Bound on minimal universal extra dimensions from $\bar{B} \to X_s \gamma$

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We reexamine the constraints on universal extra dimensional models arising from the inclusive radiative $\bar{B} \to X_s \gamma$ decay. We take into account the leading order contributions due to the exchange of Kaluza-Klein modes as well as the available next-to-next-to-leading order corrections to the $\bar{B} \to X_s \gamma$ branching ratio in the standard model. For the case of one large flat universal extra dimension, we obtain a lower bound on the inverse compactification radius $1/R > 600 \text{ GeV}$ at 95\% confidence level that is independent of the Higgs mass.

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The branching ratio of the inclusive radiative $\bar{B}$-meson decay is known to provide stringent constraints on various non-standard physics models at the electroweak scale, because it is accurately measured and its theoretical determination is rather precise.

The present experimental world average which includes the latest measurements by CLEO [1], Belle [2], and BaBar [3] is performed by the Heavy Flavor Averaging Group [4] and reads for a photon energy cut of $E_\gamma > E_0$ with $E_0 = 1.6 \text{ GeV}$ in the $\bar{B}$-meson rest-frame

$$B(\bar{B} \to X_s \gamma)_{\text{exp}} = (3.55 \pm 0.24_{-0.10}^{+0.09} \pm 0.03) \times 10^{-4}.$$ \hspace{1cm} (1)

Here the first error is a combined statistical and systematic one, while the second and third are systematic uncertainties due to the extrapolation from $E_0 = (1.8 - 2.0) \text{ GeV}$ to the reference value and the subtraction of the $\bar{B} \to X_s \gamma$ event fraction, respectively.

After a joint effort \cite{5-8}, the first theoretical determination of the total $\bar{B} \to X_s \gamma$ branching ratio at next-to-next-to-leading order (NNLO) QCD has been presented recently in \cite{6,8}. In \cite{6} this fixed-order result has been supplemented with perturbative cut-related $\mathcal{O}(\alpha_s^2)$ corrections \cite{10} and an estimate of enhanced $\Lambda_{\text{QCD}}/m_b$ non-local power corrections using the vacuum insertion approximation \cite{11}. For $E_0 = 1.6 \text{ GeV}$ the result of the improved standard model (SM) evaluation is given by \cite{20}

$$B(\bar{B} \to X_s \gamma)_{\text{SM}} = (2.98 \pm 0.26) \times 10^{-4},$$ \hspace{1cm} (2)

where the uncertainties from higher-order perturbative effects ($^{+4}_0\%$), hadronic power corrections ($\pm 5\%$), parametric dependencies ($\pm 4\%$), and the interpolation in the charm quark mass ($\pm 3\%$) have been added in quadrature to obtain the total error.

Compared with the experimental world average of Eq. (1), the new SM prediction of Eq. (2) is lower by around 1.4\,$\sigma$. Potential beyond SM contributions should now be preferably constructive, while models that lead to a suppression of the $b \to s \gamma$ amplitude are more severely constrained than in the past, where the theoretical determination used to be above the experimental one.

Among the scenarios of the latter category is the model of Appelquist, Cheng, and Dobrescu (ACD) \cite{14} as emphasized in \cite{14,15}. In the ACD framework the SM is extended from four-dimensional Minkowski space-time to five dimensions and the extra space dimension is compactified on the orbifold $S^1/Z_2$ in order to obtain chiral fermions in four dimensions. The five-dimensional fields can equivalently be described in a four-dimensional Lagrangian with heavy Kaluza-Klein (KK) states for every field that lives in the fifth dimension or bulk. In the ACD model all SM fields are promoted to the bulk. The orbifold compactification breaks KK number conservation, but preserves KK-parity. This property implies, that KK states can only be pair-produced, that their virtual effect comes only from loops, and causes the lightest KK particle (LKP) to be stable, therefore providing a viable dark matter (DM) candidate \cite{16} with promising

\begin{figure}[h!]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{\small $\mathcal{B}(\bar{B} \to X_s \gamma)$ for $E_0 = 1.6 \text{ GeV}$ as a function of $1/R$. The red (dark gray) band corresponds to the LO mUED result. The 68\% CL range and central value of the experimental/SM result is indicated by the yellow/green (light/medium gray) band underlying the straight solid line. See text for details.}
\end{figure}
prospects for direct and indirect detection. See [17] for a recent review on the DM and collider phenomenology of the ACD model.

The full Lagrangian of the ACD model includes both bulk and boundary terms. The bulk Lagrangian is determined by the SM parameters after an appropriate rescaling. The coefficients of the boundary terms, however, although volume suppressed, are free parameters and will get renormalized by bulk interactions. Flavor non-universal boundary terms would lead to unacceptably large flavor-changing-neutral-currents (FCNCs). In the following we will assume vanishing boundary terms of the KK modes corresponding to the pseudo Goldstone boson, $Q_k$, the $SU(2)$ quark dou-""
The upper/lower panel displays the 95% CL limits on $1/R$ as a function of the experimental (SM) central value (horizontal axis) and total error (vertical axis). The experimental/SM result from Eq. (1)/Eq. (2) is indicated by the black square. The contour lines represent values that lead to the same bound in TeV. See text for details.

To conclude, we have pointed out that combining the present experimental with the improved standard model result for the branching ratio of the inclusive $B \to X_s \gamma$ decay implies that the inverse compactification radius of the minimal universal extra dimension model has to satisfy $1/R > 600$ GeV at 95% confidence level if all the uncertainties are treated as Gaussian. This lower bound is independent from the Higgs mass and therefore stronger than the limits that can be derived from any other currently available measurement. This underscores the outstanding role of the inclusive radiative $B$-meson decay in searches for new physics close to the electroweak scale.

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