Axion-like particles and new solutions to the *neutral B*-anomalies

Maria Ramos

2209.11247

A work in collaboration with:
Jesús Bonilla, Belén Gavela, Arturo de Giorgi, Luca Merlo

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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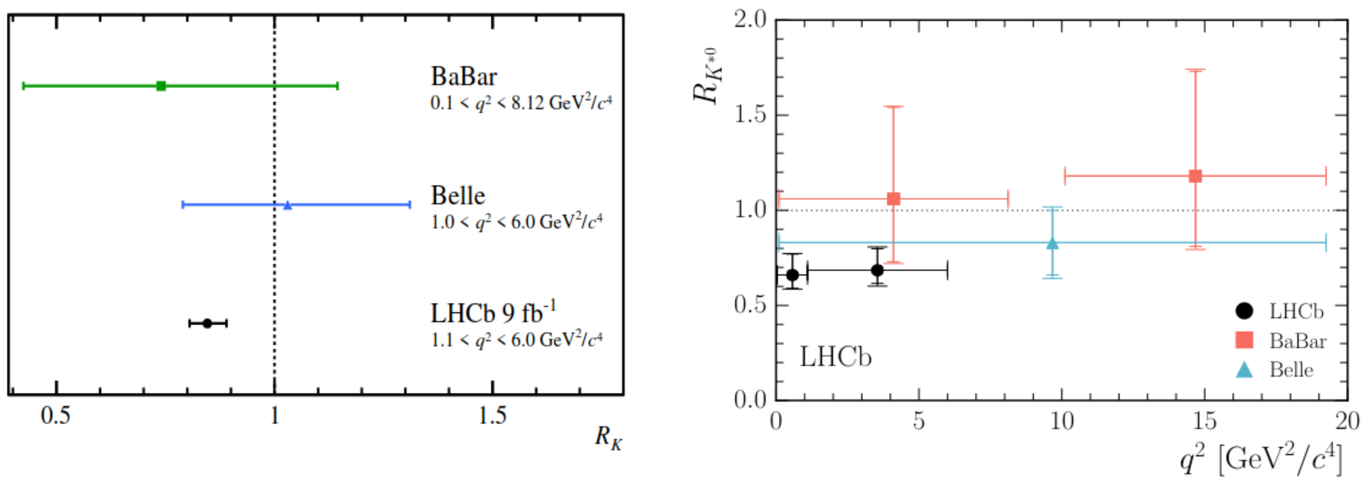
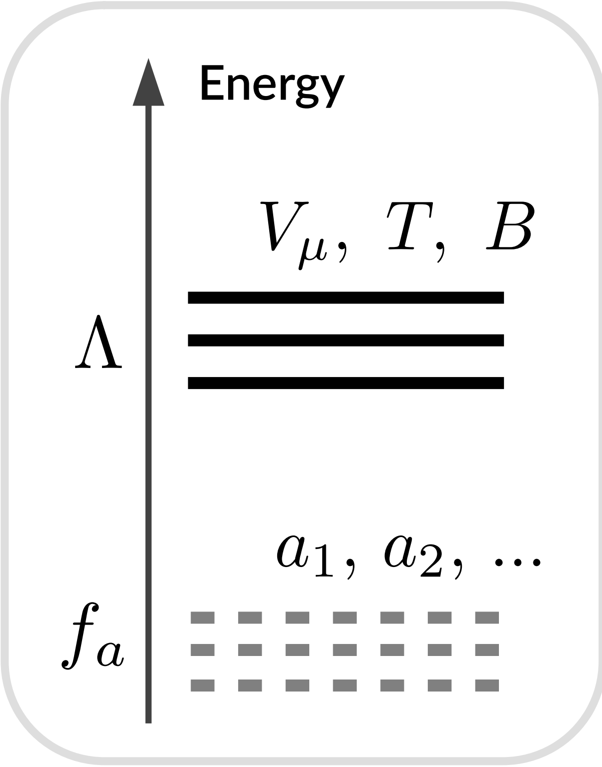
Axion-like particles and new solutions to the *neutral B*-anomalies



Where is the new physics?

No evidence in the signal regions we have looked at



New heavy physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\overline{\psi}\psi\overline{\psi}\psi + \ldots$$

New stealth light physics

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{m_a^2}{2}a^2 + c_\psi \frac{a}{f_a}\overline{\psi}\Phi\psi + \ldots$$

Searching for Goldstone bosons can help us probe the underlying UV sector to which they couple to

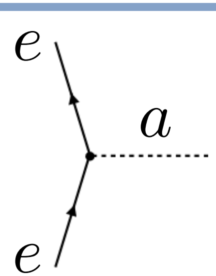
Axion-like particle framework

The global symmetry can be broken by explicit mass or anomalous terms

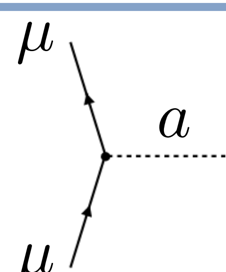
$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 + c_{aXX}\frac{a}{f_a}X_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\overline{\psi'}\gamma^\mu \mathbf{c}'_\psi \psi'$$

$$\mathcal{L}^\psi_{\partial a} \to -\frac{ia}{f_a}\left[(m_{\psi_i} - m_{\psi_j})\left(\mathbf{K}^S_\psi\right)_{ij}\overline{\psi_i}\,\psi_j + (m_{\psi_i} + m_{\psi_j})\left(\mathbf{K}^P_\psi\right)_{ij}\overline{\psi}_i\gamma_5\psi_j\right] - \Delta c_{aXX}\frac{a}{f_a}X_{\mu\nu}\tilde{X}^{\mu\nu}$$

Δf=0



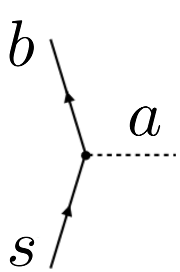
$\propto \left(\mathbf{K}^P_e\right)_{ee} m_e \ll$



$\propto \left(\mathbf{K}^P_e\right)_{\mu\mu} m_\mu$

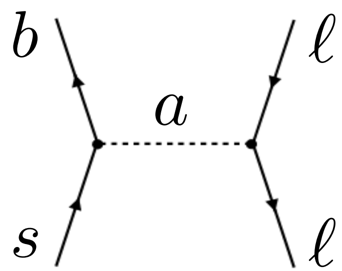
$$\mathbf{K}^{S,P}_\psi \equiv \frac{\mathbf{c}_{\psi_R} \pm \mathbf{c}_{\psi_L}}{2}$$

Δf≠0



R_K	R_{K^*}	$\mathcal{B}(B_s \to \ell^+\ell^-)$	ΔM_s
$\left(\mathbf{K}^S_d\right)_{bs}$	$\left(\mathbf{K}^P_d\right)_{bs}$	$\left(\mathbf{K}^P_d\right)_{bs}$	*mixed*

Heavy ALP exchange



$$C^{\ell}_{P_\pm} \equiv \frac{2\sqrt{2}\pi}{\alpha_{\rm em} G_F V_{tb} V^*_{ts}} \frac{m_\ell}{(f_a m_a)^2} (m_s \mp m_b) \left(\mathbf{K}_d^{S,P}\right)_{sb} \left(\mathbf{K}_e^{P}\right)_{\ell\ell}$$

$$\mathcal{L}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}} \sum_\ell V_{tb} V^*_{ts} \left(C^{\ell}_{P_+} \mathcal{O}^{\ell}_{P_+} + C^{\ell}_{P_-} \mathcal{O}^{\ell}_{P_-} \right) , \quad \mathcal{O}^{\ell}_{P_\pm} = \frac{\alpha_{\rm em}}{4\pi} [s\,(\gamma_5)\, b]\,[\ell\,\gamma_5\,\ell]$$

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to K e^+ e^-)}$$

To explain data, *O(1)* Wilson coefficients are required

$$\mathcal{B}(B \to K\ell^+\ell^-)^{7.0^2}_{1.0^2} = \left(\frac{\tau_{B^\pm}}{1.64\text{ps}}\right) \left(1.91 + 0.08\, C^{\ell 2}_{P_+} - \frac{m_\ell}{\text{GeV}} \frac{C^{\ell}_{P_+}}{1.46} - \frac{m_\ell^2}{\text{GeV}^2} \frac{C^{\ell 2}_{P_+}}{5.18^2} \right)$$

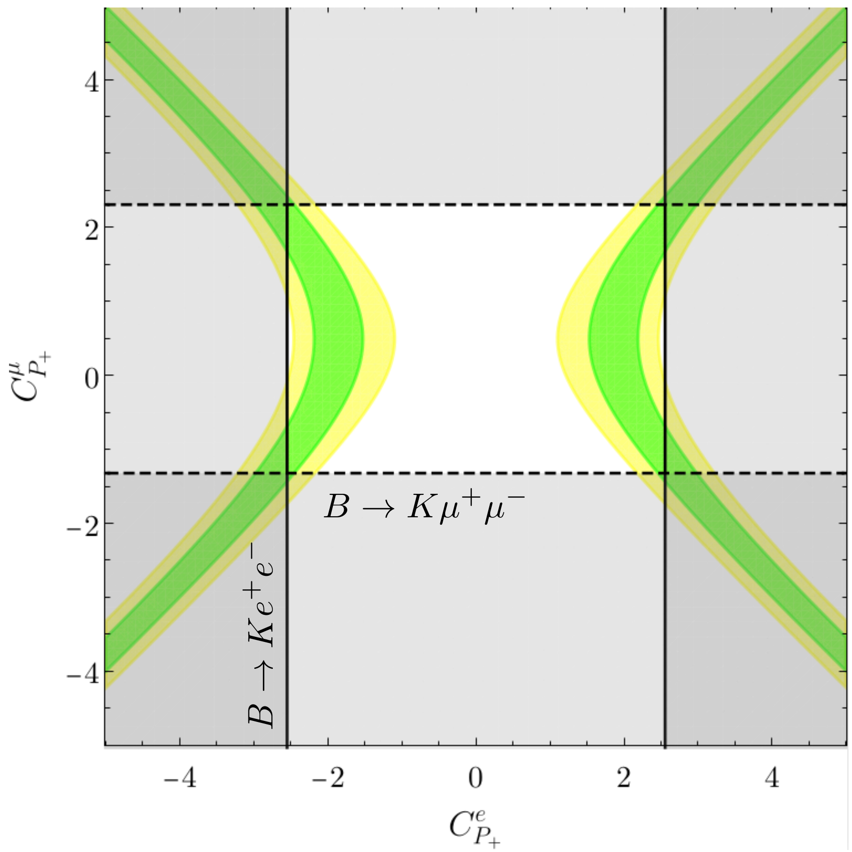
SM

Bobeth, Hiller, Piranishvlli (2007)

LFU ratios from a heavy pseudoscalar

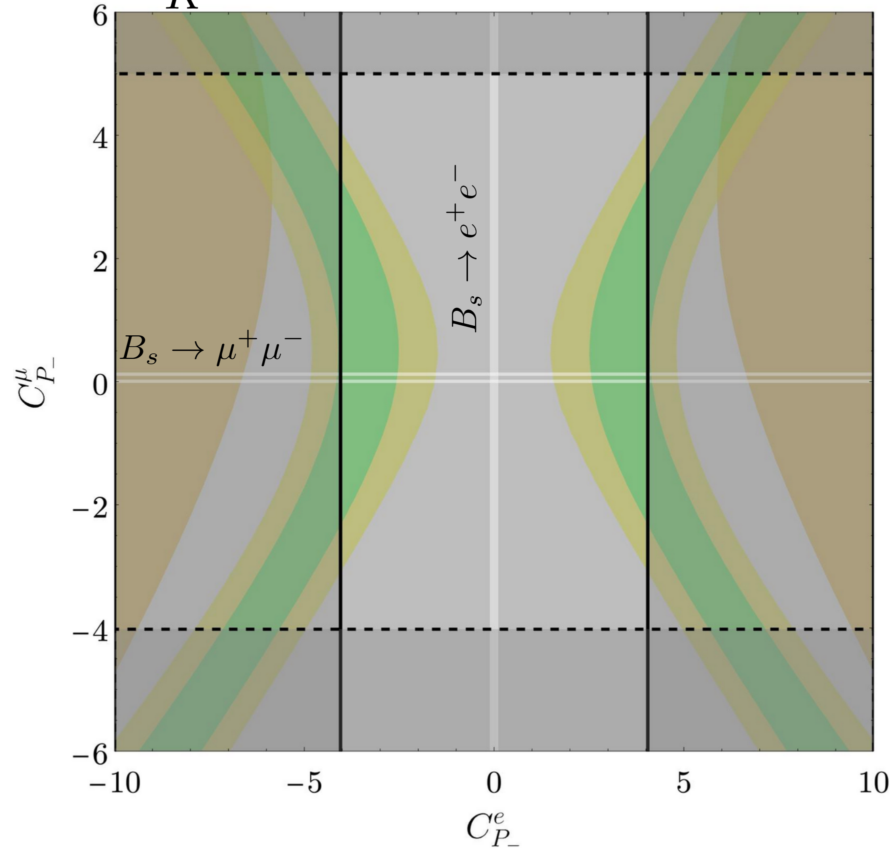
Cross-checks using Flavio and EOS

R_K.



Requires electron coupling

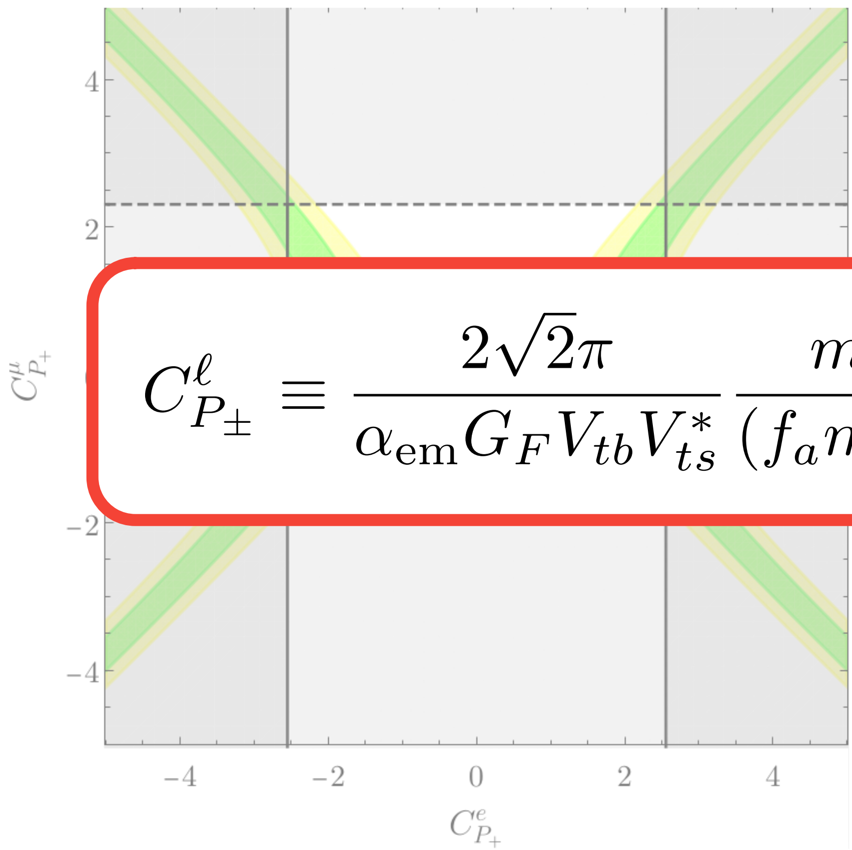
R_K^*.

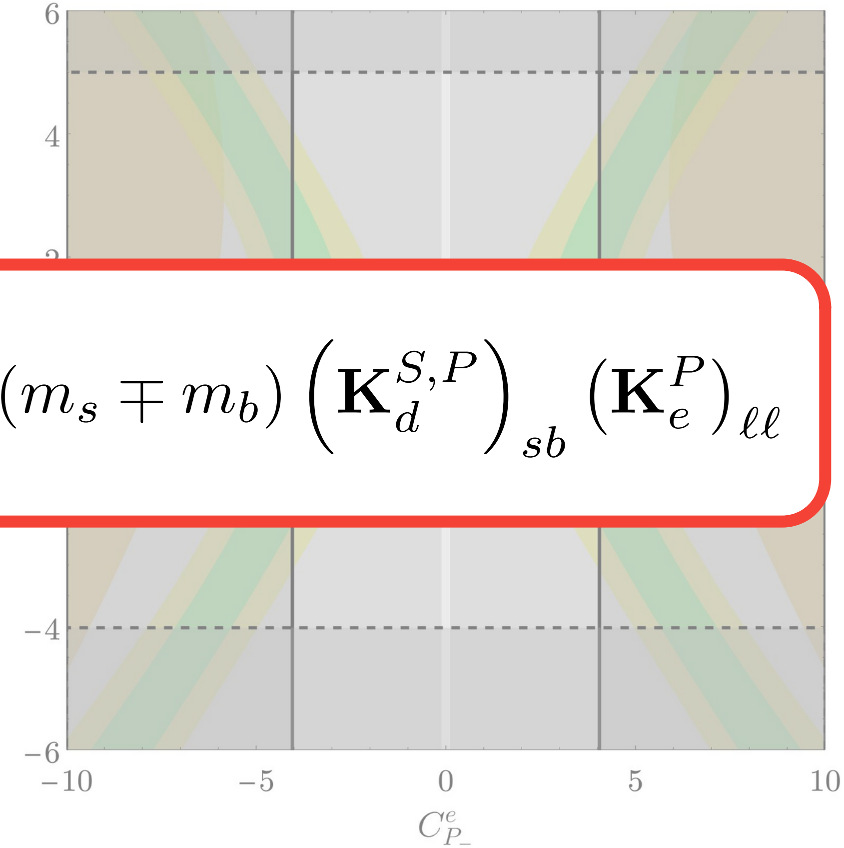


Excluded by other data

LFU ratios from a heavy pseudoscalar

Cross-checks using Flavio and EOS





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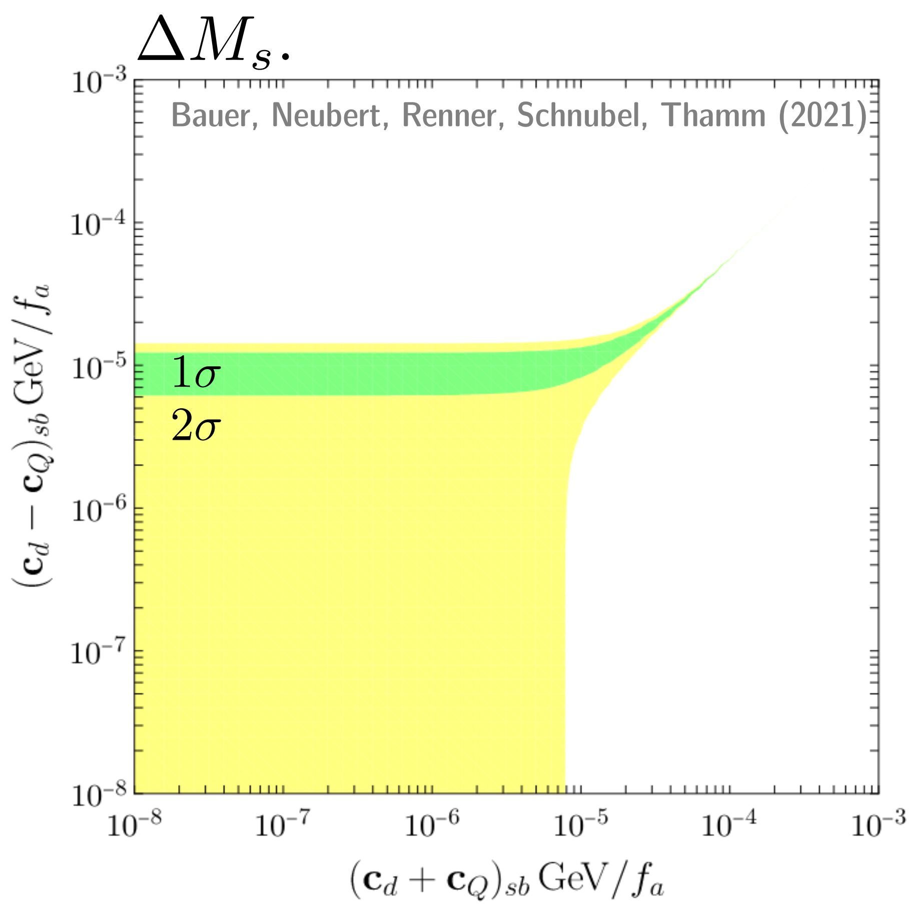
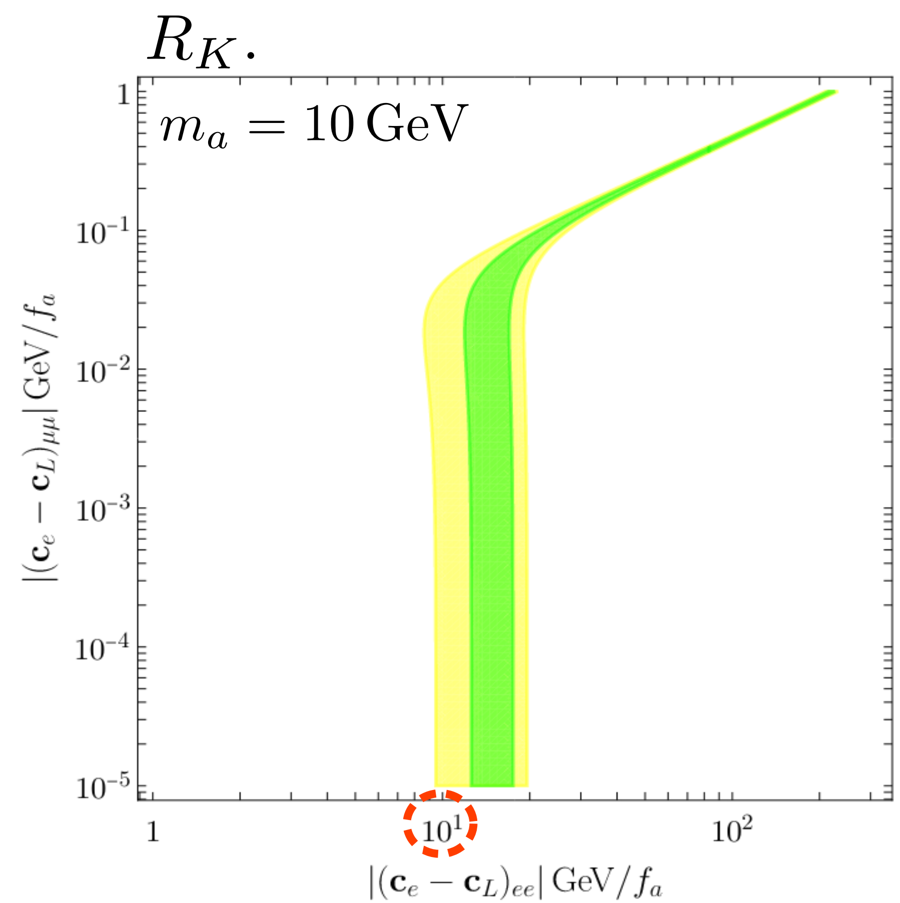
Requires electron coupling

Excluded by other data

LFU ratios from a heavy ALP



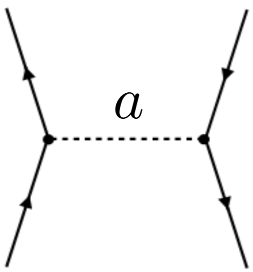


Out of the perturbative regime!

$$f_a \sim 100\,\mathrm{GeV} \to (\mathbf{c}_e - \mathbf{c}_L)_{ee} \sim 10^3$$

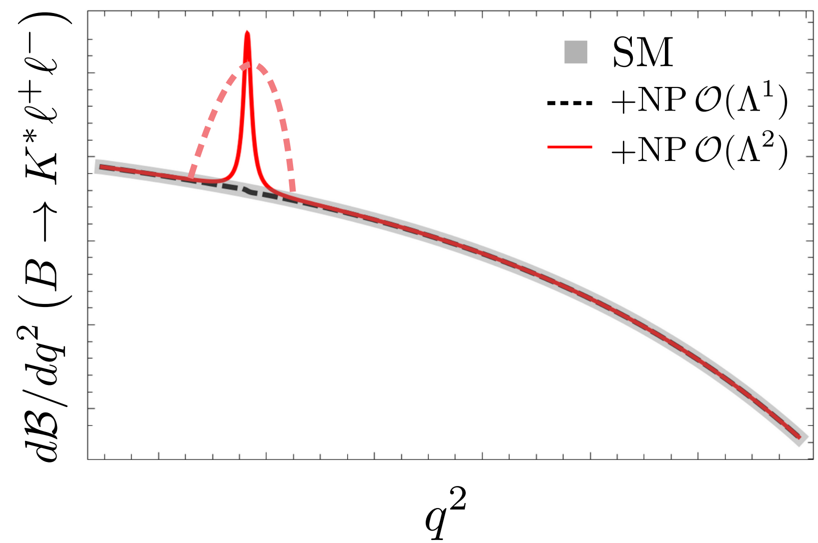
On-shell ALP exchange

Enhancement of semileptonic rates *on resonance*



$$\propto \frac{1}{G_F^2}\left|\frac{(\mathbf{c}_e-\mathbf{c}_L)_{ee}}{(q^2-m_a^2)+i m_a\Gamma_a}\right|^2$$

$$\approx \frac{1}{G_F^2}\frac{\pi\,(\mathbf{c}_e-\mathbf{c}_L)_{ee}^2}{m_a\Gamma_a}\delta(q^2-m_a^2)$$



while $\mathcal{B}(B_s\to\ell^+\ell^-)\sim \text{SM-like}\,.$

Large lepton flavour non-universal couplings are required

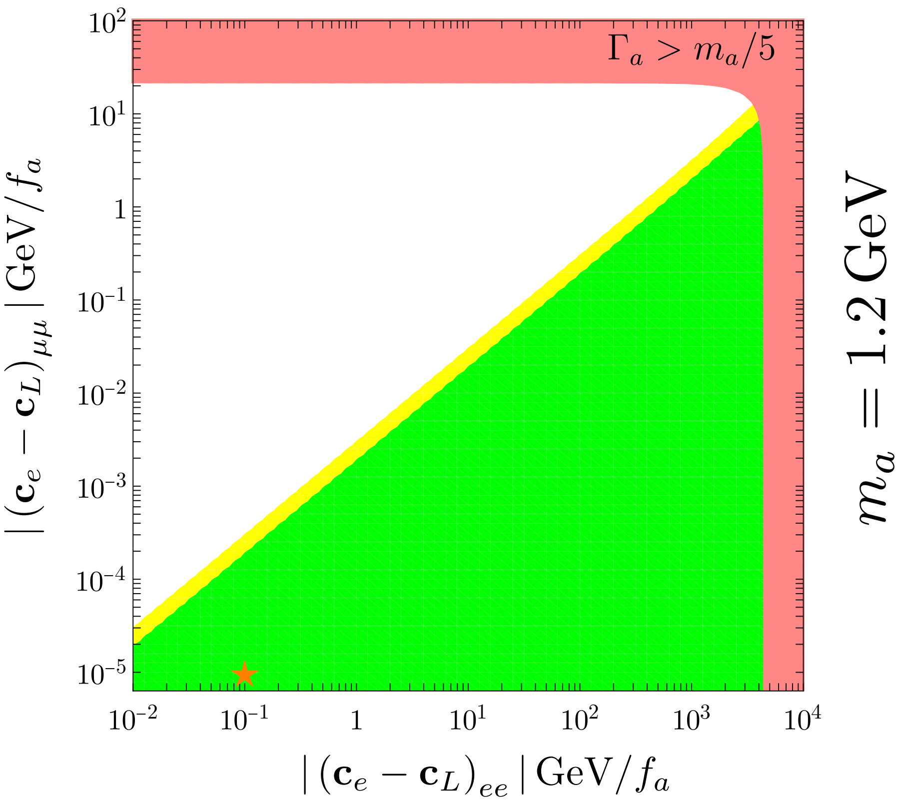
$$R_{K^{(*)}}\simeq 1+\frac{(B\to K^{(*)}a)}{(B\to K^{(*)}e^+e^-)^{\rm SM}}\frac{\left(m_\mu^2\left[(\mathbf{c}_e-\mathbf{c}_L)_{\mu\mu}\right]^2-m_e^2\left[(\mathbf{c}_e-\mathbf{c}_L)_{ee}\right]^2\right)}{\left(m_\mu^2\left[(\mathbf{c}_e-\mathbf{c}_L)_{\mu\mu}\right]^2+m_e^2\left[(\mathbf{c}_e-\mathbf{c}_L)_{ee}\right]^2\right)}\Rightarrow\frac{|(\mathbf{c}_e-\mathbf{c}_L)_{ee}|}{|(\mathbf{c}_e-\mathbf{c}_L)_{\mu\mu}|}\geq\frac{m_\mu}{m_e}$$

LFU ratios from an ALP on-shell

1. Benchmark choice $$\left\langle \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\left(B \to K^{(*)} e^+ e^-\right)\right\rangle_{1.1}^{6.0} \sim \mathcal{O}(10^{-8})\,\mathrm{GeV}^{-2}$$

LHCb 1903.09252
LHCb 1904.02440
LHCb 2108.09284
LHCb 2003.03999
LHCb 1612.07818
LHCb 1508.04094

2. Breit-Wigner validity



Solutions at 1σ (2σ)

independent of the specific value of couplings due to on-shell enhancement

LFU ratios from an ALP on-shell

1. Benchmark choice

$$\left\langle \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}\left(B \to K^{(*)}e^+e^-\right)\right\rangle_{1.1}^{6.0} \sim \mathcal{O}(10^{-8})\,\mathrm{GeV}^{-2}$$

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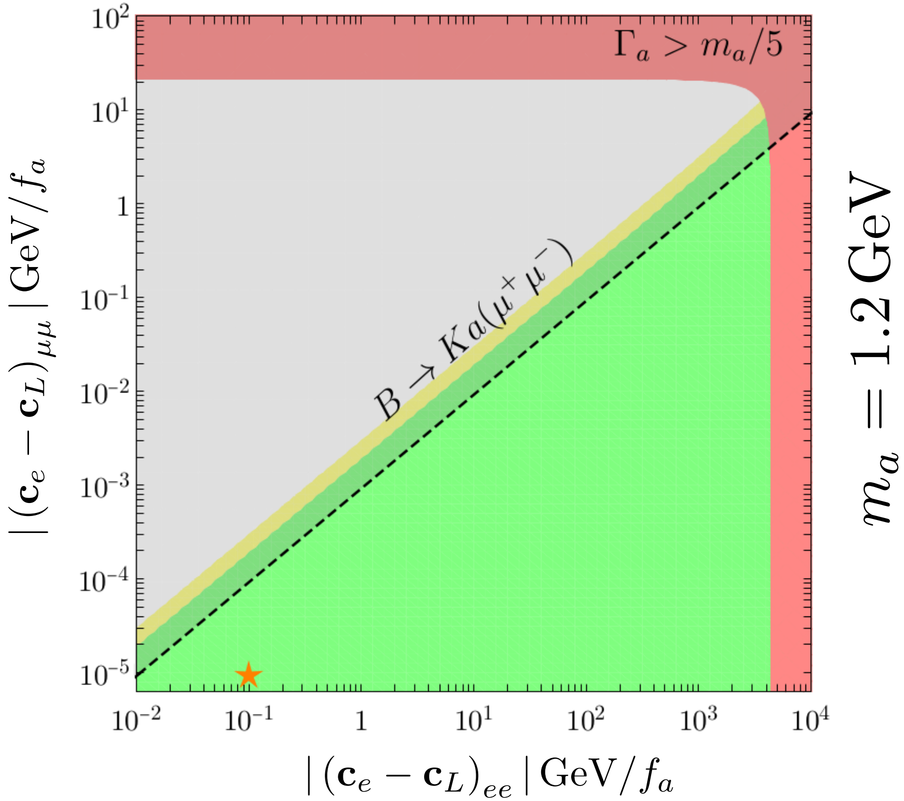
2. Breit-Wigner validity

3. Resonant searches



LFU ratios from an ALP on-shell

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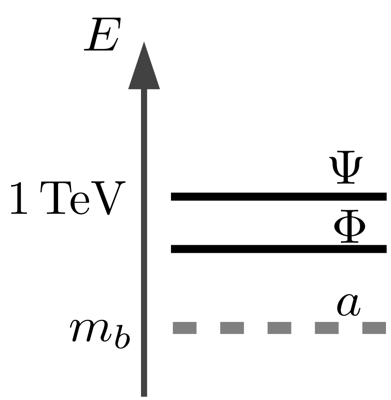
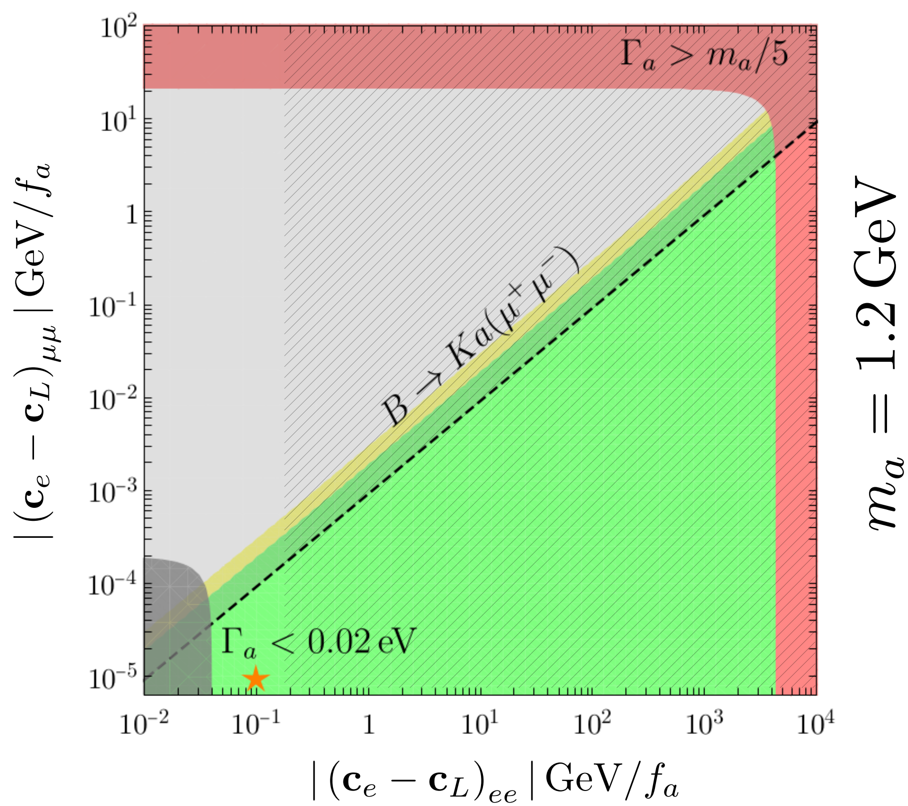
2. Breit-Wigner validity

3. Resonant searches

4. Prompt condition

& EFT validity bound





LFU ratios from an ALP on-shell

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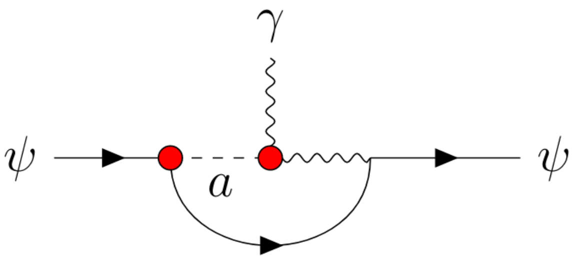
LHCb 1508.04094

2. Breit-Wigner validity

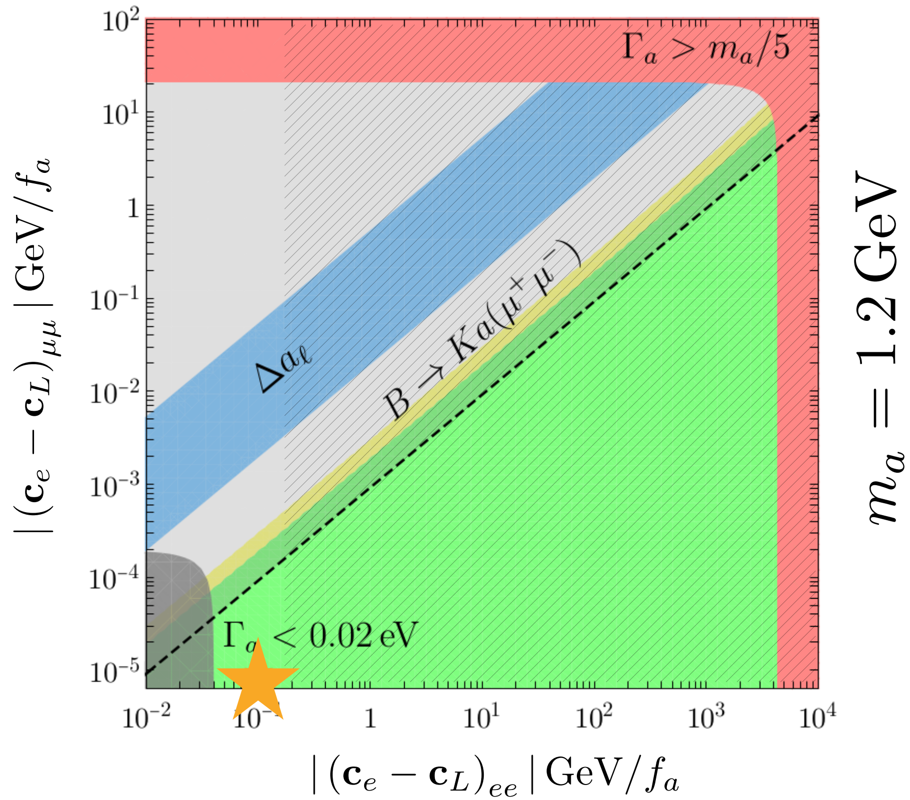
3. Resonant searches

4. Prompt condition

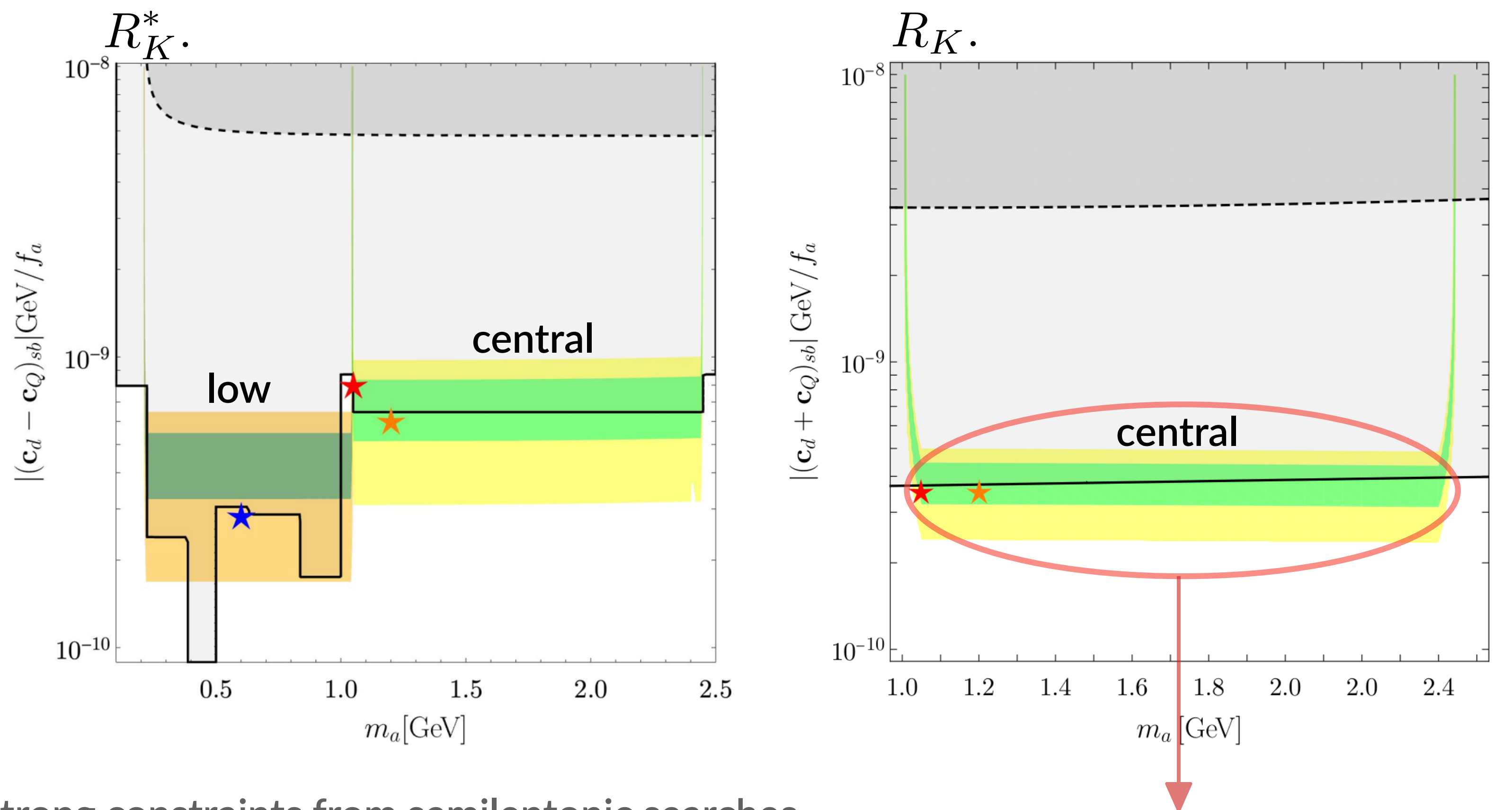
5. Magnetic moments



$$c_{a\gamma\gamma}^{\text{eff}} = c_{a\gamma\gamma}^{0} + \frac{\alpha}{4\pi}(\mathbf{c}_{ee} + \mathbf{c}_{\mu\mu})$$



LFU ratios from a light ALP



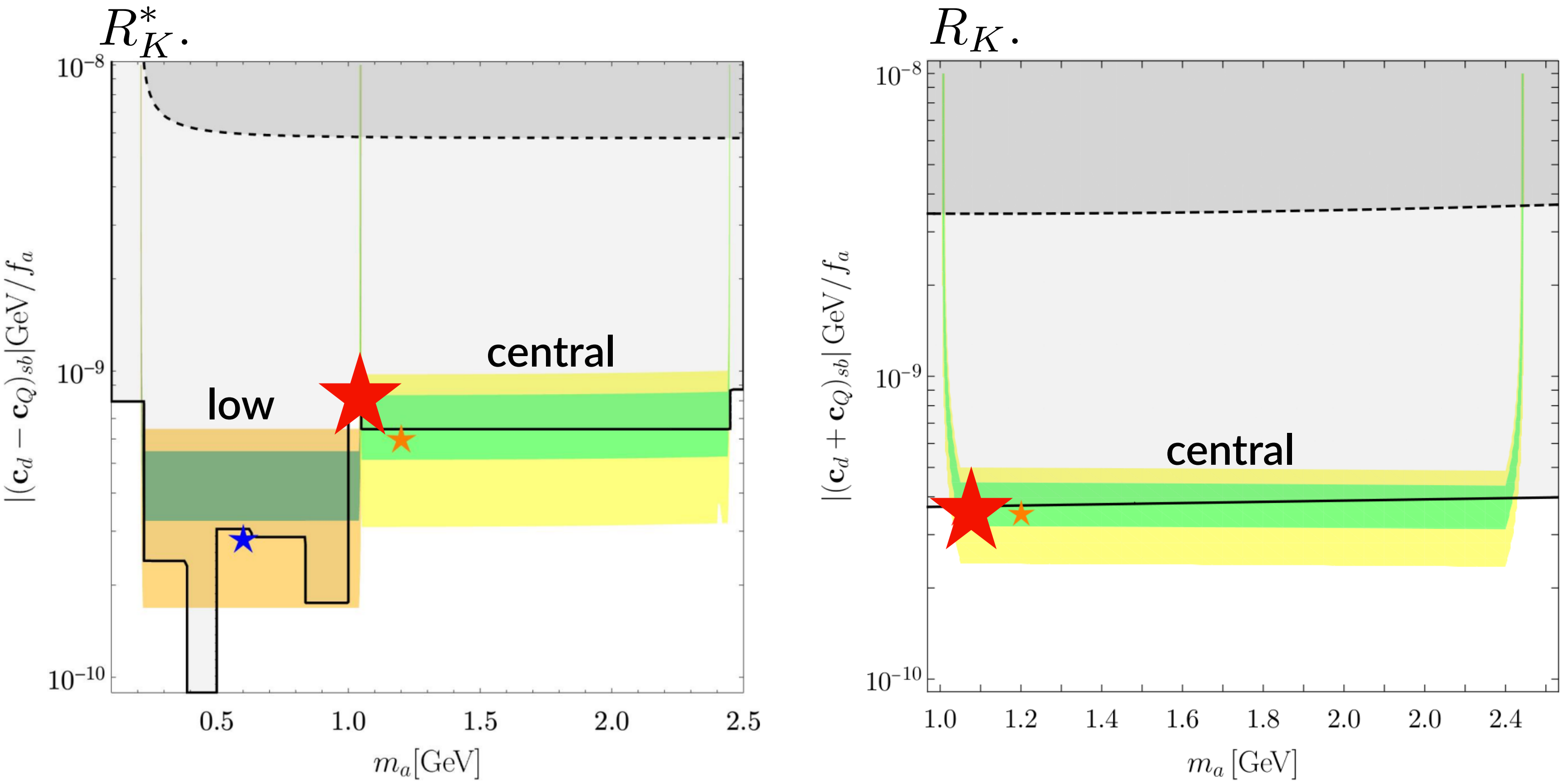
Strong constraints from semileptonic searches in electron (muon) channel

- Meson mixing bounds subleading
- Negligible corrections to *Bs* leptonic decay

Solutions to the *B*-anomalies

$$\mathcal{B}(a \to e^+e^-) \approx 100\%$$

LFU ratios from a light ALP



Three-bin threshold solutions?

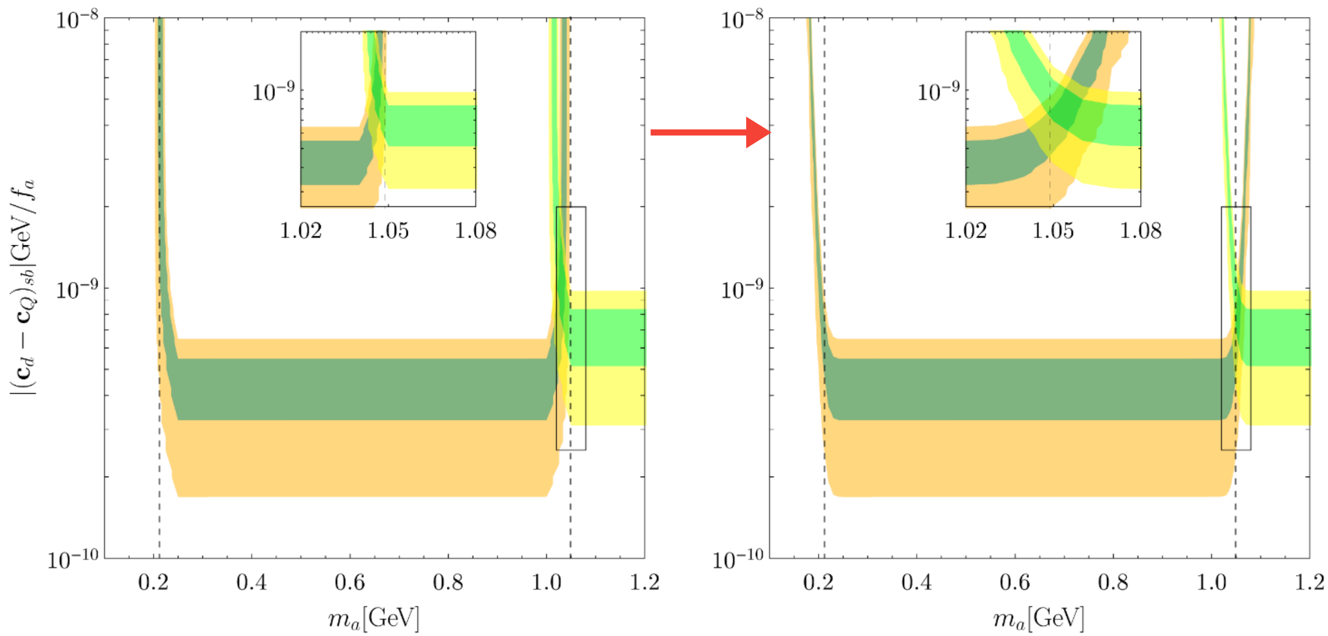
Golden ALP exchange

To parametrize the smearing effect:

Altmannshofer, Baker, Gori, Harnik, Pospelov, Stamou, Thamm (2017)

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

$$\mathcal{G}^{(r_\ell)}(q_{\text{min.}}, q_{\text{max.}}) = \frac{1}{\sqrt{2\pi}r_\ell} \int_{q_{\text{min}}}^{q_{\text{max}}} d|q| e^{-\frac{(|q|-m_a)^2}{2r_\ell^2}}, \text{ with } r_{e(\mu)} = 10\,(2)\,\text{MeV}$$

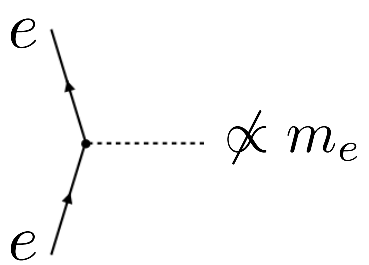


An ALP within [1.04, 1.07] GeV could explain the three q^2-bin anomalies

Preliminary study

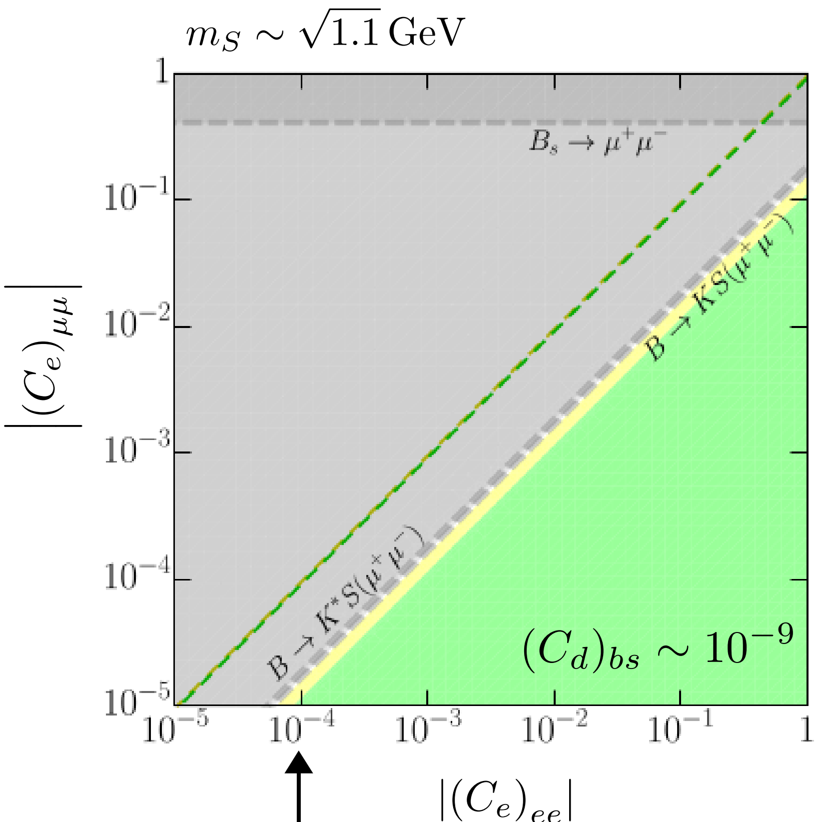
Allowing *shift-symmetry breaking* interactions in this framework

Jesús Bonilla, Arturo de Giorgi, MR



Generic (pseudo) scalar exchange

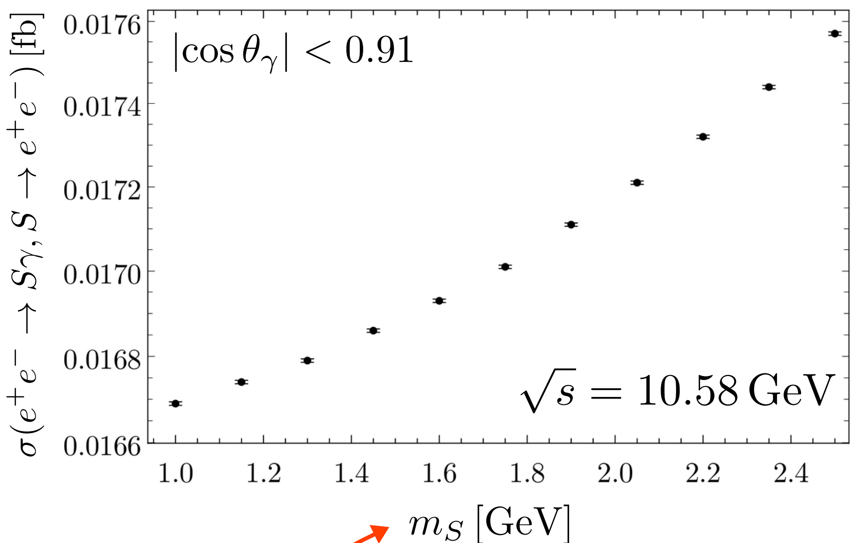
$$L_S^{\rm int} = \frac{S}{\Lambda}(\widehat{C}_\psi)_{\alpha\beta}\left(\overline{\Psi_L^\alpha}\Phi\Psi_R^\beta + \overline{\Psi_R^\beta}\Phi^\dagger\Psi_L^\alpha\right) \xrightarrow{\textbf{LEFT}} S(C_\psi)_{\alpha\beta}\left(\overline{\psi_L^\alpha}\psi_R^\beta + \overline{\psi_R^\beta}\psi_L^\alpha\right) + \dots$$



$\Lambda \gtrsim 1$ TeV : $(\widehat{C}_e)_{ee} \sim \mathcal{O}(10^{-3})$ vs. $\mathcal{O}(1)$ *for* **ALP**

Probing prompt decay:

$$(C_e)_{ee}^{\rm min.} = (\widehat{C}_e)_{ee}^{\rm min.}\frac{v}{\Lambda} \sim 10^{-5}$$



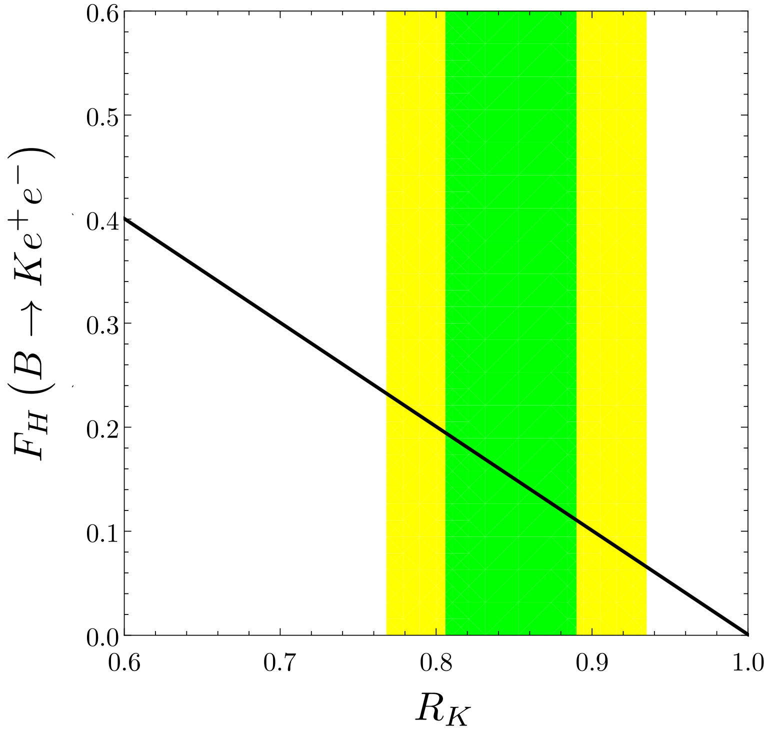
within the measured bin window

Impact on other observables

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}(B\to K\ell^+\ell^-) = \frac{3}{4}(1-F_H^\ell)\left(1-\cos^2\theta\right)+\frac{1}{2}F_H^\ell + A_{FB}^\ell\cos\theta$$

F_H^ℓ: $\propto m_\ell^2$ in SM; $\propto C_{S,P}^2$

A_{FB}^ℓ: null; $\propto C_{S,P}\times$ SM



On the other hand,

$$\frac{\mathrm{d}^4\Gamma(B\to K^*\ell^+\ell^-)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_{K^*}\,\mathrm{d}\phi} = \sum_i \frac{9}{32\pi} I_i^\ell(q^2,\theta_l,\theta_{K^*},\phi)$$

$\mathcal{B}(B_s\to e^+e^-),\ P_i^{\ell,\prime}$ SM-like

$$F_L,\ A_{FB}\sim\frac{C_{S,P}\times \mathrm{SM}}{\Gamma^*} = \mathcal{O}^{\mathrm{SM}}\left(\frac{R_{K^*}}{R_{K^*}^{\mathrm{SM}}}\right)$$

$$\langle M_2\rangle_{\mathrm{bin}} \equiv -\frac{\int_{\mathrm{bin}} dq^2\,(I_1^c+I_2^c)}{\int_{\mathrm{bin}} dq^2\, I_2^c}\sim\mathcal{O}(0.1)$$

null

Matias, Mescia, Ramon, Virto (2012)

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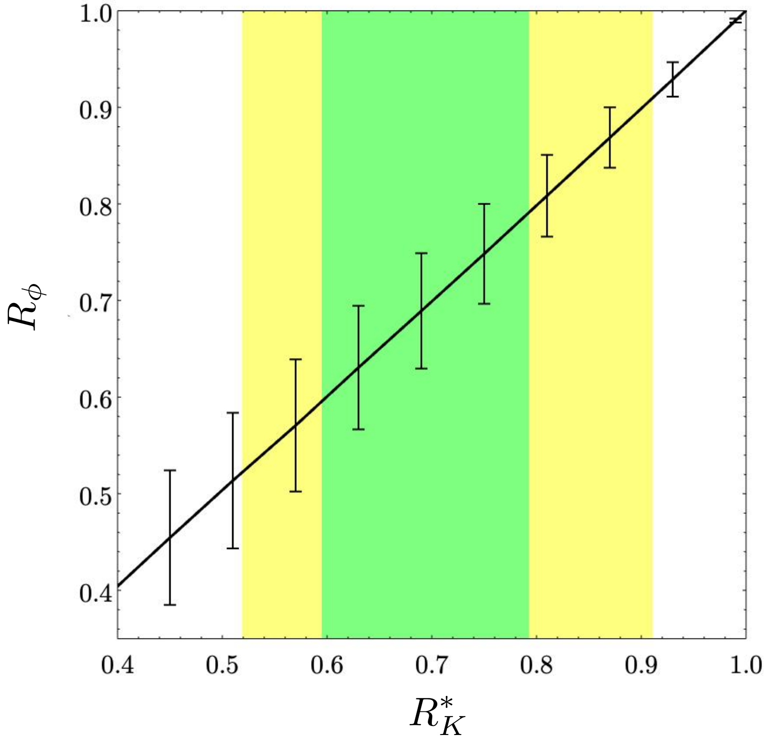

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$\mathcal{B}(B_s\to e^+e^-)$, $P_i^{\ell,\prime}$ SM-like

$$F_L,\ A_{FB}\sim\frac{C_{S,P}\times\mathrm{SM}}{\Gamma^*}=\mathcal{O}^{\mathrm{SM}}\left(\frac{R_{K^*}}{R_{K^*}^{\mathrm{SM}}}\right)$$

$$\langle M_2\rangle_{\mathrm{bin}} \equiv -\frac{\int_{\mathrm{bin}} dq^2\,(I_1^c+I_2^c)}{\int_{\mathrm{bin}} dq^2\, I_2^c} \sim \mathcal{O}(0.1)$$

$\langle M_2\rangle$: null

Matias, Mescia, Ramon, Virto (2012)

Summary

ALPs arise in well motivated theories and could be the first manifestation of a *new physics* sector. Their couplings are set by UV symmetries that can be indirectly constrained by flavour searches.

The neutral *B*-anomalies could be a sign of electrophilic ALPs that develop flavour violating couplings to quarks.

	$R_K\,[1.1, 6]$	$R_K^*\,[1.1, 6]$	$R_K^*\,[0.045, 1.1]$
$m_a^2 \in [1.08,\ 1.15]\,\mathrm{GeV}^2$	✓	✓	✓
$m_a^2 \in [1.1,\ 6.0]\,\mathrm{GeV}^2$	✓	✓	

Models where some explicit breaking propagates to the fermion couplings can accommodate a larger parameter space.

These solutions leave a rich pattern in other *b→see* observables *if measured in the q^2-bins where the resonance is localized*. The three-bin solution can be straightforwardly tested with a different binning.

ift

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Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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Thank you for your attention!

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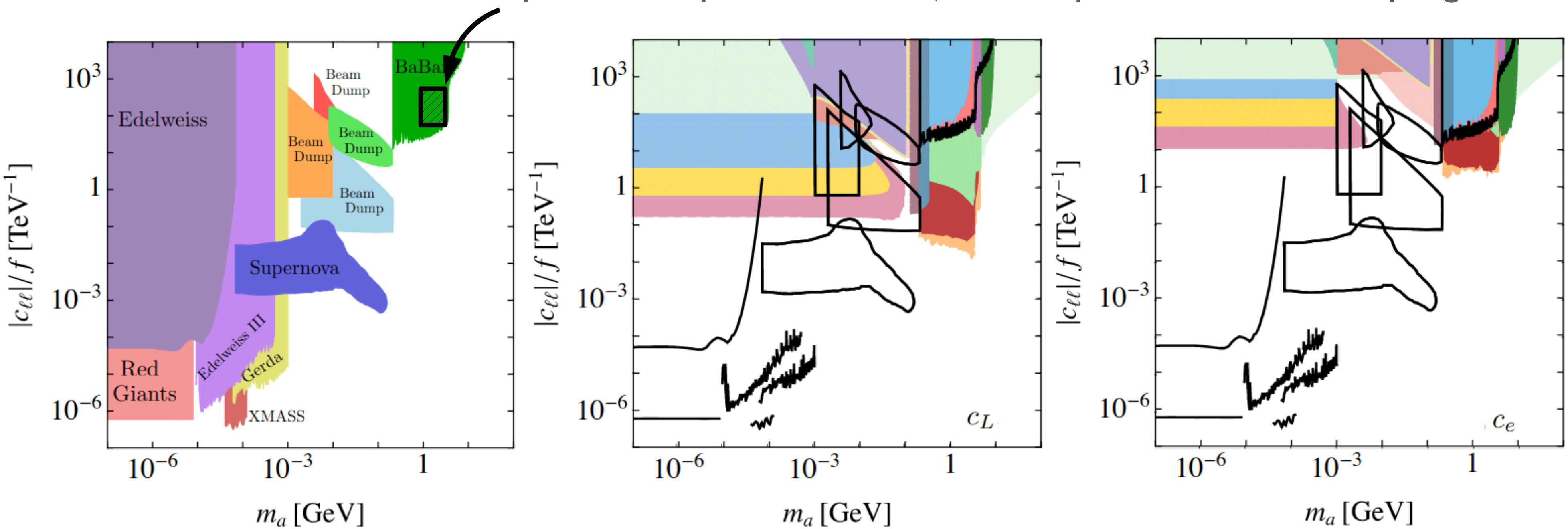
Backup

(Universal) lepton-ALP coupling constraints

The ALP parameter space of interest, with only sizable *electron* coupling



constraints in the left panel are: searches by the Edelweiss and Edelweiss III collaborations (dark and light purple respectively) [192, 193] for ALPs produced in the Sun; observations of red giants (red) [170]; searches by the neutrinoless double-beta decay experiment GERDA [194]; searches by dark matter direct detection experiment XMASS (red-brown) [195]; beam dump searches at KEK, SLAC and Fermilab in orange [196], lighter blue, light green [197] and red [186, 198]; SN1987A supernova bounds (dark blue) [199] and a dark photon search at BaBar (green) [200]. Note that the light green beam dump constraint assumes the presence of ALP-muon and ALP-electron couplings while the BaBar bound applies only to ALP-muon couplings. All other constraints have been derived for the ALP-electron coupling. The ALP-tau coupling still remains unconstrained.

Bauer, Neubertb, Renner, Schnubelb, Thamm (2021)

Backup

Flavour constraints 2209.11247

Observable	q^2 [GeV^2]	Values	Heavy	On Bin	Light
$\mathrm{d}\mathcal{B}/\mathrm{d}q^2(B^+ \to K^+e^+e^-)$	(1.1, 6)	$(28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}$ [12]	✓	✓	✓
$\mathcal{B}(B^+ \to K^+e^+e^-)$		$(14.01^{+0.98}_{-0.83} \pm 0.69) \times 10^{-8}$			
$\mathrm{d}\mathcal{B}/\mathrm{d}q^2(B^+ \to K^+\mu^+\mu^-)$	(1.1, 6)	$(24.2 \pm 0.7 \pm 1.2) \times 10^{-9}$ [89]	✓		✓
$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$		$(11.86 \pm 0.34 \pm 0.59) \times 10^{-8}$			
$\mathcal{B}(B^+ \to K^+a(\mu^+\mu^-))$	(0.06, 22.1)	$< 1 \times 10^{-9}$ [90]		✓	
$\mathcal{B}(B^0 \to K^{0*}e^+e^-)$	$(1.1, 6)$	$(1.8 \pm 0.6) \times 10^{-7}$ [91]	✓	✓	✓
	$(0.1, 8)$	$(3.7 \pm 1.0) \times 10^{-7}$ [91]		✓	
$\mathcal{B}(B^0 \to K^{0*}a(e^+e^-))$	$(0.0004, 0.05)$	$< 1.344 \times 10^{-7}$		✓	✓
	$(0.05, 0.15)$	$< 1.22 \times 10^{-8}$		✓	
	$(0.25, 0.4)$	$< 1.97 \times 10^{-8}$		✓	
	$(0.4, 0.7)$	$< 1.74 \times 10^{-8}$		✓	
	$(0.7, 1)$	$< 6.5 \times 10^{-9}$		✓	
$\mathcal{B}(B^0 \to K^{0*}\mu^+\mu^-)$	$(1.1, 6)$	$1.9^{+0.7}_{-0.6} \times 10^{-7}$ [91]	✓		✓
$\mathcal{B}(B^0 \to K^{0*}a(\mu^+\mu^-))$	$(0.05, 18.9)$	$< 3 \times 10^{-9}$ [92]		✓	

Backup

On-shell NP predictions

Preliminary

$m_{S^{(\prime)}}$ [GeV]	$\mathcal{B}(B \to K e^+ e^-)$ $[10^{-7}]$	$\mathcal{B}(B \to K^* e^+ e^-)$ $[10^{-7}]$	$F_L(B \to K^* e^+ e^-)[10^{-1}]$	$A_{FB}(B \to K^* e^+ e^-)[10^{-2}]$
1.5	$[1.8 \pm 0.3,\ 2.2 \pm 0.4]$	$[2.6 \pm 0.4, 4.5 \pm 0.6]$	$[4.0 \pm 0.2, 6.9 \pm 0.4]$	$[0.5 \pm 1.6, 0.9 \pm 2.7]$
0.6	SM-*like*	$[1.4 \pm 0.2, 2.4 \pm 0.4]$	$[1.7 \pm 0.3, 2.9 \pm 0.5]$	$[-8.9 \pm 0.7, -5.1 \pm 0.4]$

Interval of values that comply with explanations to the LFU anomalies within 2σ.

$$\langle \mathcal{B}^{\rm SM}(B \to K e^+ e^-) \rangle_{1.1}^{6.0} = (1.71 \pm 0.29)10^{-7}$$
$$\langle \mathcal{B}^{\rm SM}(B \to K^* e^+ e^-) \rangle_{1.1}^{6.0} = (2.34 \pm 0.34)10^{-7}$$
$$\langle \mathcal{B}^{\rm SM}(B \to K^* e^+ e^-) \rangle_{0.045}^{1.1} = (1.29 \pm 0.20)10^{-7}$$
$$F_L^{\rm SM}(B \to K^* e^+ e^-)_{1.1}^{6.0} = 0.76 \pm 0.04$$
$$A_{FB}^{\rm SM}(B \to K^* e^+ e^-)_{1.1}^{6.0} = 0.01 \pm 0.03$$
$$F_H^{\rm SM}(B \to K^* e^+ e^-)_{0.045}^{1.1} = 0.31 \pm 0.05$$
$$A_{FB}^{\rm SM}(B \to K^* e^+ e^-)_{0.045}^{1.1} = -0.094 \pm 0.007$$