On the $^{\text{cost of an}}$ ALP solution to the *neutral* *B*-anomalies

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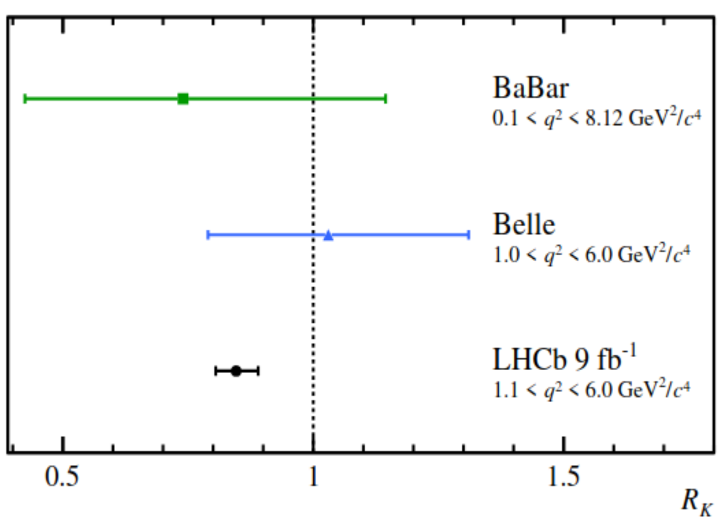
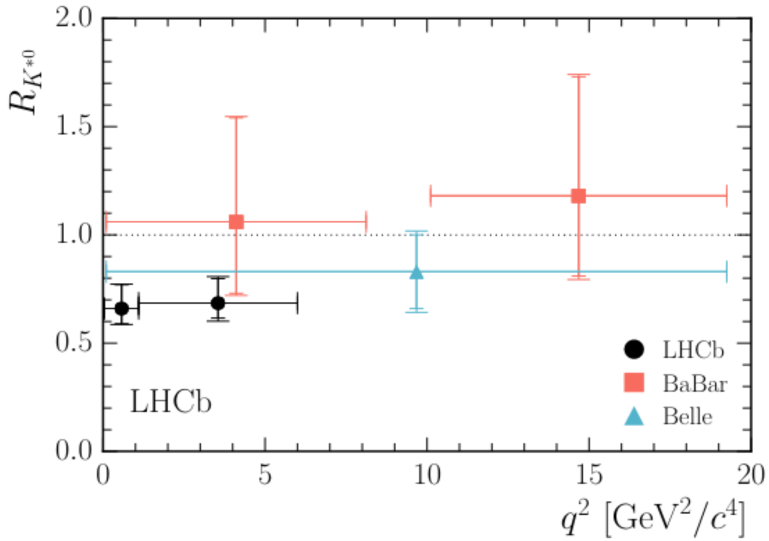
This project has received funding /support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN.

Introduction

LFU is an intrinsic property of the **SM**. Hence, tests of LFU are an ideal place to search for **new physics**:

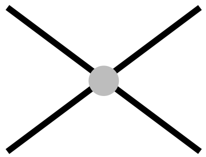
$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} \boldsymbol{= 1}$$





Combined tension >4σ!

Which new physics?



$$|\mathcal{M}|^2 \propto C_9 C_9^{\rm NP} \quad C_9^{\rm NP} \sim \lambda_{sb}\lambda_{\ell\ell}\frac{v^2}{M^2}$$

BSM non-generic

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.846^{+0.042}_{-0.039}\,^{+0.013}_{-0.012} \quad \text{for } 1.1\ \text{GeV}^2 \le q^2 \le 6.0\ \text{GeV}^2$$

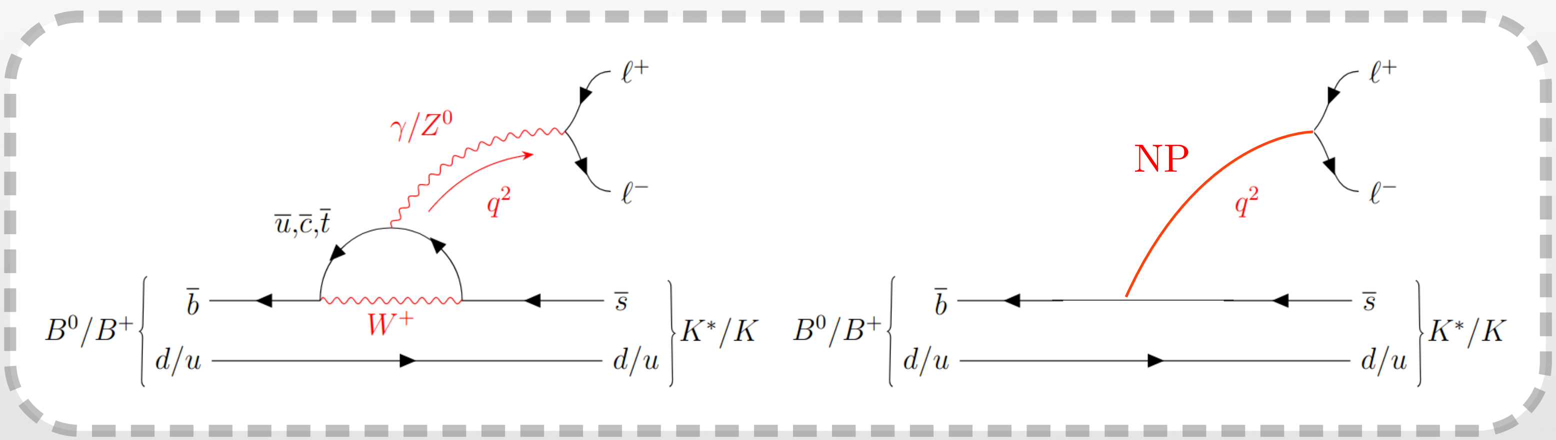
✓

$$R_{K^*} \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)} = \begin{cases} 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1\text{GeV}^2 \le q^2 \le 6.0\ \text{GeV}^2 \\ 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045\ \text{GeV}^2 \le q^2 \le 1.1\ \text{GeV}^2 \end{cases}$$

✓

hard

Kumar, London (2019)



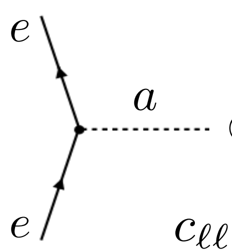
Altmannshofer, Baker, Gori, Harnik, Pospelov, Stamou, Thamm (2017); Sala, Straub (2017); Datta, Kumar, Marfatia (2018)

The ALP as the flavour source

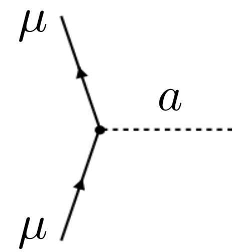
ALPs are one of the most common and promising BSM candidates. Being **naturally flavour-violating**, can they accommodate the B-anomalies?

$$\mathcal{L}_a = \frac{\partial_\mu a}{f_a}\left[\bar{Q}'_L\gamma_\mu c'_Q Q'_L + \bar{u}'_R\gamma_\mu c'_u u'_R + \bar{d}'_R\gamma_\mu c'_d d'_R + \bar{L}'_L\gamma_\mu c'_L L'_L + \bar{e}'_R\gamma_\mu c'_e e'_R\right]$$

$$\xrightarrow{\textbf{LEFT}} -\frac{\mathrm{i}a}{2f_a}\sum_{i,j}\Big((m_{\mathrm{f}_i}-m_{\mathrm{f}_j})(c_\mathrm{f}+c_\mathrm{F})_{ij}\,\bar{\mathrm{f}}^i\,\mathrm{f}^j + (m_{\mathrm{f}_i}+m_{\mathrm{f}_j})(c_\mathrm{f}-c_\mathrm{F})_{ij}\,\bar{\mathrm{f}}^i\gamma_5\mathrm{f}^j\Big)$$

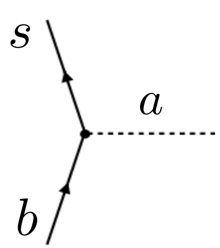


$\propto c_{ee}m_e \quad \lll$



$\propto c_{\mu\mu}m_\mu$

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



R_K	R_{K^*}	$B_s \to \ell^+\ell^-$	$B \to K^{(*)}\ell^+\ell^-$	ΔM_s
$+$	$-$	$-$	$+(-)$	*mixed*

The ALP as the flavour source

ALPs are one of the most common and promising BSM candidates. Being **naturally flavour-violating**, can they accommodate the B-anomalies?

aim: **check the parameter space of potential explanations and then assess their viability**

$$\left(\frac{c_{ee}}{f_a}, \frac{c_{\mu\mu}}{f_a}, \frac{c_{sb}}{f_a}, m_a\right) \; @$$

① **Heavy ALP** (off-shell of the bin): $m_b < m_a < v$

② **Light ALP** (on-shell on the bin): $2m_\mu \lesssim m_a \lesssim m_b$

①

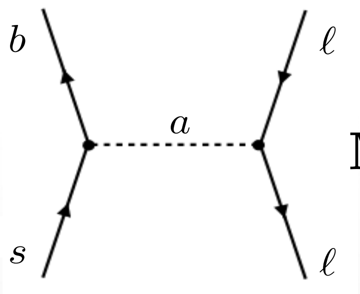
③ **Lighter ALP** (off-shell of the bin): $m_a \lesssim 2m_\mu$

beyond Bauer, Neubert, Renner, Schnubel, Thamm, 2021

Heavy ALP

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' + C_P \mathcal{O}_P + C_P' \mathcal{O}_P' \right)$$

$$\mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2} \left(\bar{s} P_{R(L)} b \right) \left(\bar{\ell} \gamma_5 \ell \right)$$



Matching to the ALP Lagrangian,

$$C_\pm \equiv \frac{C_P \pm C_P'}{2} \propto \frac{1}{\alpha G_F V_{tb} V_{ts}^*} \frac{m_\ell}{(f_a m_a)^2} c_{\ell\ell} (m_b \mp m_s)(c_Q \pm c_d)_{sb}$$

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

Bobeth, Hiller, Piranishvlli, 2021

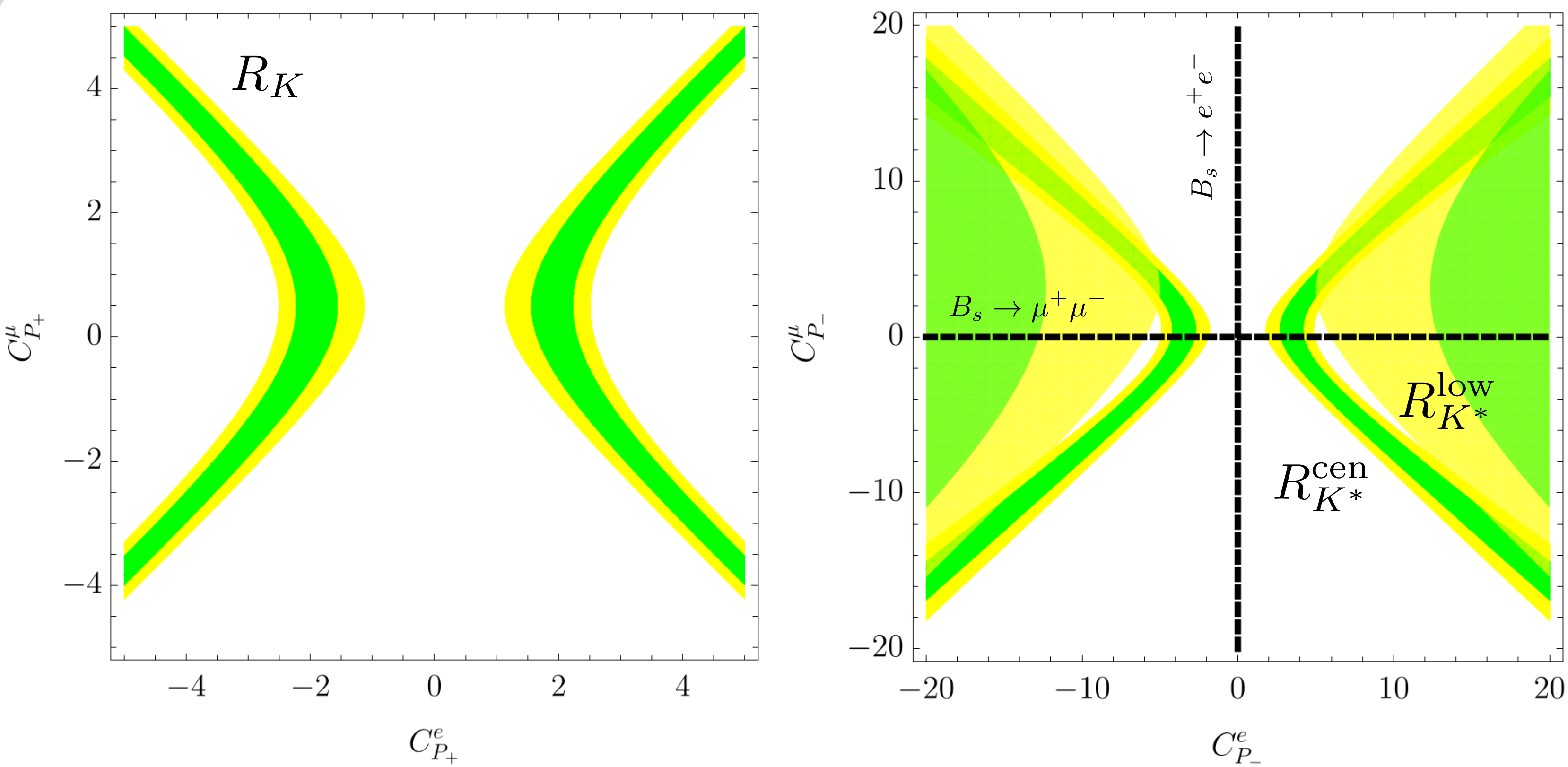
SM

$$\mathcal{B}(B^\pm \to K^\pm \bar{l} l) = \left[\frac{\tau_B^\pm}{1.64\text{ps}} \right] \left[1.91 + 0.02 (C_S^{l2} + C_P^{l2}) + 0.06 (C_T^{l2} + C_{T5}^{l2}) + \frac{m_l}{\text{GeV}} \left(\frac{C_T^l}{0.99} - \frac{C_P^l}{2.92} \right) \right.$$
$$\left. + \frac{m_l^2}{\text{GeV}^2} \left(\frac{C_T^{l2}}{3.28^2} - \frac{C_{T5}^{l2}}{3.28^2} - \frac{C_P^{l2}}{10.36^2} - \frac{C_S^{l2}}{5.98^2} \right) + \mathcal{O}(m_l^3) \right] \times 10^{-7}$$

BSM requires $C_P^l \gtrsim \mathcal{O}(1)$

LFU ratios from a heavy pseudoscalar

1D analysis: Ghosh (2017)

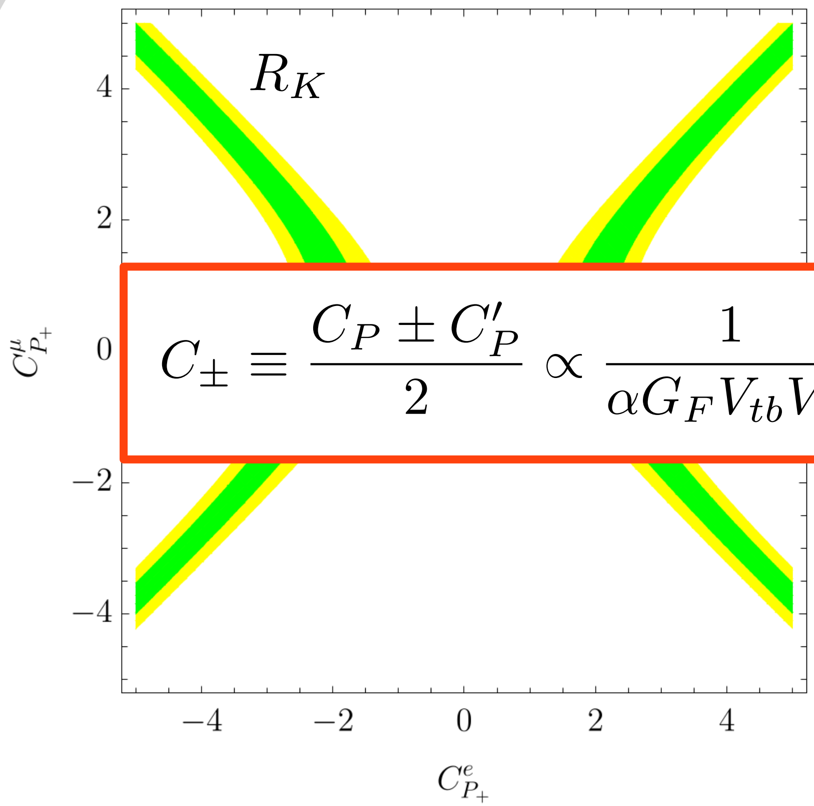


Requires NP in electron sector **Excluded by other data**

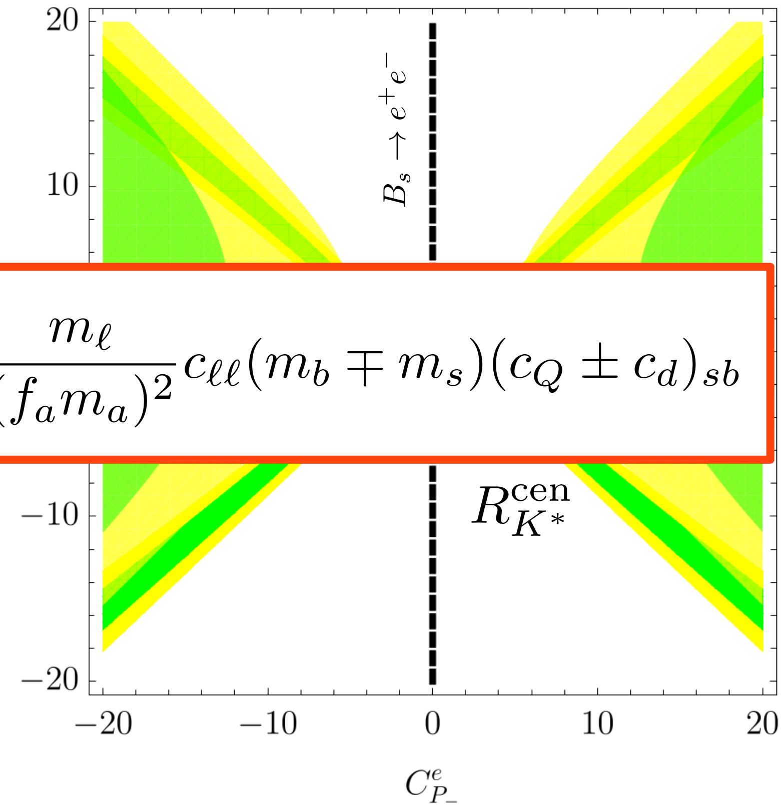
LFU ratios from a heavy pseudoscalar

1D analysis: Ghosh (2017)

$$C_\pm \equiv \frac{C_P \pm C'_P}{2} \propto \frac{1}{\alpha G_F V_{tb} V^*_{ts}} \frac{m_\ell}{(f_a m_a)^2} c_{\ell\ell}(m_b \mp m_s)(c_Q \pm c_d)_{sb}$$

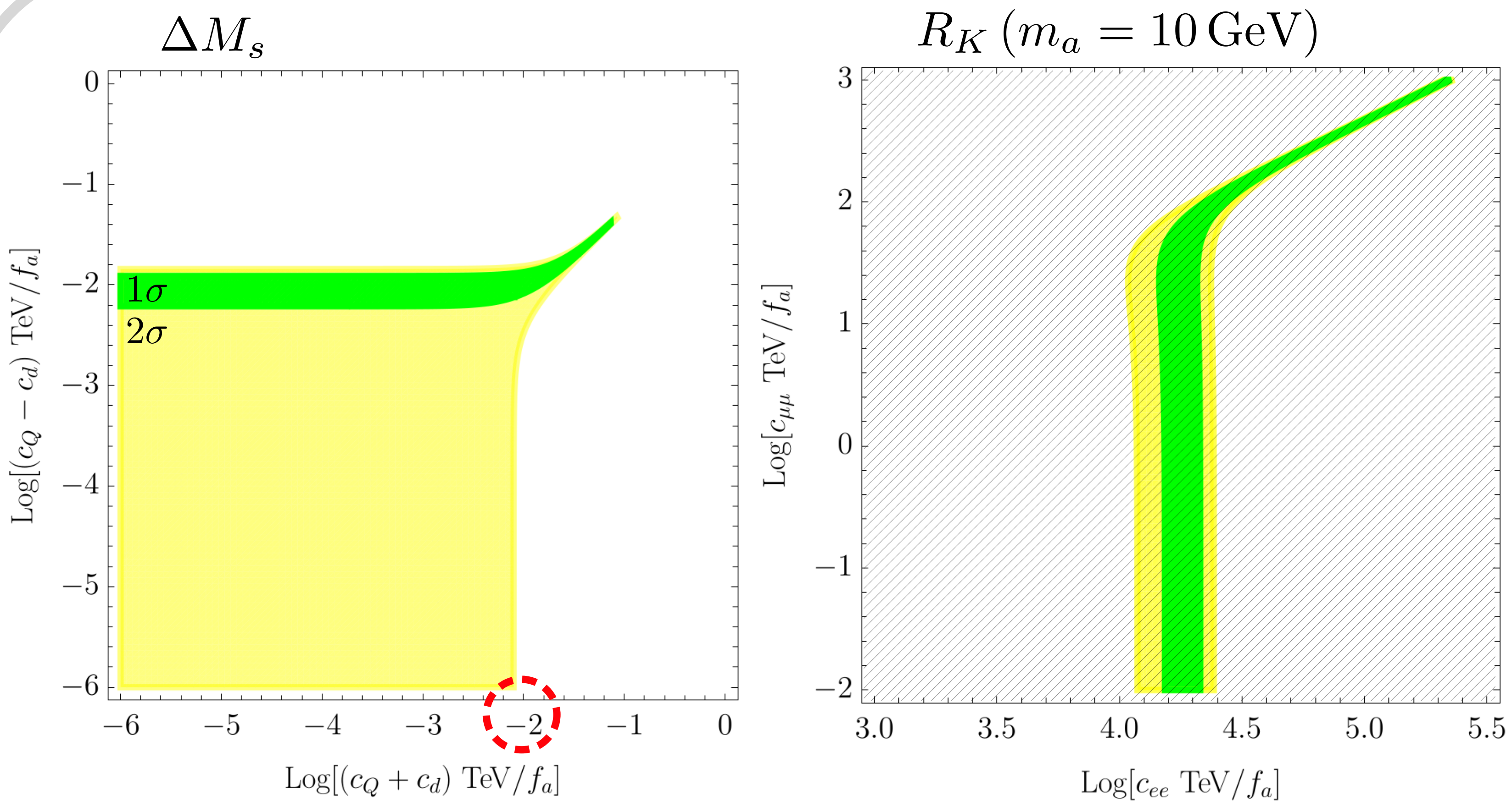


Requires NP in electron sector



Excluded by other data

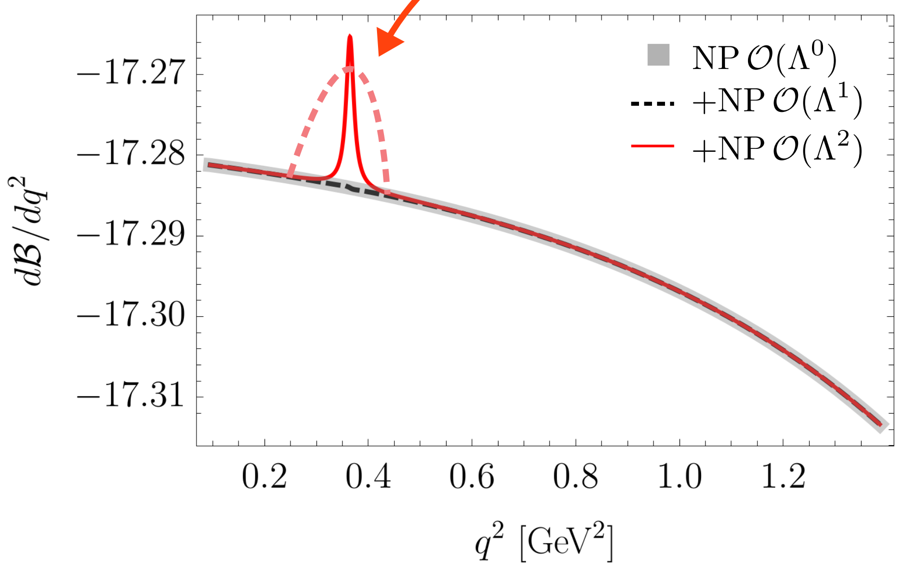
LFU ratios from a heavy ALP



Keeping the max. quark coupling still requires a too large c_{ee}

Light ALP

Enhancement on-shell



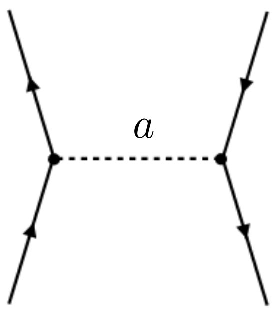
- **Fully on bin:**

$$\mathcal{B}(a \to e^+e^-) \gg \mathcal{B}(a \to \mu^+\mu^-)$$

- **Partially on bin:**

Broader resonance due to **experimental effects**. Possible kinematic enhancement.

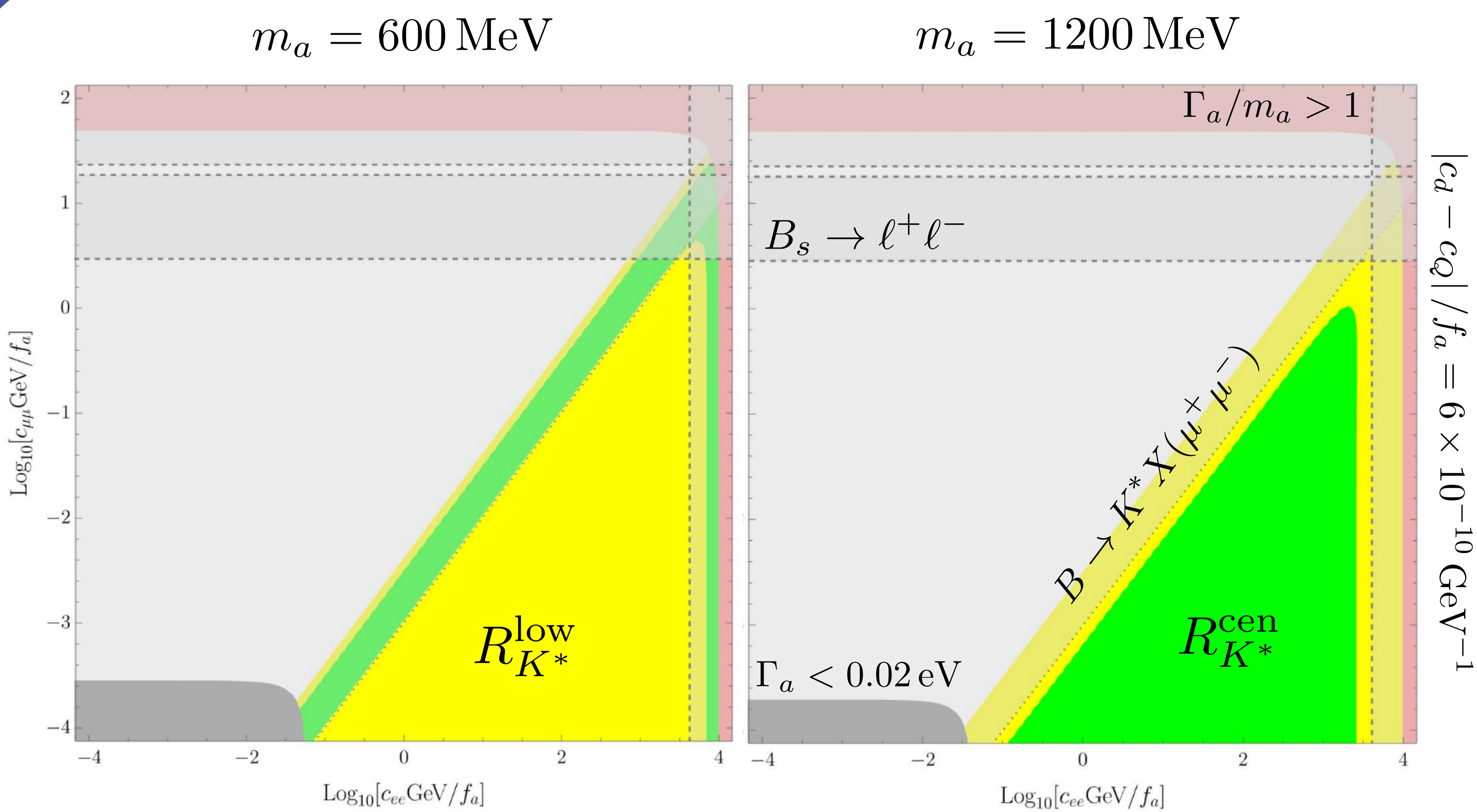
$$C_P^{(\prime)}(m_a,\, q^2): \qquad \frac{1}{q^2 - m_a^2 + \mathrm{i}\Gamma_a m_a} =$$



Full analytical computation cross-checked with EOS

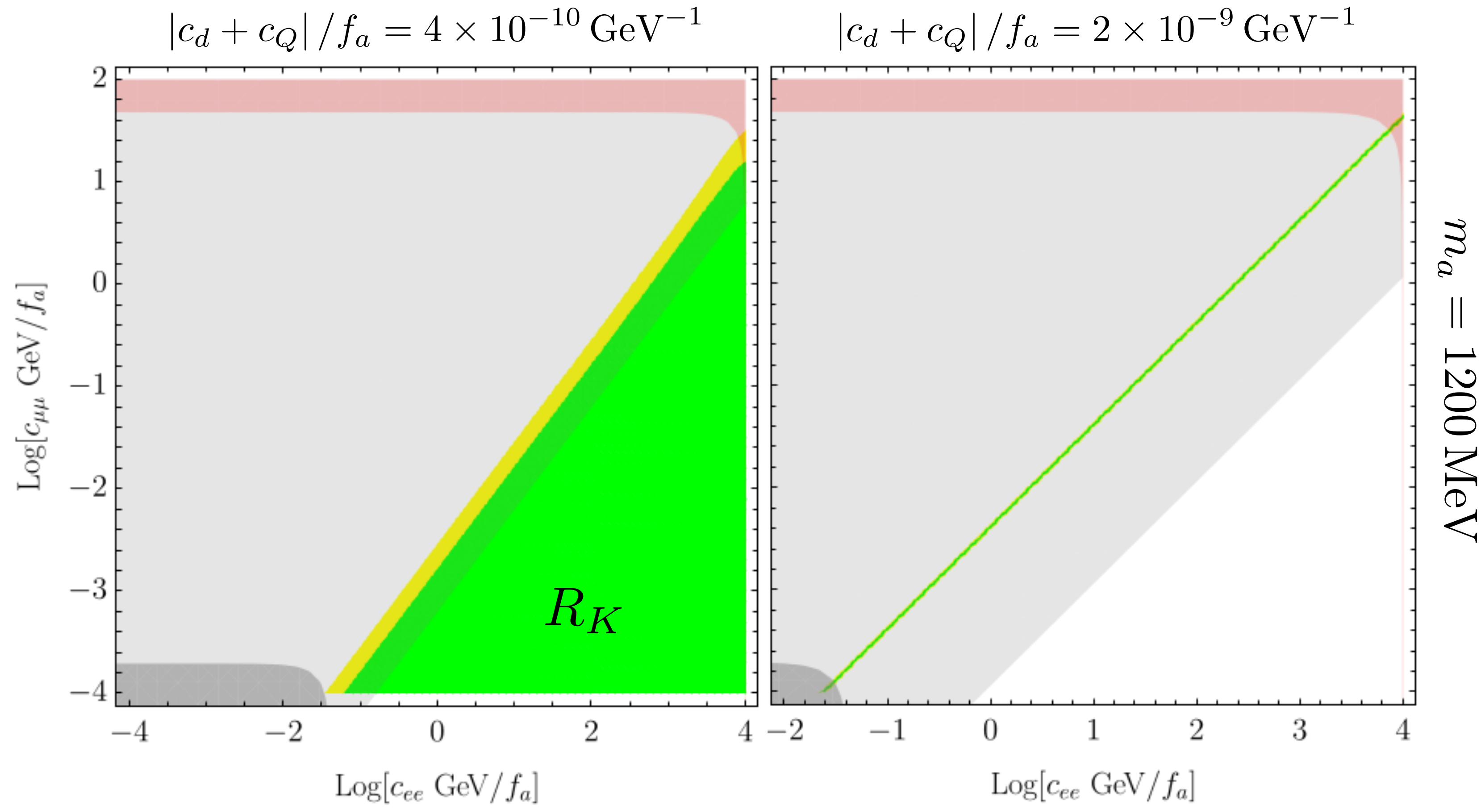
LFU ratios from a light ALP

LHCb 2003.03999
LHCb 1703.05747
LHCb 1508.04094



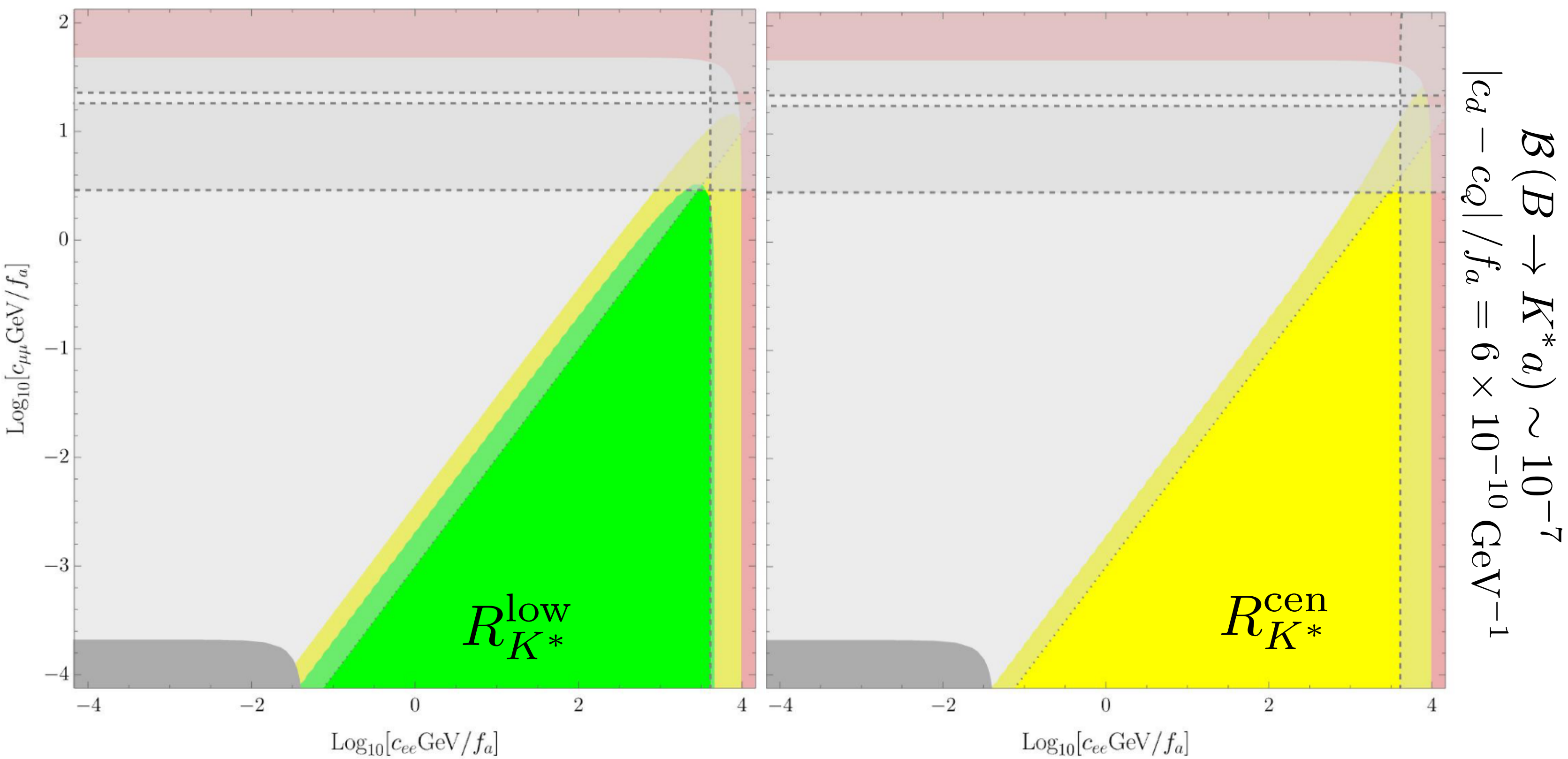
LFU ratios from a light ALP

LHCb 1612.07818



LFU ratios from an ALP at the threshold

$m_a \approx 1049\,\mathrm{MeV}$



Potential explanation to both q^2 bins

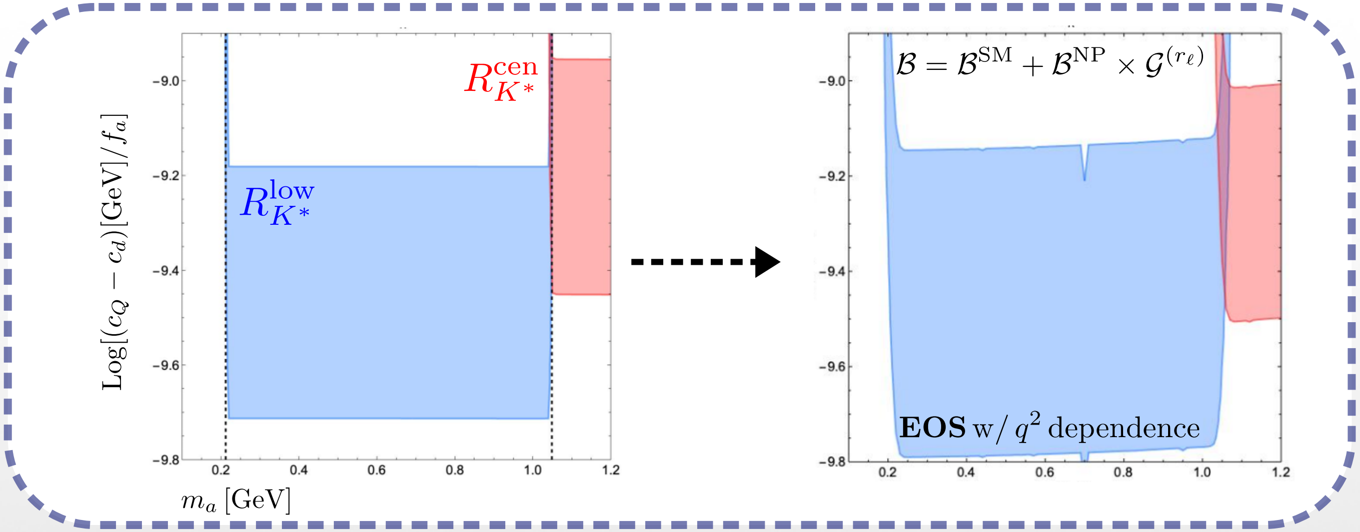
The smearing effect

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

We must account for imperfect di-lepton resolution:

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

e.g. $(c_{ee}/f_a,\, c_{\mu\mu}/f_a) = (10^{-1},\, 10^{-5})\ \text{GeV}^{-1}$

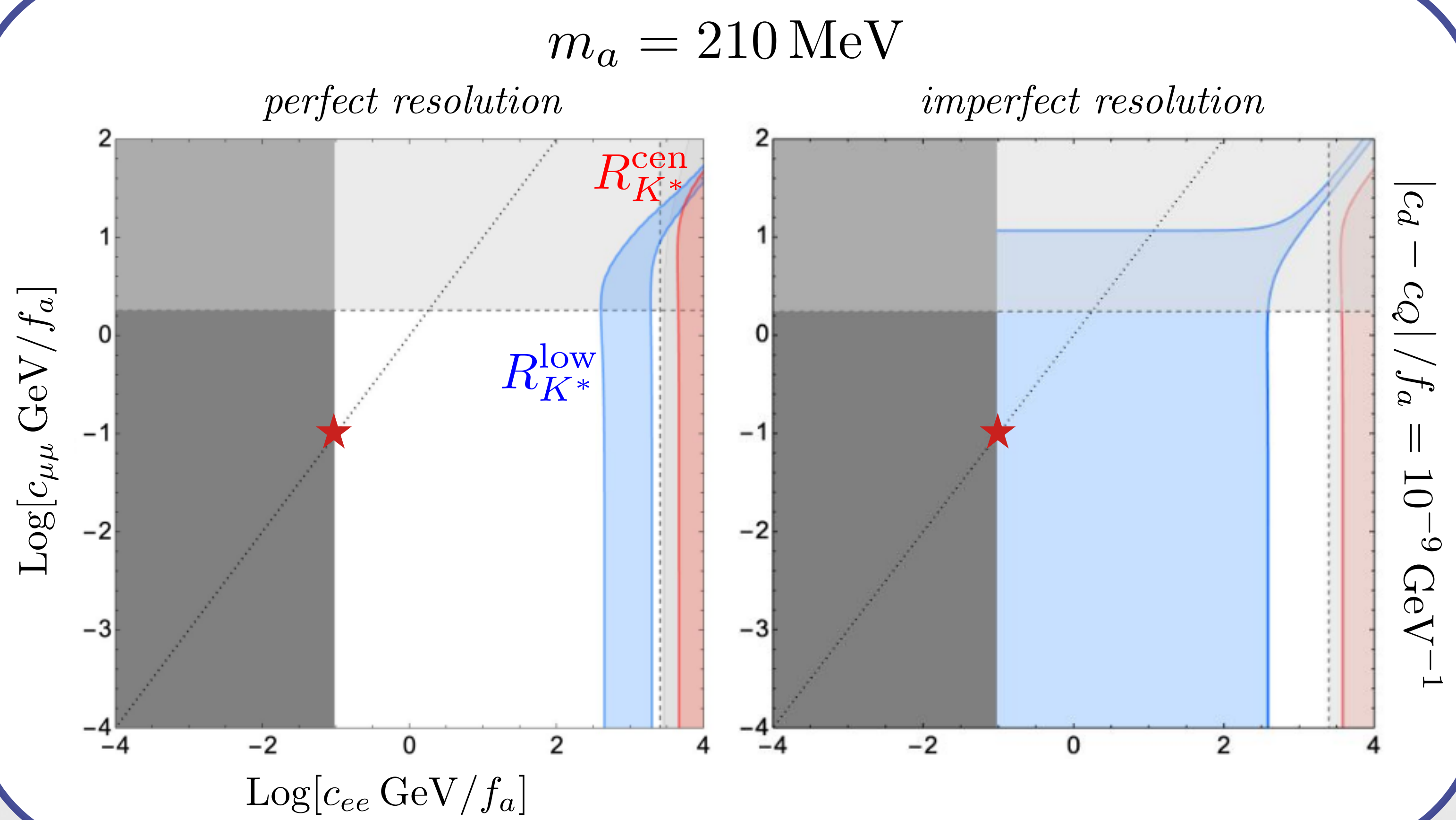


- **Extension of the golden ALP solution to:** $\pm 10\,\text{MeV}$
- **Accommodation of the LB anomaly with:** $m_a < 2m_\mu$

leading to $\mathcal{B}(a \to e^+e^-) \gg \mathcal{B}(a \to \mu^+\mu^-)$ without $c_{ee} \gg 1\,\text{GeV}^{-1}$

Recasting the flavour universal scenario★

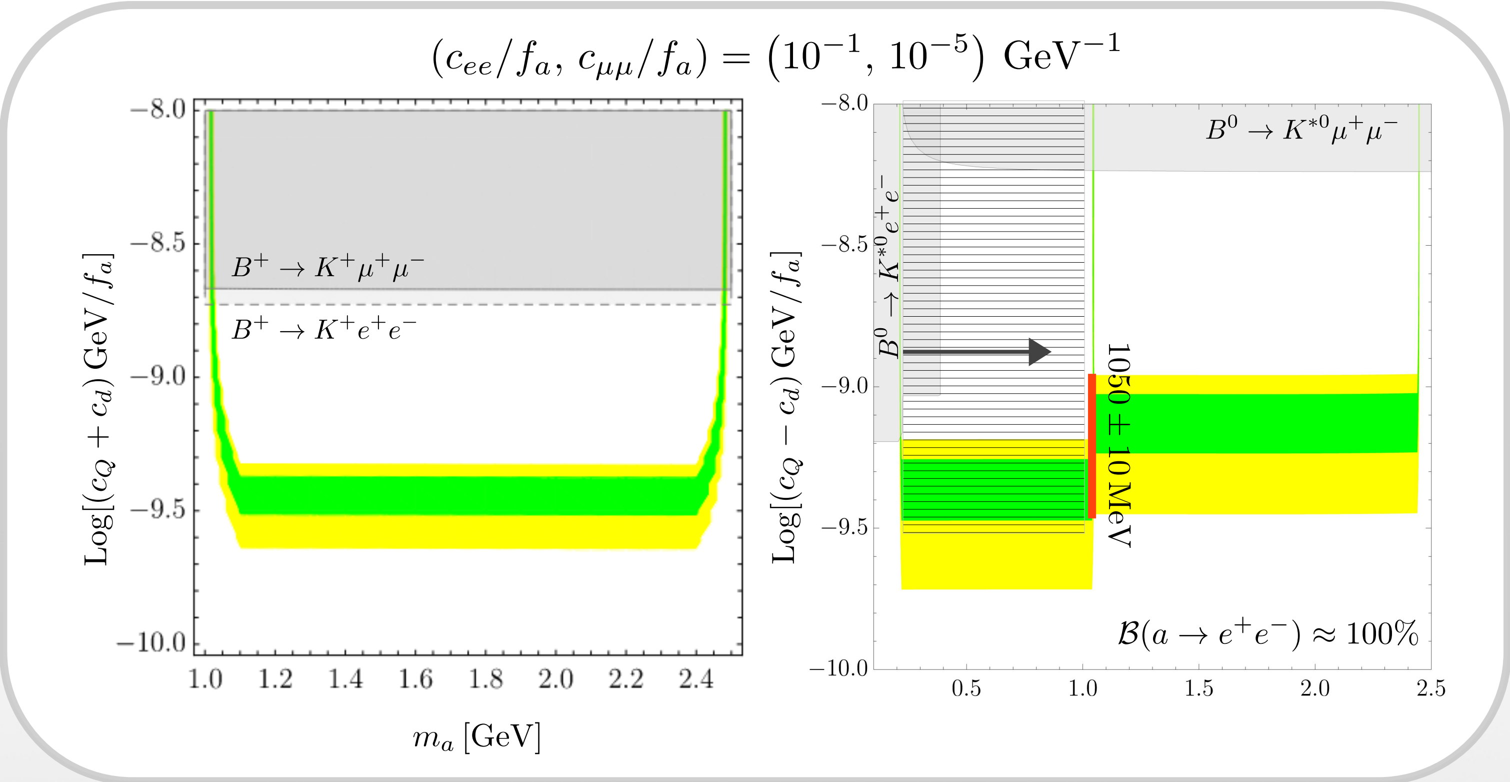
Bauer, Neubert, Renner, Schnubel, Thamm (2021)



To probe the universal scenario, need to resolve electrons as well as the muons.

Gathering the ALP parameter space

LHCb 1612.07818
LHCb 1508.04094
LHCb 1501.03038
LHCb 1304.3035 (less constraining in the low bin)

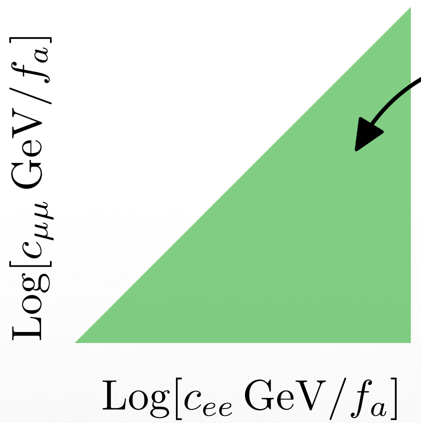


ALP solutions to each anomaly are possible across masses, as well as a combined explanation to the central bins (plus the low bin). The cost is big:

$$\frac{c_{ee}}{c_{Q,d}} \sim 10^8 \gg \frac{c_{ee}}{c_{\mu\mu}} \sim 10^4$$

Additional constraints

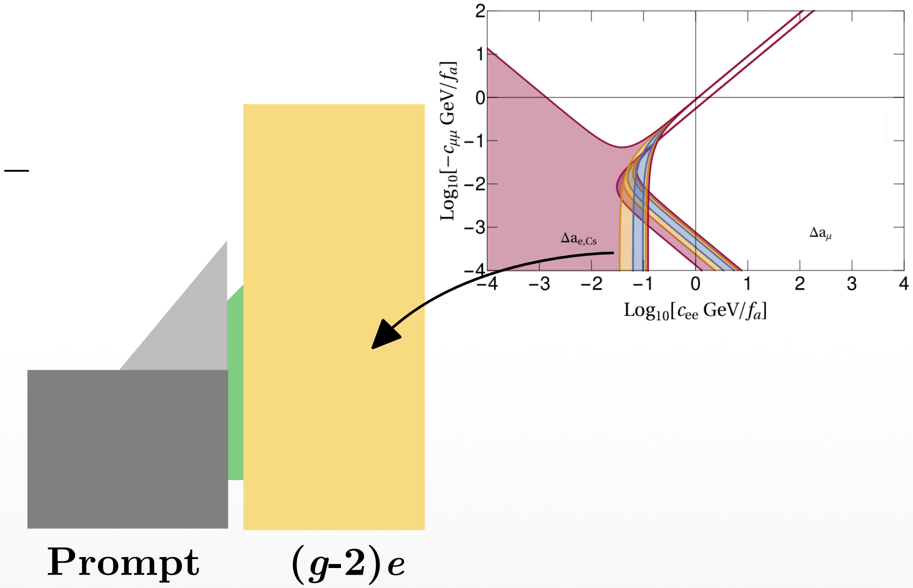
$m_a \sim 1\,\mathrm{GeV}$



$\approx 100\%$ decay to e^+e^-

Astrophysical bounds ✓

Collider bounds ✓



Shrink the parameter space to a line:
where the full (tree level) ALP solution is contained

$$\frac{c_{ee}}{f_a} \lesssim 0.1\,\mathrm{GeV}^{-1}$$

$$c_{ee} \sim \mathcal{O}(1) \to \Lambda = 4\pi f_a \sim \mathcal{O}(100)\,\mathrm{GeV}$$

Requires new light d.o.f.

More complete models specifying the origin of the lepton couplings have to be considered, exactly as found in ALP explanations for the $(g\text{-}2)\mu$.

Buen-Abad, Fan, Reece, Sun (2021)

ALPs are one of the most common and promising BSM candidates. Being **naturally flavour-violating**, can they accommodate the B-anomalies?

Conclusions

There are potential solutions in the on-shell case. However, the defining properties of an ALP *(1)* spin-0 and *(2)* derivative interactions push us to the **electrophilic regime with large axion-lepton couplings**. Therefore, new light states should be present which are strongly constrained and should be considered together with the ALP.

On the other hand, we find more parameter space for a generic resonance explanation across masses, that could be tested with:

- An improvement of the electron resolution at LHCb
- A smaller binning and no overlap between $q^{\text{low}}_{\text{max}}$, $q^{\text{cen}}_{\text{min}}$
- Larger constraining power from $(g\text{-}2)e$ data

Thank you for your attention!

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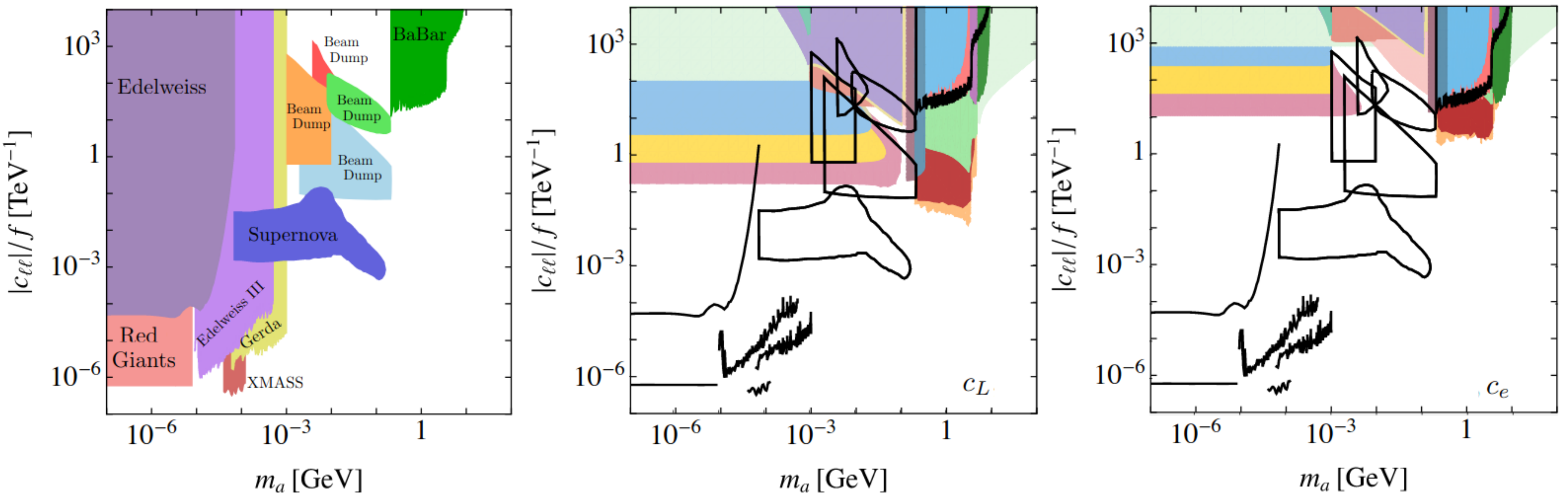
Backup

Bauer, Neubert, Renner, Schnubel, Thamm (2021)

(Universal) ALP coupling to leptons



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.

Backup

Bauer, Neubert, Renner, Schnubel, Thamm (2021)

Universal ALP solution

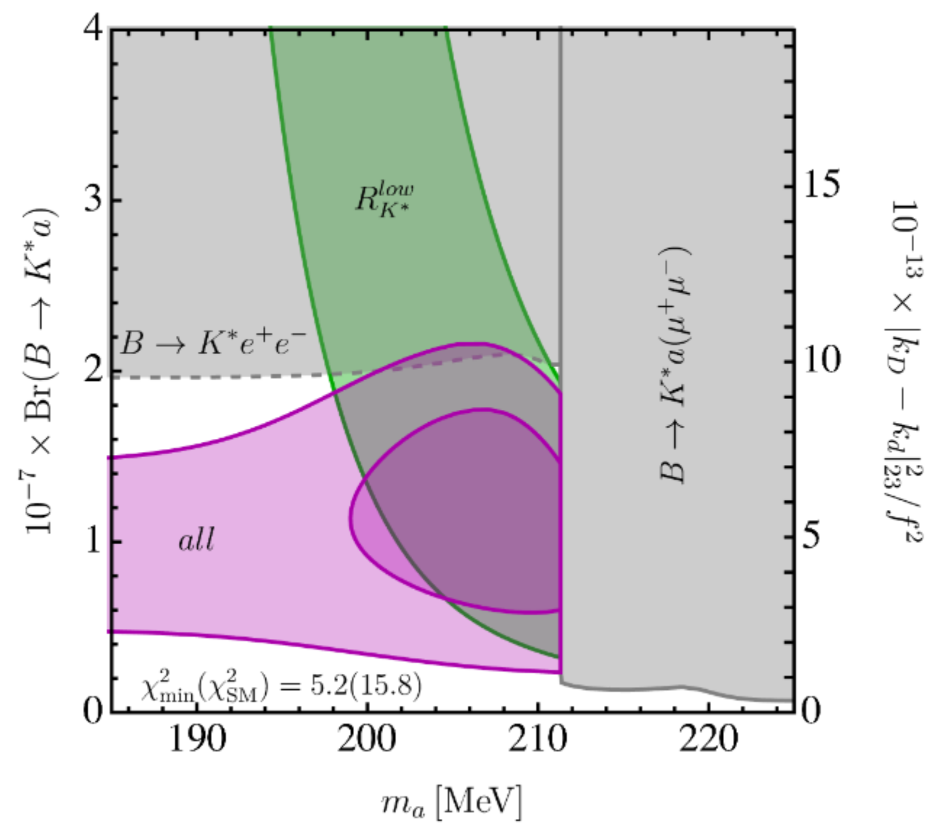
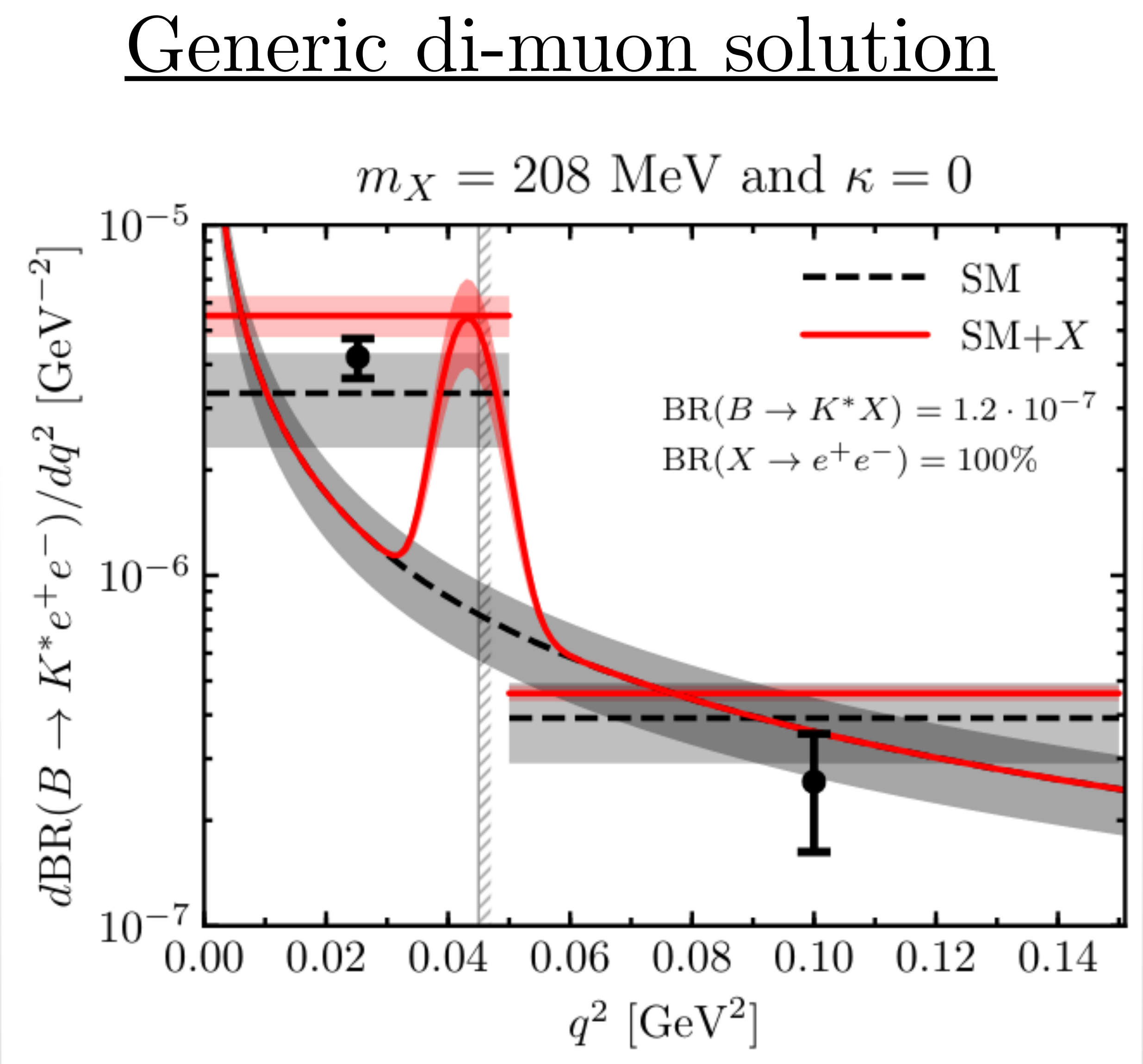


Figure 29: The parameter space where a light ALP resonance with flavor universal couplings $c_{ee}/f = c_{\mu\mu}/f = c_{\tau\tau}/f$ can explain the low-q^2 bin of the R_{K^*} measurement at 68.27% CL (green). The bounds from $B \to K^* e^+ e^-$ [159] (dashed) and from searches for peaks in the di-muon mass spectrum [201] (solid) are shown at 95% CL in grey. The preferred regions of $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ corresponding to 68.27% CL and 95.45% CL are shown in light and dark purple, respectively.

Backup

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



Backup

Off-shell ALP contribution

$m_a = 2.5$ GeV