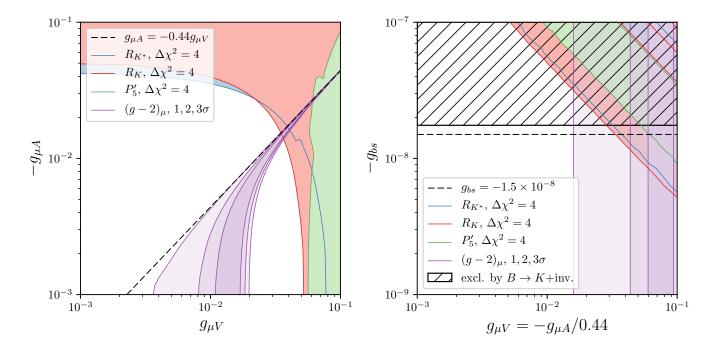
FIG. 2. Preferred regions from flavour anomalies and constraints for the benchmark case of $m_V = 2.5$ GeV. Left: $g_{\mu V}$ vs. $g_{\mu A}$ fixing $g_{bs} = -1.5 \times 10^{-8}$. Right: $g_{\mu V}$ vs. g_{bs} fixing $g_{\mu A} = -0.44 g_{\mu V}$.

Independently of Dark Matter, this scenario makes a number of clear-cut predictions,

  ⋄ a strongly q^2-dependent deviation from e-μ universality in $B \to K \ell^+ \ell^-$ and $B \to K^* \ell^+ \ell^-$,

  ⋄ a branching ratio $B \to K$ + invisible not far from present bounds on $B \to K \nu \bar{\nu}$,

  ⋄ an effect in $(g-2)_\mu$ that can explain the observed discrepancy with the SM.

A moderate tuning at the level of a few per cent is required in the muon couplings in order to satisfy the $(g-2)_\mu$ constraint.

Especially the first prediction – a marked q^2 dependence in R_K and R_{K^*} – is a unique signature that will allow to confirm or refute this setup experimentally. We look forward to precise measurements of the q^2 dependence of these observables.

Note added After the first version of this paper appeared, ref. [42] pointed out that precise measurements of the invariant mass of dimuons from Drell-Yann production significantly constrain resonances of the kind studied in this letter. The limits derived in [42] reduce the parameter space where P_5' can be addressed, but leave ample margin to explain R_K and R_{K^*}.

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