The Cost of an ALP Solution to the Neutral B-anomalies

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JB, A. de Giorgi, B. Gavela, L. Merlo and M. Ramos [soon on the arXiv]

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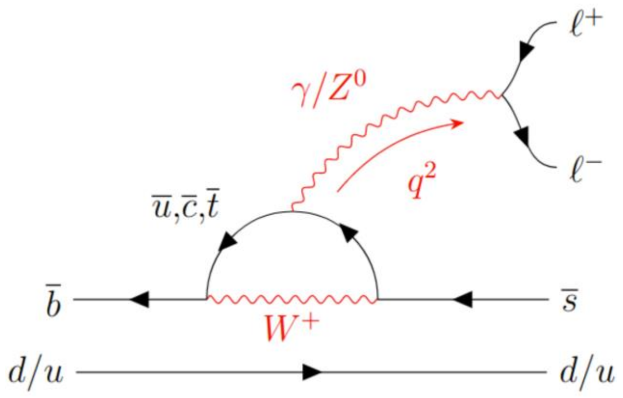
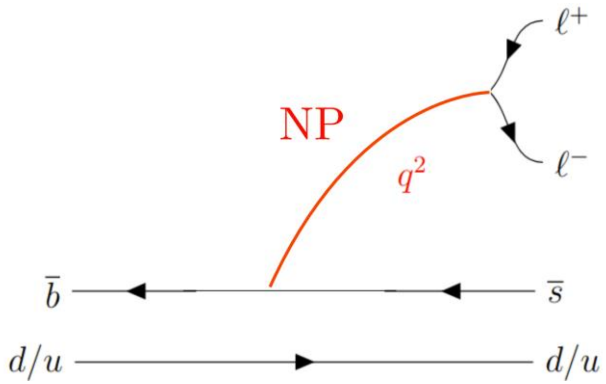
Tests of Lepton Flavour Universality

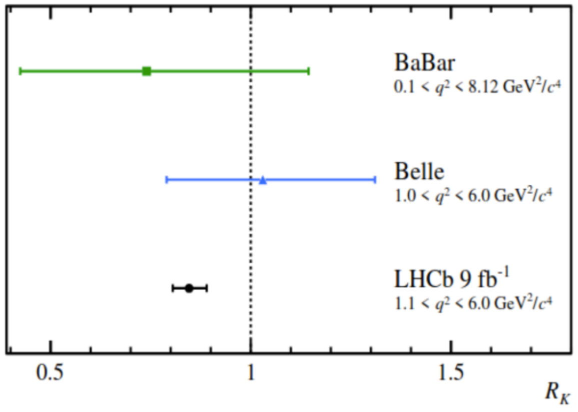
- **LFU** is an intrinsic property of the **SM**

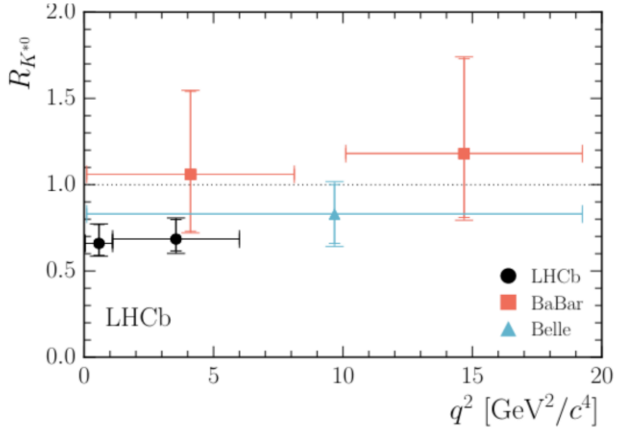
$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \approx 1 \quad \text{in the SM}$$





- Experimentally we find:





LHCb [2103.11769]
LHCb [1705.05802]

$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012} \quad \text{for} \quad 1.1\ \text{GeV}^2 \leq q^2 \leq 6.0\ \text{GeV}^2$$

$$R_{K^*} = \begin{cases} 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for} \quad 1.1\ \text{GeV}^2 \leq q^2 \leq 6.0\ \text{GeV}^2 \\ 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for} \quad 0.045\ \text{GeV}^2 \leq q^2 \leq 1.1\ \text{GeV}^2 \end{cases}$$

Combined deviation of 4.3σ!!!

Axion-like Particles as flavour source

- ALPs are (spin 0) pseudo-Goldstone bosons with derivative couplings to SM particles (+ anomalous couplings to SM gauge bosons)

- Predicted by many BSM theories: axions, majoron, axiflavons, extra dimensions, string theory, etc…

- ALP EFT can easily accommodate flavour-violating fermion interactions:

$$\mathscr{L}_a^{\psi} = \frac{\partial_\mu a}{f_a}\left[\overline{Q}_L\gamma_\mu \mathbf{c_Q} Q_L + \overline{u}_R\gamma_\mu \mathbf{c_u} u_R + \overline{d}_R\gamma_\mu \mathbf{c_d} d_R + \overline{L}_L\gamma_\mu \mathbf{c_L} L_L + \overline{e}_R\gamma_\mu \mathbf{c_e} e_R\right]$$

low energy

$$-\frac{ia}{2f_a}\sum_{i,j}\left((m_{\mathrm{f}_i} - m_{\mathrm{f}_j})(\mathbf{c}_\mathrm{f} + \mathbf{c}_\mathrm{F})_{ij}\,\bar{\mathrm{f}}^i\,\mathrm{f}^j + (m_{\mathrm{f}_i} + m_{\mathrm{f}_j})(\mathbf{c}_\mathrm{f} - \mathbf{c}_\mathrm{F})_{ij}\,\bar{\mathrm{f}}^i\gamma_5\mathrm{f}^j\right) + \mathcal{O}(\alpha)(\mathbf{c}_\mathrm{f} - \mathbf{c}_\mathrm{F})_{ii}\frac{a}{f_a}X\tilde{X}$$

proportional to fermion masses

Bonilla, Brivio, Gavela, Sanz [2107.11392]
Bauer, Neubert, Renner, Schnubel, Thamm [2012.12272]

Axion-like Particles as flavour source

- **ALPs** are (spin 0) pseudo-Goldstone bosons with **derivative couplings** to SM particles (+ anomalous couplings to SM gauge bosons)

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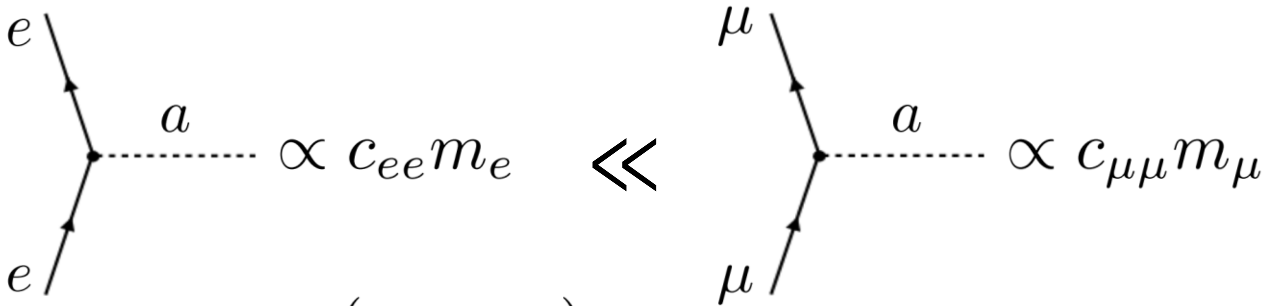


$$c_{\ell\ell} \equiv (c_e - c_L)_{\ell\ell}$$

Solutions to R_K and R_{K^*} require to invert this relation:

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} < 1$$

- Electrophilic ALP: $c_{ee} \gg c_{\mu\mu}$
- Kinematic suppression

Heavy ALP solution

- Let's consider a **heavy ALP** ($m_a > m_b$): **off-shell** contribution to R_K and R_{K^*}

- Equivalent to **SMEFT** analysis with **pseudoscalar** operators:

$$\mathscr{L}_a^{\text{eff.}} \supset -\frac{4G_F}{\sqrt{2}} \sum_{\ell=e,\mu,\tau} V_{tb}V_{ts}^* \left(C_{P_+}^\ell \, \mathcal{O}_{P_+}^\ell + C_{P_-}^\ell \, \mathcal{O}_{P_-}^\ell\right)$$

$$\mathcal{O}_{P_+}^\ell = \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\, b) \left(\bar{\ell}\, \gamma_5\, \ell\right)$$

$$\mathcal{O}_{P_-}^\ell = \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\, \gamma_5\, b) \left(\bar{\ell}\, \gamma_5\, \ell\right)$$

- Matching to the ALP Lagrangian:

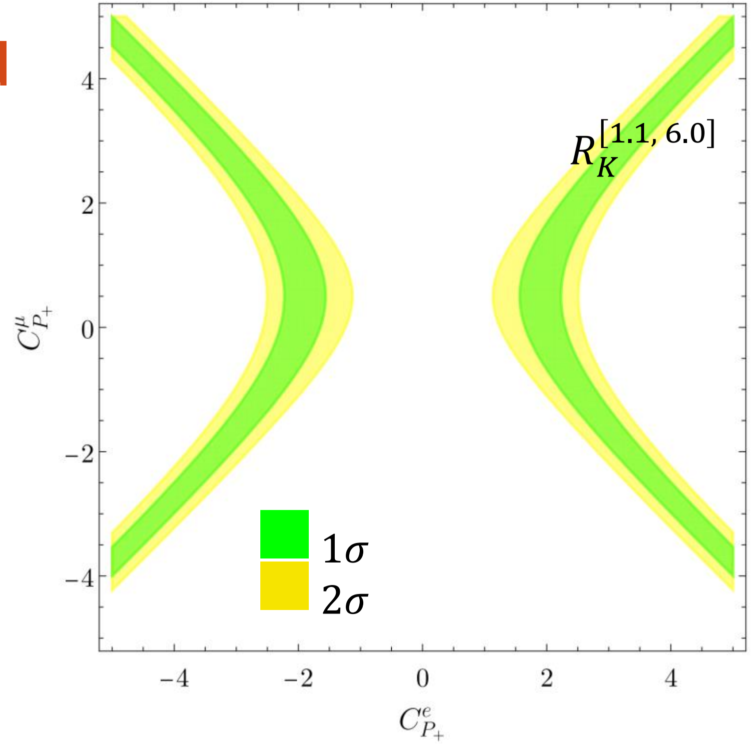
$$C_{P_\pm}^\ell \equiv \frac{\pi}{\sqrt{2}\alpha_{\text{em}} G_F V_{tb} V_{ts}^*} \frac{m_\ell}{(f_a m_a)^2} (m_s \mp m_b) \left(\mathbf{c}_d \pm \mathbf{c}_Q\right)_{sb} c_{\ell\ell}$$

see also *Bauer, Neubert, Renner, Schnubel, Thamm* [2110.10698]

Heavy ALP solution

- Solution to R_{K^*} is excluded due to the contribution of $C^{\ell}_{P_-}$ to $\mathcal{B}(B_s^0 \to \ell^+\ell^-)$

- Solution to R_K is allowed but it requires $|C^e_{P_+}| \gtrsim 2$



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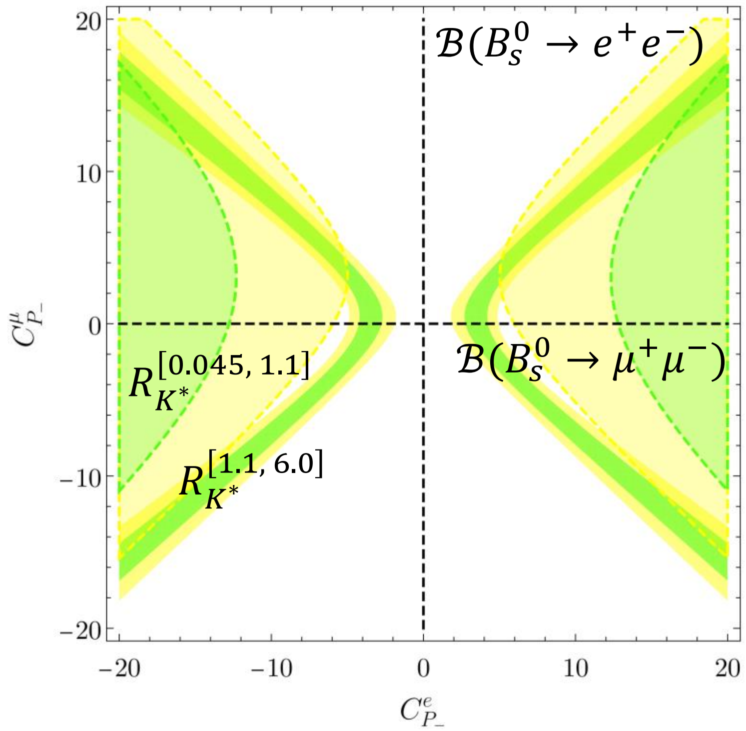


- $$C^e_{P_+} \propto \frac{m_e(m_s - m_b)}{m_a^2} \frac{(\mathbf{c}_d + \mathbf{c}_Q)_{sb}\, c_{ee}}{f_a^2}$$

- $B_s^0 - \overline{B}_s^0$ oscillations impose $\frac{(\mathbf{c}_d + \mathbf{c}_Q)_{sb}}{f_a} \lesssim 10^{-2}\ \mathrm{TeV}^{-1}$

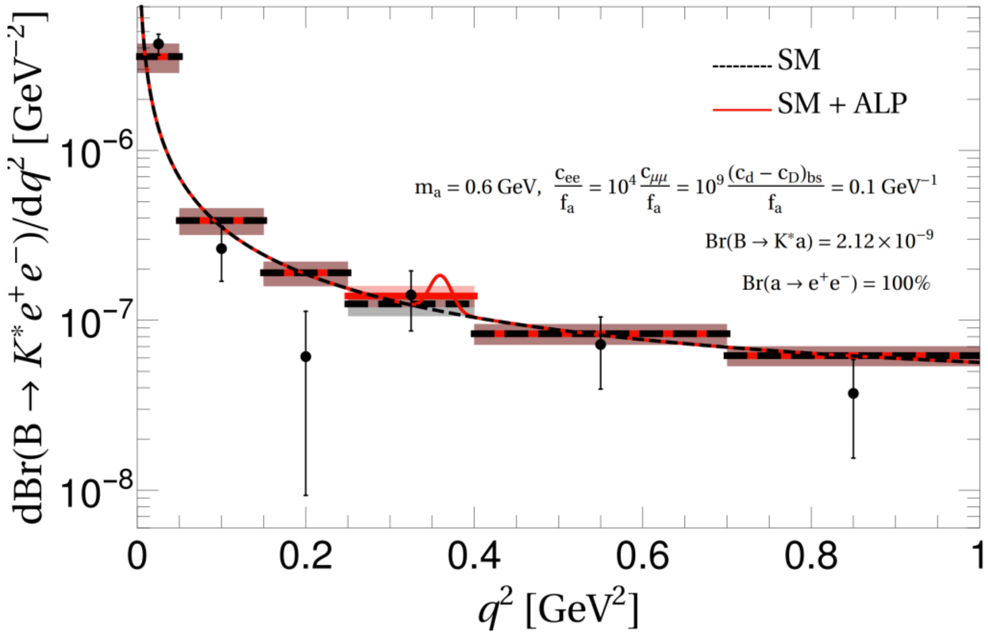
$$\frac{c_{ee}}{f_a} \gtrsim 10^{4.2}\ \mathrm{TeV}^{-1}$$

huge contribution to Δa_e !!

Light resonant ALP solution

- Solution via light resonances of ALPs ($m_b > m_a > 2m_e$) within R_K and R_{K^*} q^2-kinematic bins
- ALP contribution to B-meson branching fractions (narrow-width approx.):

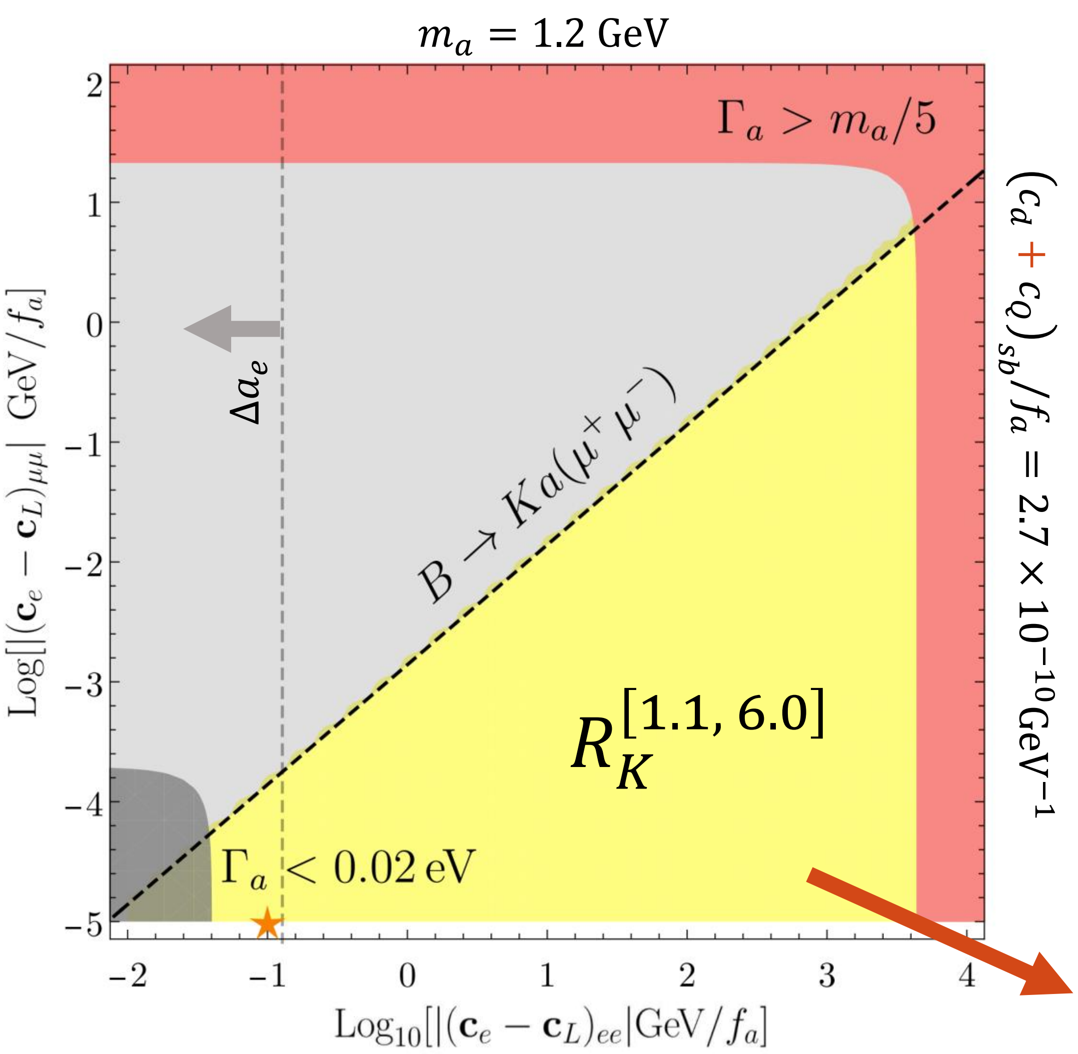
$$\mathcal{B}(B \to K^{(*)}\ell^+\ell^-) = \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)^{\rm SM} + \mathcal{B}(B \to K^{(*)}a) \times \mathcal{B}(a \to \ell^+\ell^-)$$



$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi f_a^2}[(\mathbf{c}_e - \mathbf{c}_L)_{\ell\ell}]^2 \left(1 - \frac{4m_\ell^2}{m_a^2}\right)^{1/2}$$

$c_{ee} \gg c_{\mu\mu}$ for $\mathcal{B}(B \to K^{(*)}e^+e^-) > \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)$

Light resonant ALP solution



$\mathcal{B}(a \to e^+e^-) \approx 1$

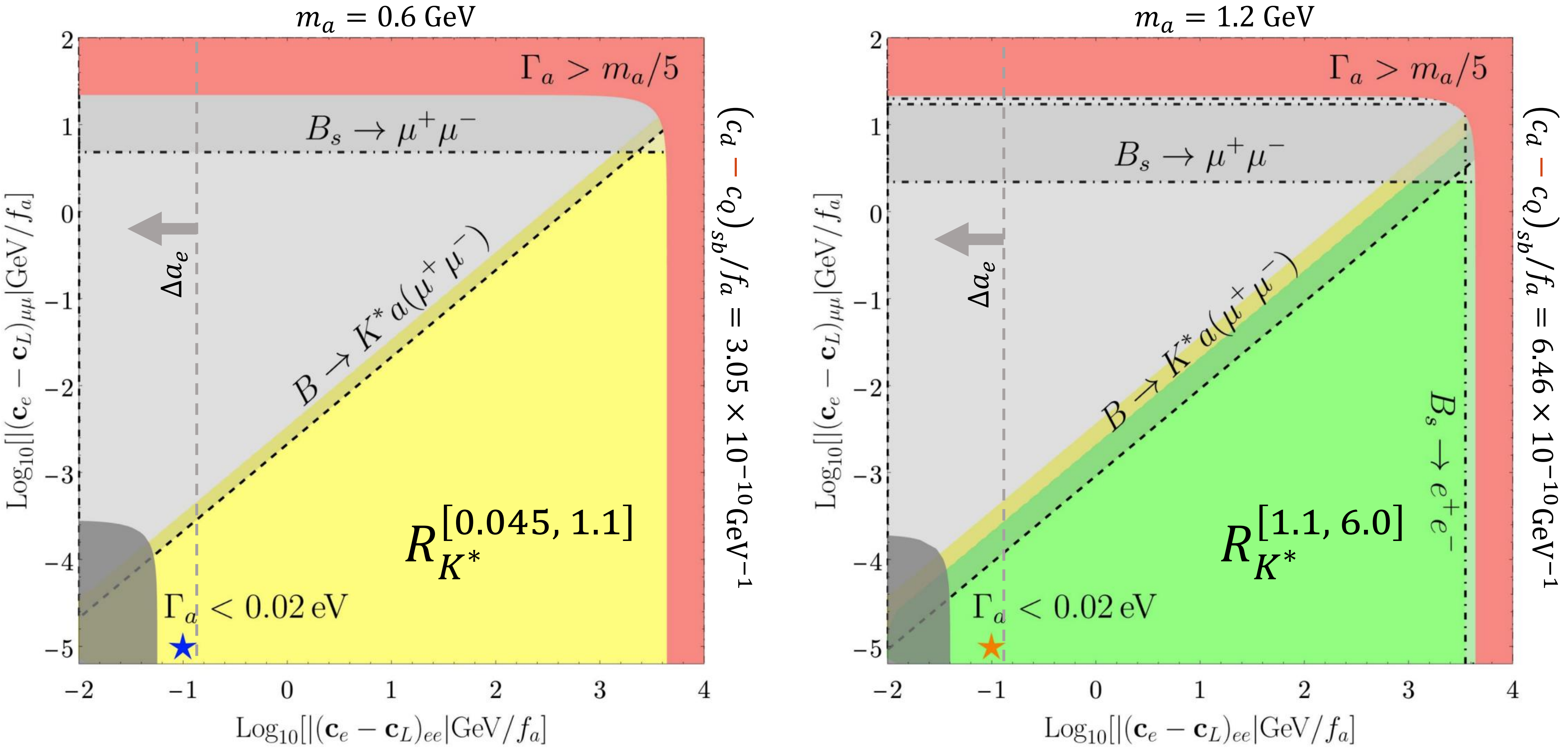
- 5 independent parameters:

$$\left(m_a, \frac{c_{ee}}{f_a}, \frac{c_{\mu\mu}}{f_a}, \frac{(c_d + c_Q)_{sb}}{f_a}, \frac{(c_d - c_Q)_{sb}}{f_a}\right)$$

R_K $\qquad R_{K^*}$

- Solution to R_K is allowed but:
  1. Parameter space is strongly constrained by $\boldsymbol{\Delta a_e}$ (if ALP is the only source of NP)
  2. Large hierarchy among the ALP couplings is required: $c_{ee} \gg c_{\mu\mu} \gg c_{sb}$
  3. Perturbativity ($c_{ee} \sim 1$) imposes a low ALP physics energy scale: $\Lambda = 4\pi f_a \sim 100$ GeV

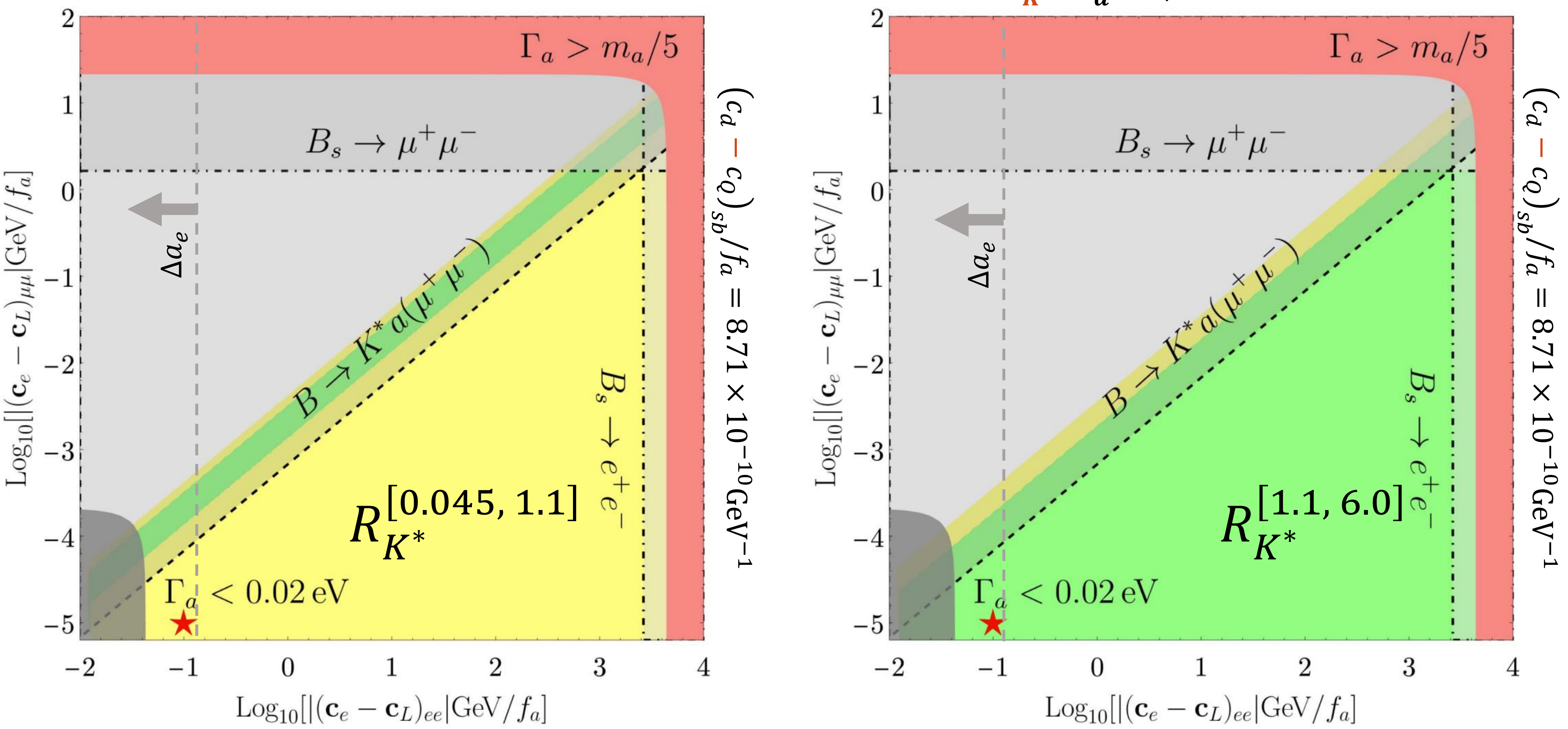
Light resonant ALP solution



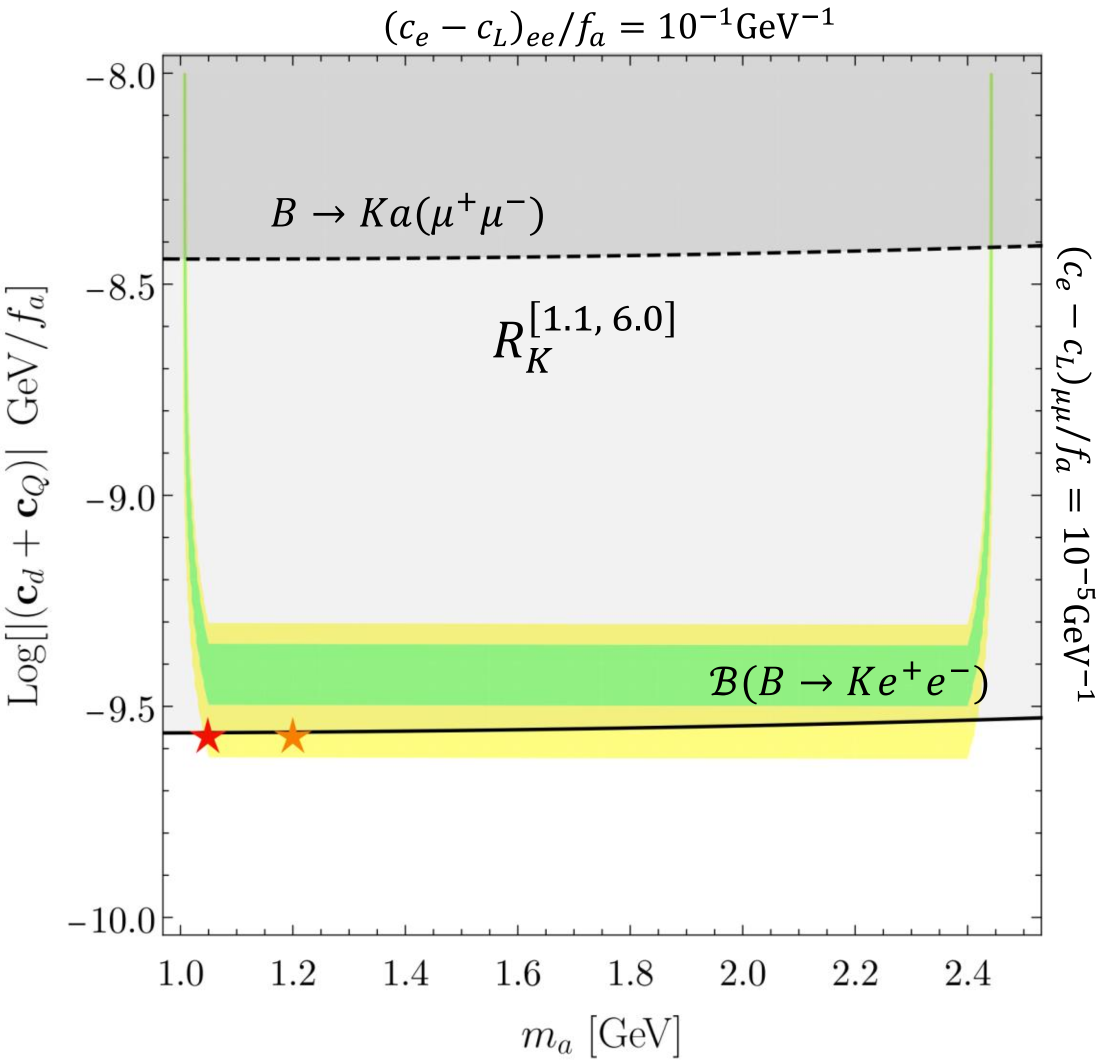
Light resonant ALP solution

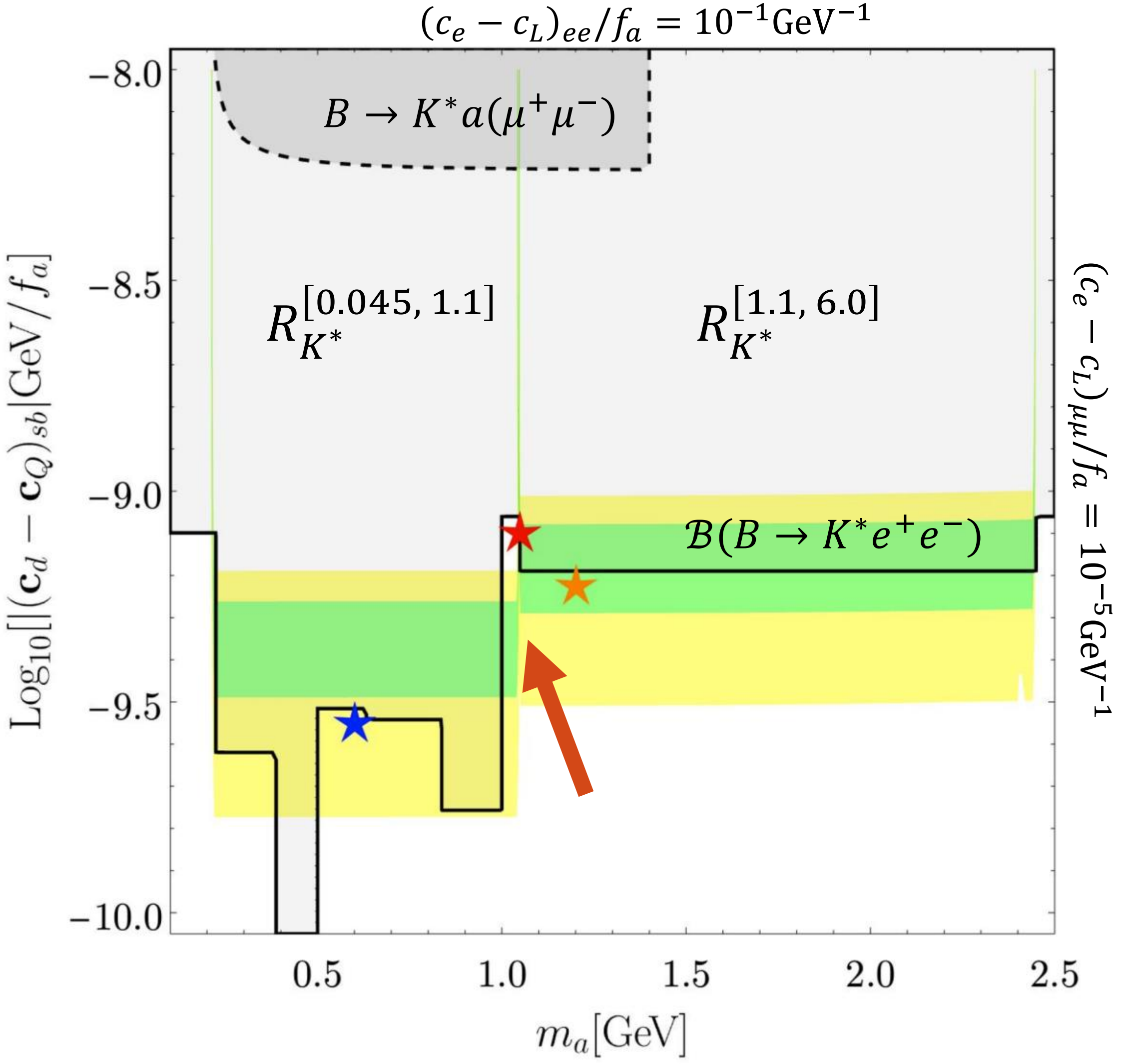
m_a exactly between the two q^2-bins of R_{K^*}

"Golden" ALP mass for R_{K^*} $m_a = \sqrt{1.1}$ GeV



Light resonant ALP solution





Summary

- Solutions to R_K and R_{K^*} anomalies involving **off-shell ALPs** are not possible
  - $\longrightarrow R_{K^*}$ solution is **excluded** by $\mathcal{B}(B_s^0 \to \ell^+\ell^-)$
  - $\longrightarrow R_K$ solution requires a **large ALP-electron coupling** which is excluded by Δa_e if the the ALP is the only source of new physics

- Solutions to R_K and R_{K^*} anomalies involving **resonant decays of ALPs** are possible, but present some issues ("the cost"!):
  1. Parameter space is **strongly constrained** by Δa_e
  2. **Large hierarchy** among the ALP couplings is required: $c_{ee} \gg c_{\mu\mu} \gg c_{sb}$
  3. **Perturbativity** imposes a **low** ALP physics **energy scale**: $\Lambda \sim 100\ \mathrm{GeV}$
  4. **Small ALP mass window** to explain the R_{K^*} anomaly in both q^2-bins (mass window can be enlarged once detector resolution is included)

Back-up slides

Pseudoscalar operator contributions

$$\mathcal{B}(B \to K\mu^+\mu^-)_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.5 - 7.0 \times 10^{-2}\, C_{P_+}^{\mu} + 7.1 \times 10^{-2}\, C_{P_+}^{\mu 2}\right)$$

$$\mathcal{B}(B \to Ke^+e^-)_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.5 - 3.4 \times 10^{-4}\, C_{P_+}^{e} + 7.1 \times 10^{-2}\, C_{P_+}^{e2}\right)$$

$$\mathcal{B}(B \to K^*\mu^+\mu^-)_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.9 - 7.4 \times 10^{-2}\, C_{P_-}^{\mu} + 7.5 \times 10^{-2}\, C_{P_-}^{\mu 2}\right)$$

$$\mathcal{B}(B \to K^*e^+e^-)_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.9 - 3.6 \times 10^{-4}\, C_{P_-}^{e} + 7.5 \times 10^{-2}\, C_{P_-}^{e2}\right)$$

$$\mathcal{B}(B \to K^*\mu^+\mu^-)_{0.045\ \mathrm{GeV}^2}^{1.1\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.2 - 9.3 \times 10^{-3}\, C_{P_-}^{\mu} + 1.5 \times 10^{-3}\, C_{P_-}^{\mu 2}\right)$$

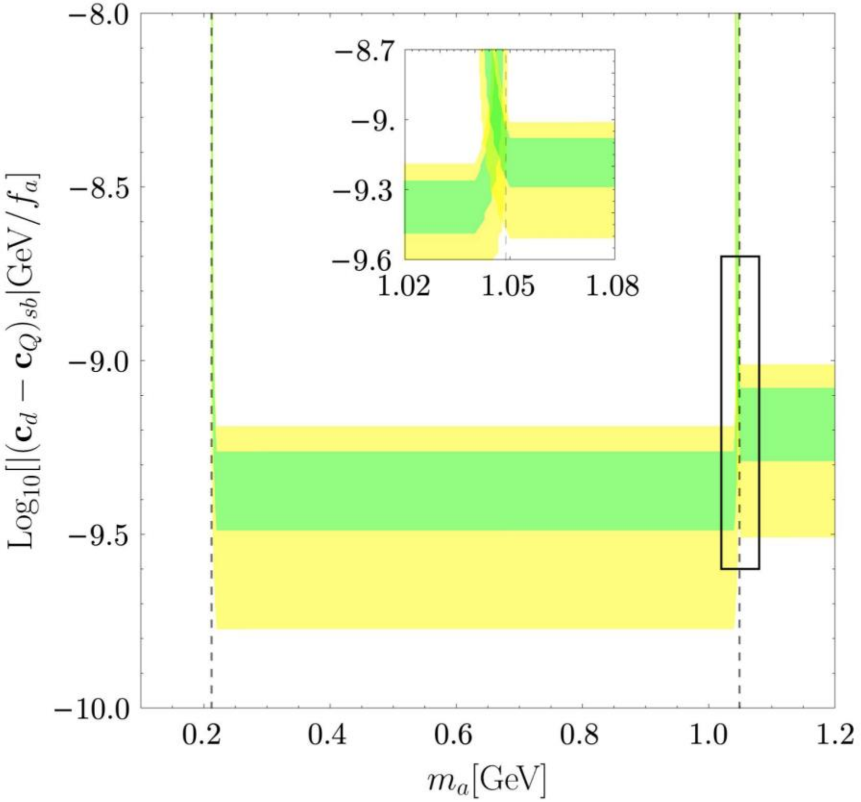
$$\mathcal{B}(B \to K^*e^+e^-)_{0.045\ \mathrm{GeV}^2}^{1.1\ \mathrm{GeV}^2} = 10^{-7} \times \left(1.3 - 4.8 \times 10^{-5}\, C_{P_-}^{e} + 1.6 \times 10^{-3}\, C_{P_-}^{e2}\right)$$

$$\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-) = 10^{-9} \times \left(3.67 - 1.15 \times 10^{2}\, C_{P_-}^{\mu} + 9.04 \times 10^{2}\, C_{P_-}^{\mu 2}\right)$$

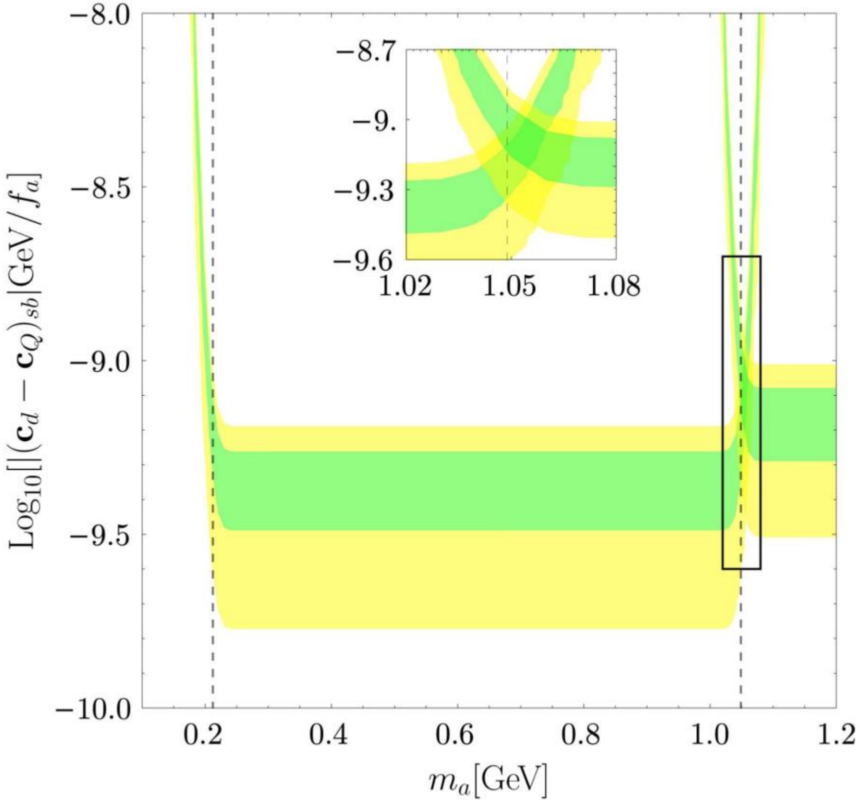
$$\overline{\mathcal{B}}(B_s^0 \to e^+e^-) = 10^{-14} \times \left(8.58 - 5.57 \times 10^{4} C_{P_-}^{e} + 9.05 \times 10^{7}\, C_{P_-}^{e2}\right)$$

The effect of the smearing

$$\mathcal{B}(B \to K^{(*)} a(\ell^+\ell^-)) = \mathcal{B}(B \to K^{(*)} a) \times \mathcal{B}(a \to \ell^+\ell^-) \times \mathcal{G}^{(r_\ell)}(q_{\text{min.}}, q_{\text{max.}})$$



(a) Without smearing function.



(b) With smearing function.

$$\mathcal{G}^{(r_\ell)}(q_{\text{min.}}, q_{\text{max.}}) \equiv \frac{1}{\sqrt{2\pi} r_\ell} \int_{q_{\text{min.}}}^{q_{\text{max.}}} \mathrm{d}|q| \, e^{-\frac{(|q|-m_a)^2}{2r_\ell^2}}$$

$$r_e = 10 \text{ MeV} \qquad r_\mu = 2 \text{ MeV}$$