Magnetic-dipole corrections to R_K and R_{K^*} observables in the Standard Model and beyond

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3rd of December 2019

The observables R_K and R_{K^*}

$$R_{K(K^*)} = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\,\mathsf{BR}(B^{+(0)} \to K^+(K^*)\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\,\mathsf{BR}(B^{+(0)} \to K^+(K^*)e^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2},$$

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- they come from FCNC processes $\to$ they are sensitive to NP effects
- factorization of hadronic form factors $\to$ low uncertainties
- LFU $\to$ they should be 1 in the SM

  $\to\approx 1\sigma$ discrepancy for R_{K^*} (Belle + LHCb)
  $\to\approx 2.5\sigma$ discrepancy for R_K (LHCb)

The work of Bordone, Isidori, Pattori

- universal corrections
- corrections $\propto \alpha_{\text{em}} \log^2(m_\ell/m_B)$
- corrections of the BRs from $\sim -17\%$ to $\sim -2\%$

$$R_{K^*}^{\rm SM} = \begin{cases} 0.906 \pm 0.028 & 0.045\,\text{GeV}^2 < q^2 < 1.1\,\text{GeV}^2 \\ 1.00 \pm 0.01 & 1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2 \end{cases}$$

$$R_K^{\rm SM}[1.0, 6.0] = 1.00 \pm 0.01$$

Outline of the work

Goal 1: improve the SM estimate

- LFUV corrections
- long-distance non-universal corrections

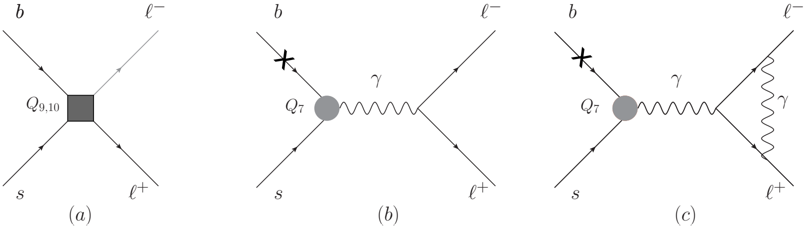
  $\rightarrow$ magnetic-dipole correction

  $\rightarrow$ Sommerfeld correction

Goal 2: massless dark photon scenario

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i Q_i$$



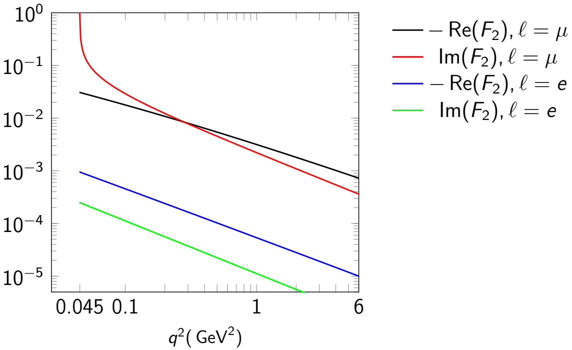
$$Q_7 = \frac{e}{8\pi^2}[m_b \bar{s}_a \sigma^{\mu\nu}(1+\gamma_5) b_a F_{\mu\nu} + o(m_s)]$$

$$Q_9 = (\bar{s}b)_{V-A}\left(\bar{\ell}\ell\right)_V \qquad Q_{10} = (\bar{s}b)_{V-A}\left(\bar{\ell}\ell\right)_A$$

Magnetic-dipole correction

$$\bar{\ell}\gamma^\mu \ell \to \bar{\ell}\left[\gamma^\mu F_1(q^2) + \mathrm{i}F_2(q^2)\sigma^{\mu\nu}\hat{q}_\nu\right]\ell$$

- $F_2 \propto m_\ell \quad \to \quad$ LFUV term
- the interference with the LO expression is chiral suppressed $\to$ enanchment for the muon case



Sommerfeld correction

- regime $\rightarrow$ non-relativistic
- ordinary QM $\rightarrow$ deviation from free states due to Coulombian interaction
- QED $\rightarrow$ virtual corrections
- it consists in a modification of the differential decay rate:

$$\mathrm{d}\Gamma(P_0 \rightarrow P_1 \dots P_N) = \Omega \cdot \mathrm{d}\Gamma^0 \, (P_0 \rightarrow P_1 \dots P_N)$$

$$\Omega_C = \prod_{0 \leq i < j} \frac{2\pi\alpha Q_i Q_j}{\beta_{ij}} \frac{1}{\exp\left(\frac{2\pi\alpha Q_i Q_j}{\beta_{ij}}\right) - 1}$$

Amplitudes

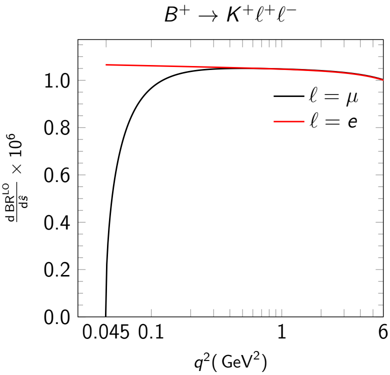
- the leading SM expression of the differential decay rates has been recovered
- Adding the corrections:

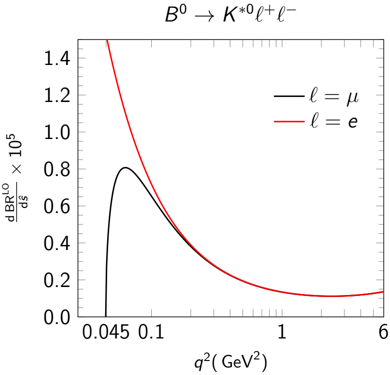
$$\frac{\mathrm{d}^2\,\mathsf{BR}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} = \Omega\frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{LO}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} + \frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{M}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} \equiv \frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{LO}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} + \frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{M}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} + \frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{S}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}}$$

so

$$\frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{S}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}} = (\Omega - 1)\frac{\mathrm{d}^2\,\mathsf{BR}^{\mathrm{LO}}}{\mathrm{d}\hat{s}\,\mathrm{d}\hat{u}}$$

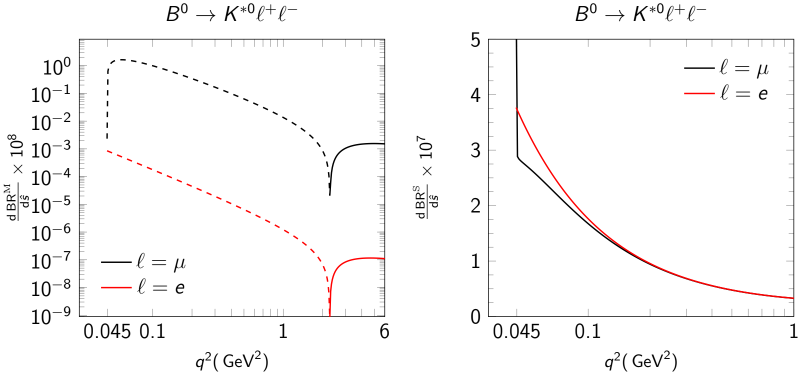
Branching ratios at LO





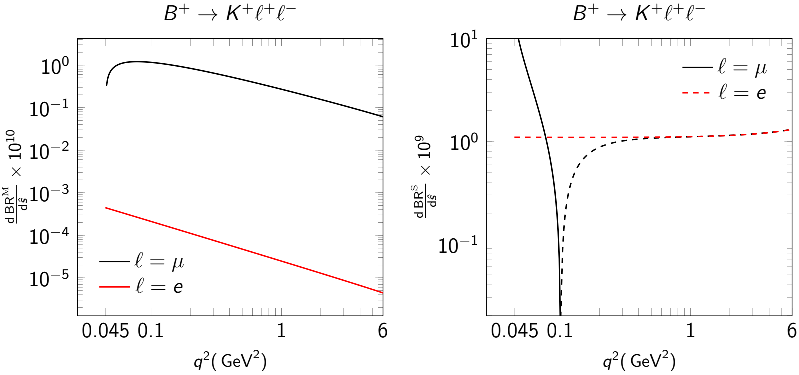
Corrections to $B^0 \to K^{*0}\ell^+\ell^-$

We recall that $\frac{\mathrm{d\,BR^{LO}}}{\mathrm{d}\hat{s}} \sim 10^{-5}$



Corrections to $B^+ \to K^+\ell^+\ell^-$

We recall that $\frac{\mathrm{d\,BR^{LO}}}{\mathrm{d}\hat{s}} \sim 10^{-6}$



Bin integration for $B^0 \to K^{*0}\ell^+\ell^-$

$$R_{K^*} = R_{K^*}^{\mathrm{LO}}\left(1 + \Delta R_{K^*}^{\mathrm{M}} + \Delta R_{K^*}^{\mathrm{S}}\right)$$

$[q^2_{\min}, q^2_{\max}]$ (GeV^2)	$\Delta R_{K^*}^{\mathrm{M}}$	$\Delta R_{K^*}^{\mathrm{S}}$
$[0.0447, 0.3]$	-1.3×10^{-3}	$\sim 2 \times 10^{-3}$
$[0.0447, 0.5]$	-1.0×10^{-3}	$\sim 1 \times 10^{-3}$
$[0.0447, 1.1]$	-7.4×10^{-4}	-
$[1.1, 6]$	2.5×10^{-6}	-
$[0.5, 0.8]$	-2.2×10^{-4}	-
$[0.8, 1]$	-1.2×10^{-4}	-
$[1, 3]$	-1.8×10^{-5}	-
$[3, 6]$	1.2×10^{-5}	-

Bin integration for $B^+ \to K^+ \ell^+ \ell^-$

$$R_K = R_K^{\mathrm{LO}} \left(1 + \Delta R_K^{\mathrm{M}} + \Delta R_K^{\mathrm{S}}\right)$$

$\left[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}\right]$ (GeV^2)	ΔR_K^{M}	ΔR_K^{S}
$[0.0447, 0.3]$	9.4×10^{-5}	$\sim 1 \times 10^{-3}$
$[0.0447, 0.5]$	7.4×10^{-5}	$\sim 5 \times 10^{-4}$
$[0.0447, 1.1]$	5.0×10^{-5}	-
$[1.1, 6]$	1.1×10^{-5}	-
$[0.5, 0.8]$	3.6×10^{-5}	-
$[0.8, 1]$	2.8×10^{-5}	-
$[1, 3]$	1.6×10^{-5}	-
$[3, 6]$	8.0×10^{-6}	-

Dark photon contribution: motivations

possibility of a new s-channel contribution to $b \to s\ell^+\ell^-$:

- unbroken $U(1)_D$ gauge interaction in the dark sector
  $\to$ exchange of a massless dark photon $\overline{\gamma}$
- millicharged tree-level interaction with the γ
- no tree-level interactions with SM fermions (even in case of $\gamma\overline{\gamma}$ kinetic mixing)
- 1-loop interactions with SM fermions trough heavy messengers
- effective couplings are provided by operator of dimension 5
- built-in suppression $\to$ possibility of larger α_D
- the magnetic dipole operator is the lowest dimensional operator we can consider in this scenario

Dark photon contribution: matrix element

$$\mathcal{L}_{\text{eff}}^{\text{DP}} = \sum_{q,q'} \frac{1}{2\Lambda_{qq'}^{L}} \left[\bar{q}_R \sigma_{\mu\nu} q'_L\right] F_D^{\mu\nu} + \frac{1}{2\Lambda_{qq'}^{R}} \left[\bar{q}_L \sigma_{\mu\nu} q'_R\right] F_D^{\mu\nu} + \\ + \sum_{\ell\ell'} \frac{1}{2\Lambda_{\ell\ell'}} \left[\bar{\ell} \sigma_{\mu\nu} \ell\right] F_D^{\mu\nu}$$

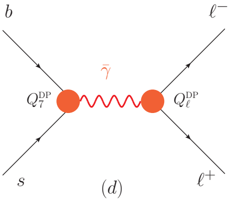
$$\mathcal{M}^{\text{DP}} = -\left(\frac{\eta_R}{\Lambda_{bs}^{R}\Lambda_{\ell\ell}} \left[\bar{s}_L \sigma_{\mu\alpha} \hat{q}^{\alpha} b_R\right] + \frac{\eta_L}{\Lambda_{bs}^{L}\Lambda_{\ell\ell}} \left[\bar{s}_R \sigma_{\mu\alpha} \hat{q}^{\alpha} b_L\right]\right) \left[\bar{\ell} \sigma^{\mu\beta} \hat{q}_{\beta} \ell\right] \frac{\text{i}}{\hat{s}}$$

- assuming unique $\Lambda_{\ell\ell}$ for all leptons
- neglecting the term with Λ_{bs}^{L} because its interference term with the LO SM amplitude is proporional to m_s

Dark dipole contribution: results

$$C_7^{\mathrm{eff}} F_2 \to \frac{\pi\eta}{G_F\sqrt{2}\alpha V_{ts}^* V_{tb}\Lambda_{\mathrm{eff}}^2 \hat{m}_B}$$

$$\text{with } \Lambda_{\mathrm{eff}} = \sqrt{\Lambda_{bs}^R \Lambda_{\ell\ell}}$$



	$\Lambda_{\mathrm{eff}} = 70$ TeV	
$[q^2_{\mathrm{min}}, q^2_{\mathrm{max}}]$ (GeV^2)	$\Delta R_{K^*}^{\mathrm{DP}}$	ΔR_K^{DP}
$[0.0447, 0.5]$	1.3×10^{-1}	5.4×10^{-3}
$[0.0447, 1.1]$	1.2×10^{-1}	5.8×10^{-3}
$[1.1, 6]$	4.6×10^{-2}	6.0×10^{-3}

Model-independent analysis

Bounds on $\Lambda_{bs}^{L,R}$ from $b \to sX_{\text{inv}}$:

$$\Lambda_{bs}^{L} = \Lambda_{bs}^{R} \quad \Rightarrow \quad \Lambda_{bs}^{L,R} \gtrsim 3\,\text{TeV}$$

Bounds on $\Lambda_{\mu\mu}$ from $a = g - 2$:

$$\text{NP under } 2\sigma \to \Lambda_{\mu\mu} > 300\,\text{GeV}$$

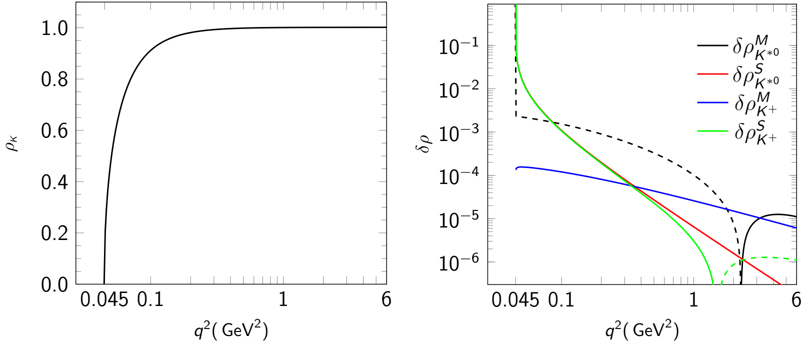
$$\Lambda_{\text{eff}} = \sqrt{\Lambda_{bs}^{R}\Lambda_{\ell\ell}} > 0.6\,\text{TeV}$$

Conclusions

- Sommerfeld correction
  - more relevant in low q^2 bins ($\sim$ ‰ in R_{K^*} and R_K)
  - a more precise integration is needed to compute its size in higher q^2 bins
- SM magnetic-dipole correction:
  - more relevant in low q^2 bins ($\sim$ ‰ in R_{K^*} and $\sim 10^{-5}$ in R_K)
- dark dipole correction
  - with a scale of 70 TeV it could explain the anomaly on R_{K^*} but not on R_K
  - we also carried out a model-dependent analysis $\rightarrow$ 70 TeV is too low
- $m_B^2/m_{K^*}^2$ enhanchment $\rightarrow$ larger effects on $B \rightarrow K^*$

Backup slides

Behaviour of the ratios



$$\rho(q^2) = \frac{\frac{\mathrm{d}\,\mathrm{BR}(B\to K\mu^+\mu^-)}{\mathrm{d}q^2}}{\frac{\mathrm{d}\,\mathrm{BR}(B\to Ke^+e^-)}{\mathrm{d}q^2}} \equiv \rho^{\mathrm{LO}}(1 + \delta\rho^{\mathrm{M}} + \delta\rho^{\mathrm{S}})$$