Tackling ALP searches in meson decays with ALPaca

A phenomenological approach

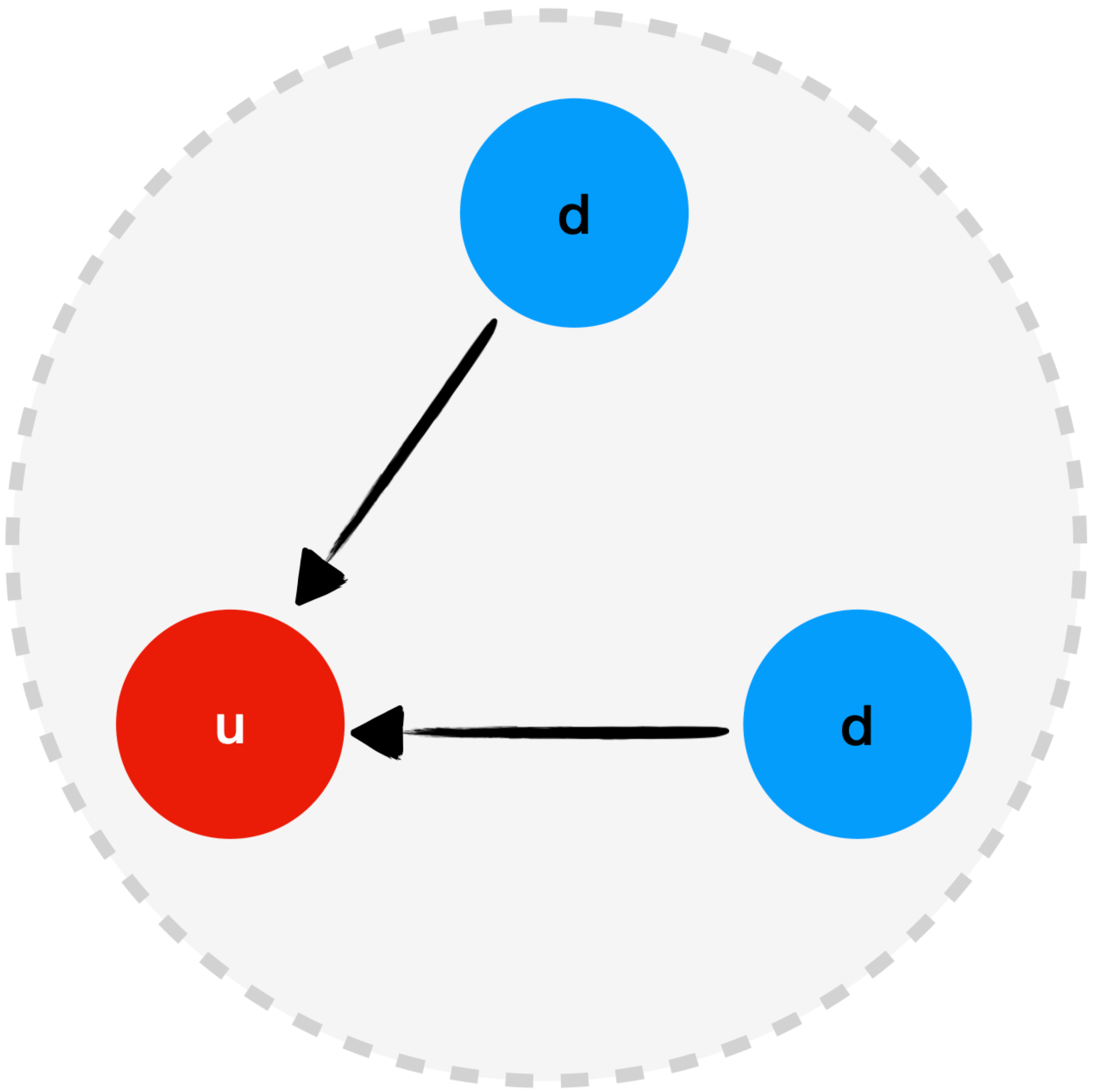
Marta Fuentes Zamoro

Based on 2507.XXXXX, in collaboration with Jorge Alda, Luca Merlo, Xavier Ponce Díaz and Stefano Rigolin

Strong CP problem and ALPs

$$\mathcal{L}_{QCD} \supset \theta_{QCD} \frac{g_S^2}{16\pi^2} \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$

Neutron electric dipole moment



$$d_n \simeq 10^{-16}\bar{\theta}\,\mathrm{e}\cdot\mathrm{cm}$$

$$\bar{\theta} = \theta_{QCD} + \arg(\det(M))$$

$$d_n \lesssim \mathcal{O}(10^{-26})$$

$$\bar{\theta} \lesssim \mathcal{O}(10^{-10})$$

[C. Abel et al., Phys. Rev. Lett., vol. 124, no.8, p. 081803, 2020]

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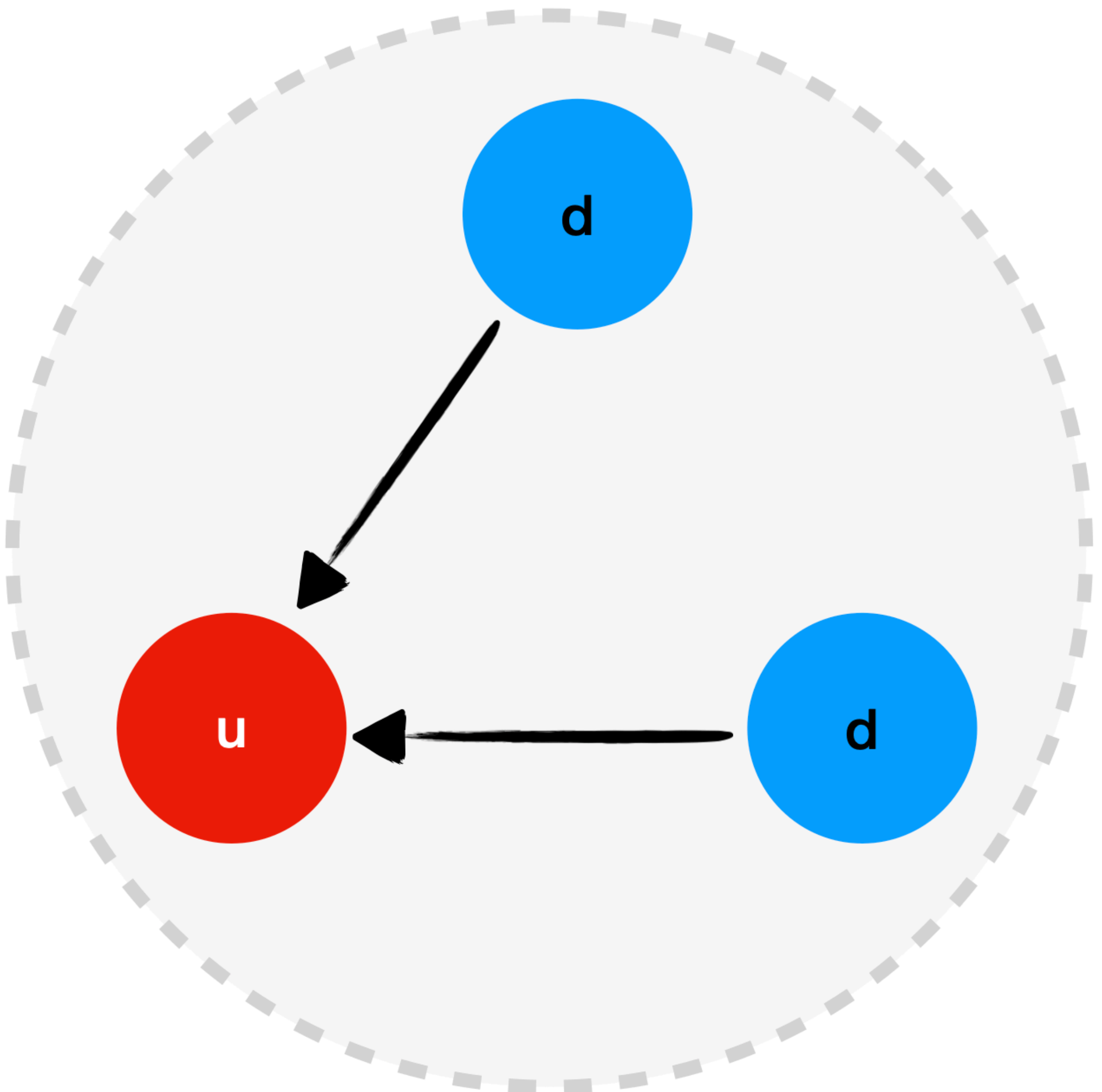

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Solution

$\mathscr{U}(1)_{PQ}$

SSB

Axion

[R. D. Peccei, H. R. Quinn, Phys. Rev. Lett., vol. 38, pp. 1440-1443, 1977]

[R. D. Peccei, H. R. Quinn, Phys. Rev. D, vol.16, pp. 1791-1797, 1977]

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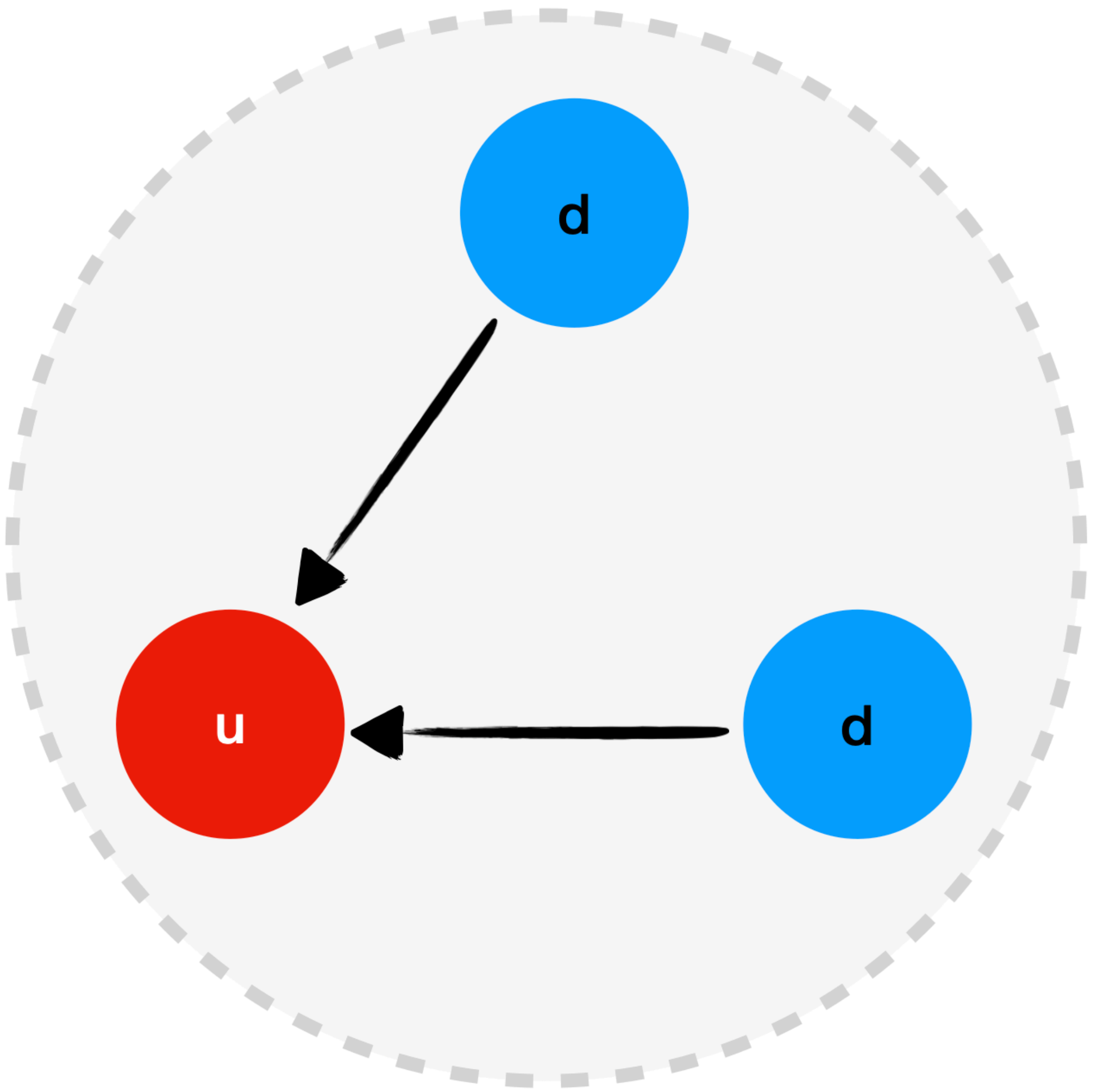

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Solution

Axion $m_a \propto \frac{1}{f_a}$

ALP → Free parameters

Possible to work with **lower scales for ALPs ⇒** Not solve Strong CP

ALP EFT

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + C_{\tilde{B}}O_{\tilde{B}} + C_{\tilde{W}}O_{\tilde{W}} + C_{\tilde{G}}O_{\tilde{G}} + C_u O_u + C_d O_d + C_e O_e + C_Q O_Q + C_L O_L$$

$$O_{\tilde{B}} = \frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu}\,,$$

$$O_{\tilde{W}} = \frac{a}{f_a} W^i_{\mu\nu}\tilde{W}^{i\mu\nu}\,,$$

$$O_{\tilde{G}} = \frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\,,$$

$$O_{f,ij} = \frac{\partial^\mu a}{f_a}(\overline{f_i}\gamma_\mu f_j)$$

[H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]

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Pure ALP

Gauge fields

Fermions

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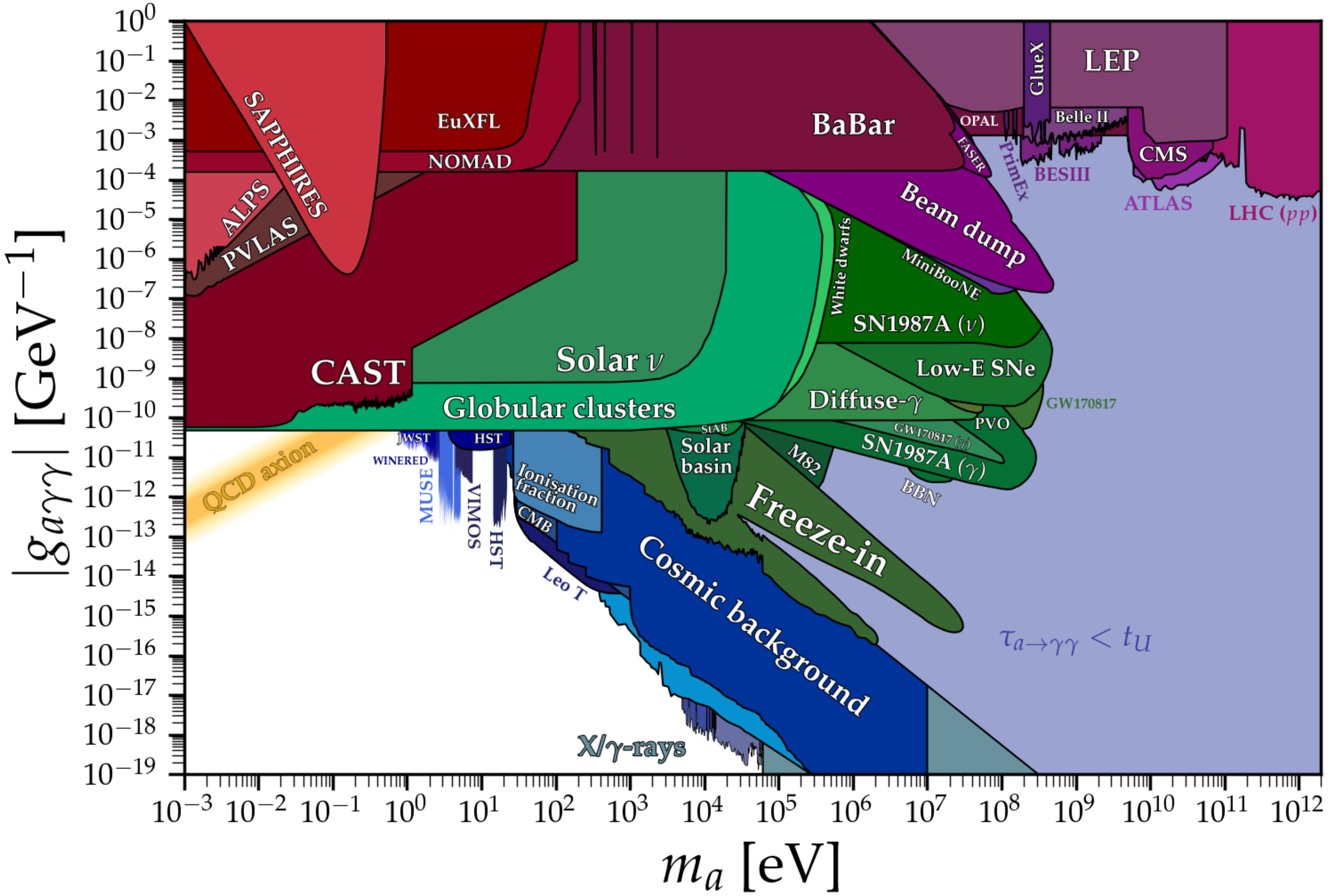
Shift-invariant $a \to a + C$

[H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]

Why meson searches?



[Extracted from **Ciaran O'Hare,** https://cajohare.github.io/AxionLimits/]

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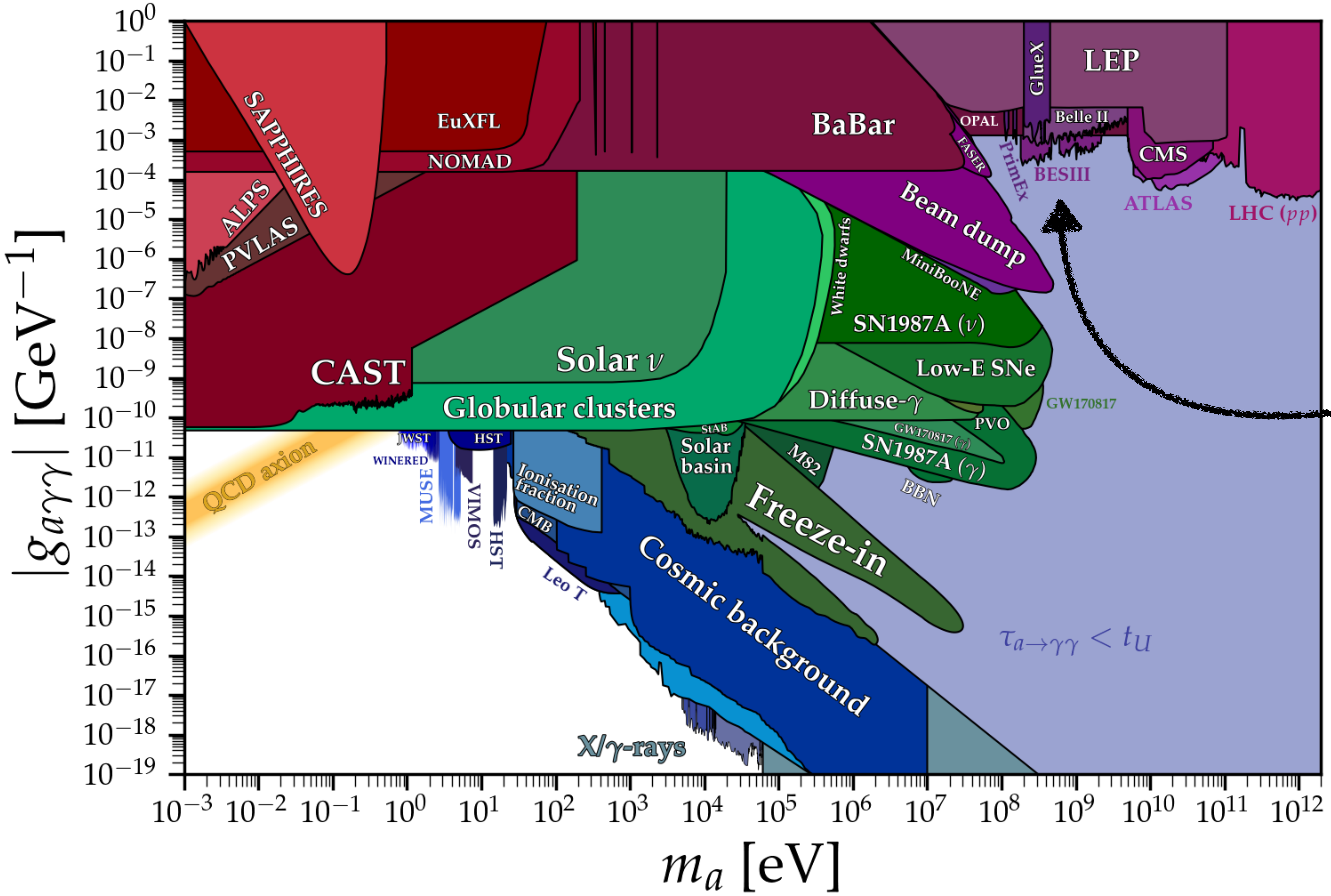
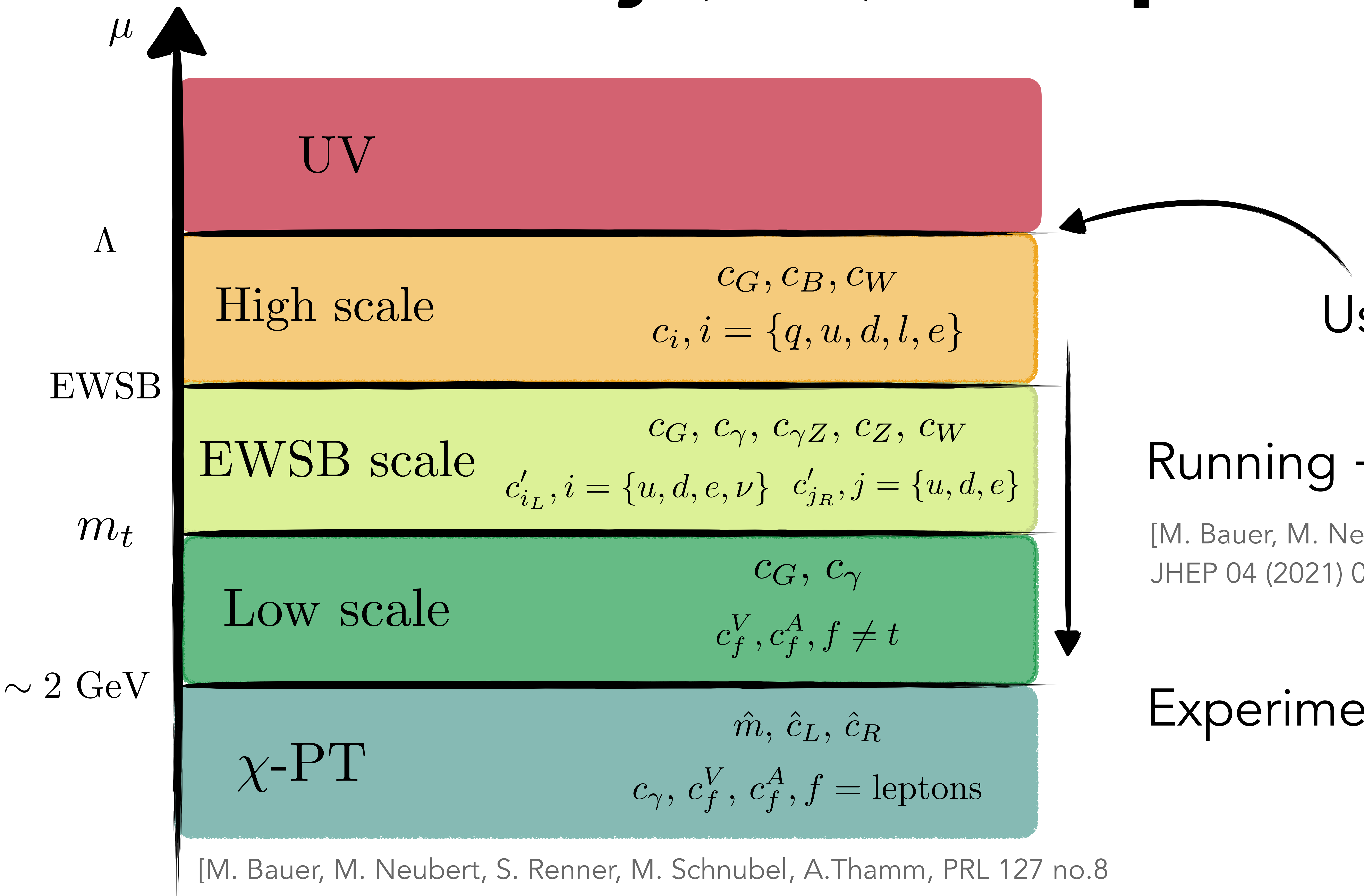


Too heavy for astrophysics, too light for colliders

[Extracted from **Ciaran O'Hare,** https://cajohare.github.io/AxionLimits/]

From theory (UV) to experiment (IR)



User input

Running + matching

[M. Bauer, M. Neubert, S. Renner, M. Schnubel, A.Thamm, JHEP 04 (2021) 063]

Experimental signature analysis

[M. Bauer, M. Neubert, S. Renner, M. Schnubel, A.Thamm, PRL 127 no.8 (2021) 081803]

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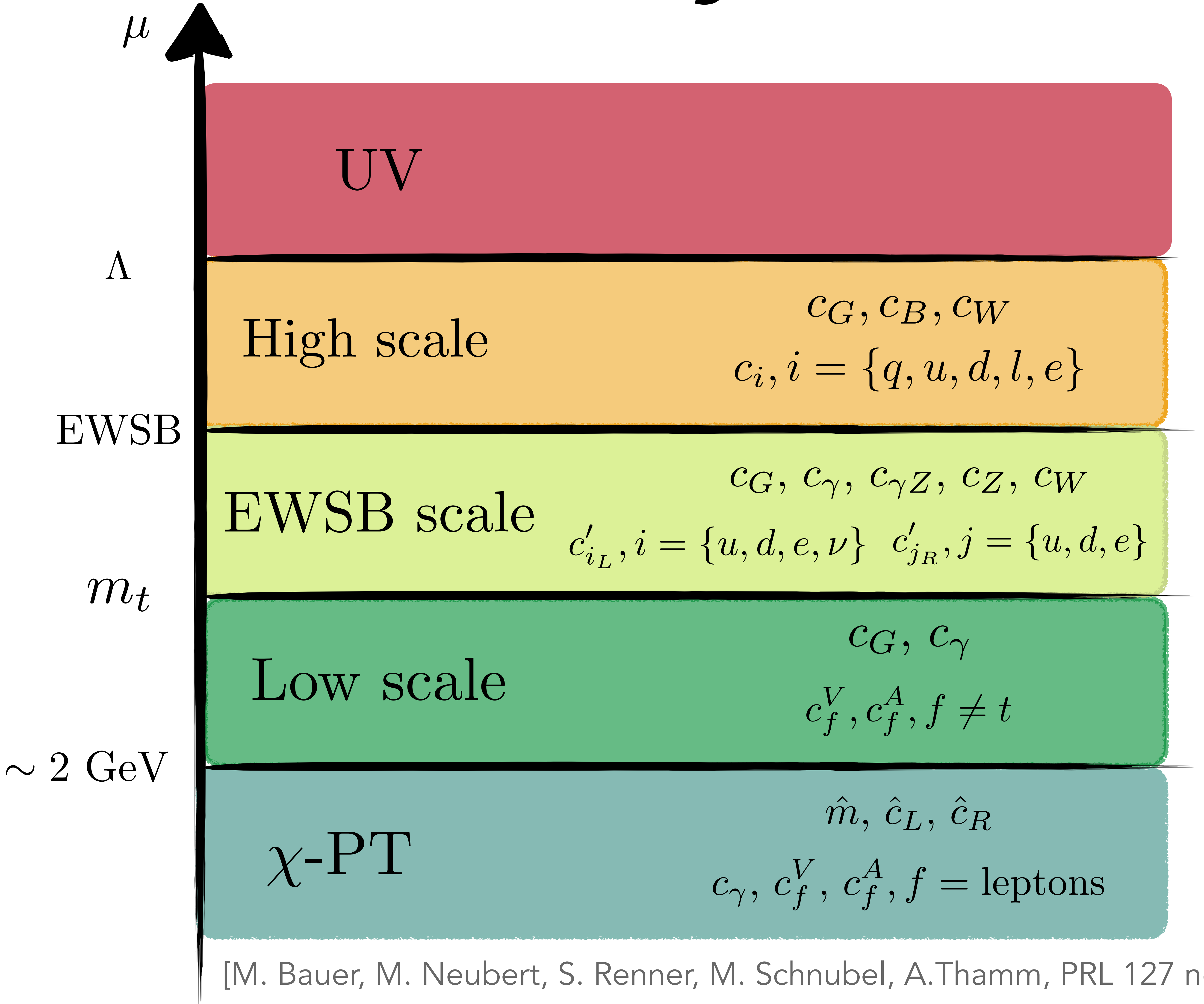
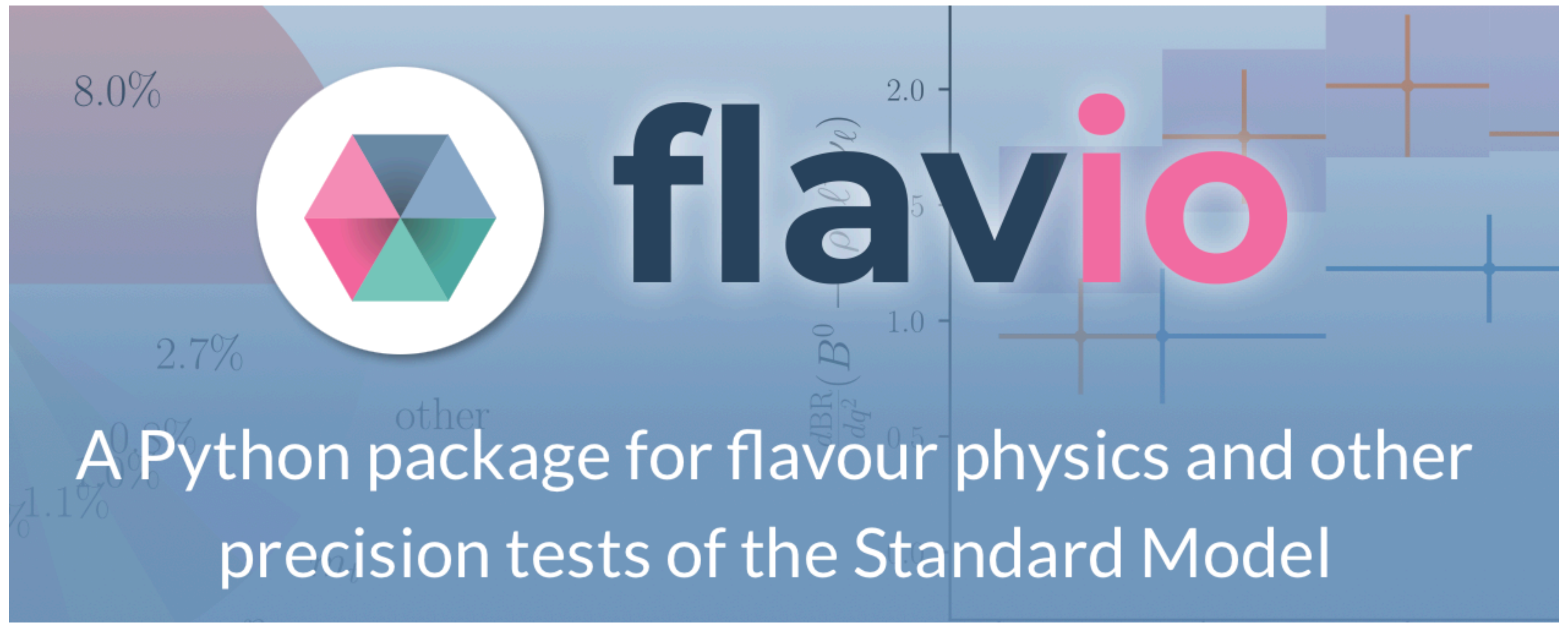


[M. Bauer, M. Neubert, S. Renner, M. Schnubel, A.Thamm, PRL 127 no.8 (2021) 081803]

In SMEFT



[D. Straub, 1810.08132]

In ALP EFT?

ALPaca

[Extracted from https://cottoncreekfarms.com/alpaca-behavior/]

ALP-automated computing algorithm

[Credit to Xavier Ponce Díaz]

ALP-automated computing algorithm

Benchmark models or

coefficients at High scale

```
couplings_1000 = alpaca.ALPcouplings(
    {'cqL': 1.0},
    scale=1000,
    basis='derivative_above'
)
```

User input:

Fed with

$$\Gamma(B \to K\, a),\ \Gamma(J/\Psi \to a\gamma),\ \ldots$$

$$\Gamma(a \to \gamma\gamma),\ \Gamma(a \to f\, f),\ \ldots$$

and

a library of >100 low-energy

searches & observables

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Automatic running and matching

```python
couplings_10 = couplings_1000.match_run(
    scale_out=10,
    basis='VA_below',
    integrator='scipy',
    beta='full',
    match_2loops=False,
)
```

Computes parameters at low energy

[Credit to Xavier Ponce Díaz]

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Automatic bounds

$$\frac{c_i(m_a)}{f_a} \leq \#\,[\mathrm{GeV}^{-1}]$$

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+ simplified syntax and many functionalities: statistics, plotting, benchmark models ...

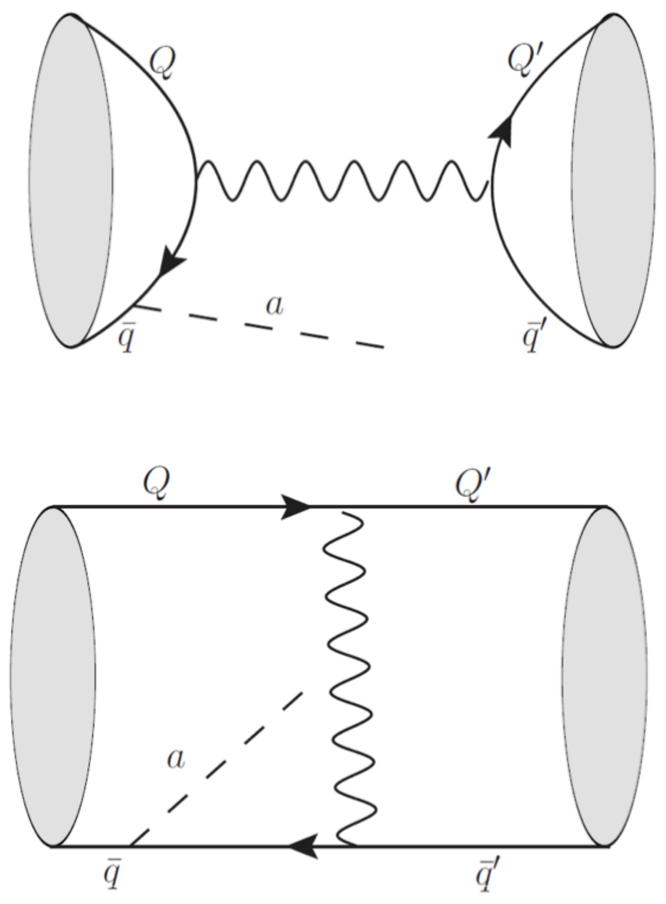
Soon to be public

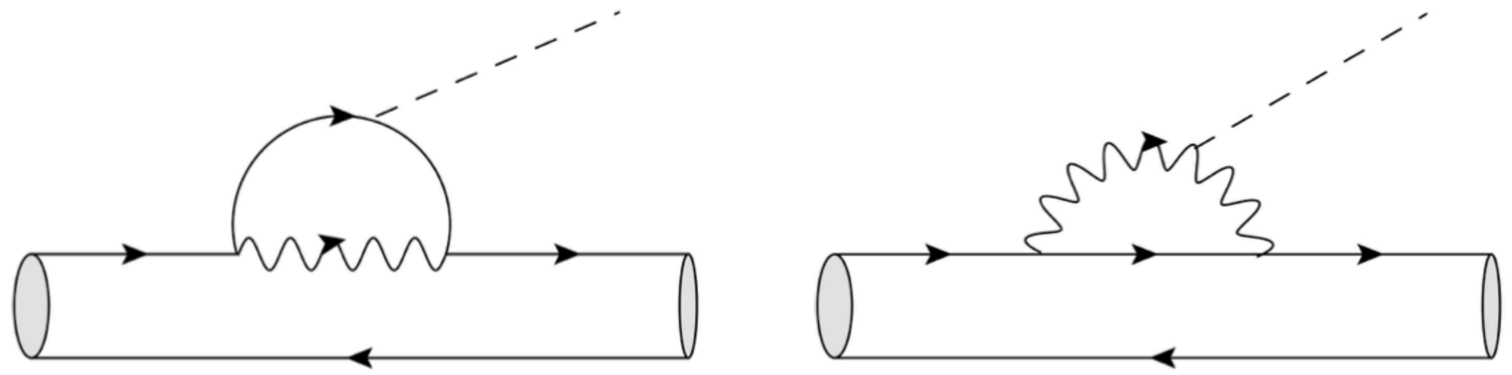
ALP production

FCNC meson decays

Tree level vs Loop level

$P \to P(V)$
$V \to V(P)$





Form factor

$$R_{T/L} = \left| \frac{\mathcal{M}_{\rm T}^{(s,t)}}{\mathcal{M}_{\rm L}} \right| \approx 2\,\pi^2 \frac{f_I\, f_F}{m_f^2} \left| \frac{V_{\rm T}^{\rm CKM}}{V_{\rm L}^{\rm CKM}} \right|$$

Need to consider both contributions

Lepage-Brodsky, χ PT

[G. P. Lepage and S. J. Brodsky, Phys. Rev. D, 22:2157, 1980]

[A. Guerrera, S. Rigolin, *Fortsch.Phys.* 71 (2023) 2-3, 2200192]

[C. Cornella, A. M. Galda, M. Neubert, D. Wyler, *JHEP* 06 (2024) 029]

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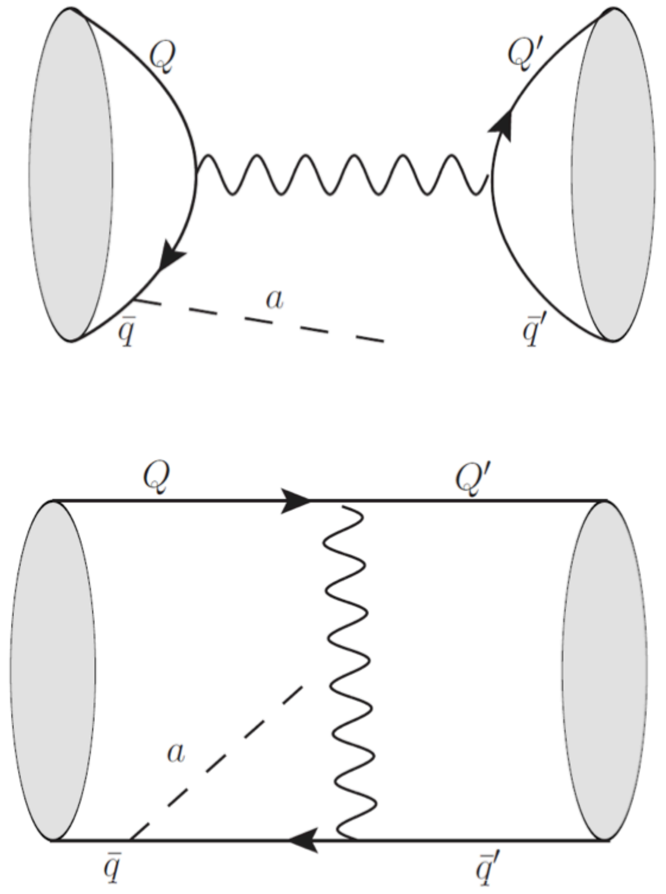

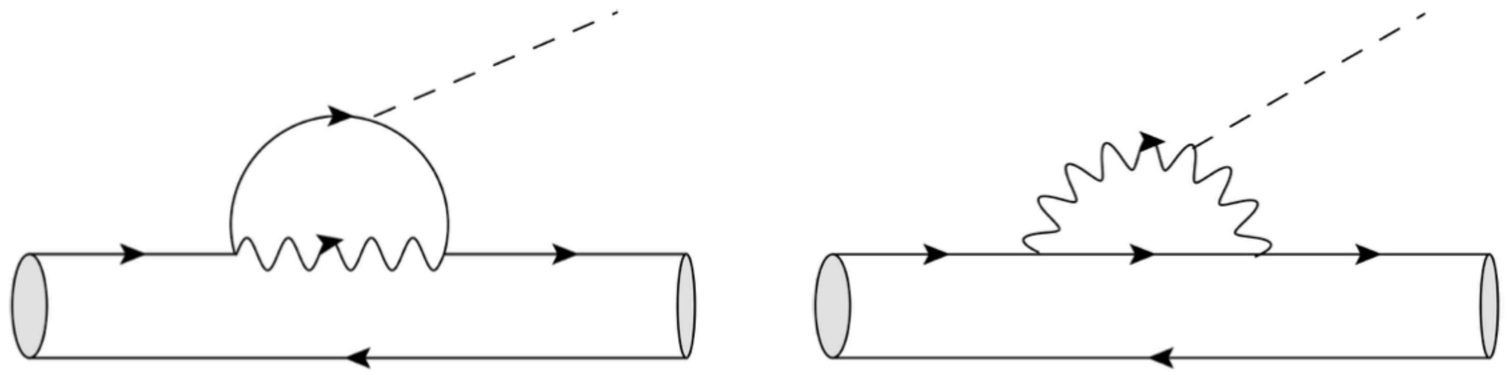

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Need to consider both contributions

Other observables:

- Neutral meson mixing
- Radiative quarkonia decays
- Off-shell ALP $\quad M^0 \to a \to \gamma\gamma \quad (\ell\ell)$
- Lepton flavour violation

ALP decays

Three main decay channels: **photons, hadrons, fermions**

Photons $\Gamma(a \to \gamma\gamma) = \frac{\alpha_{\rm EM}^2 m_a^3}{(4\pi)^3 f_a^2} \left| c_\gamma + \mathcal{C}_\gamma^\ell + \mathcal{C}_\gamma^\chi + \mathcal{C}_\gamma^{\rm VMD} + \mathcal{C}_\gamma^{\rm pQCD} + \mathcal{C}_\gamma^W \right|^2$

[M. Bauer, M. Neubert, S. Renner, M. Schnubel, A.Thamm, JHEP 09 (2022) 056]

[D. Aloni, Y. Soreq, M. Williams, PRL 123 no.3 (2019) 031803]

Tree level

Loop level

Hadronic

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Hadrons ALP mixing with mesons: $\pi, \eta, \eta' \ldots$ → Mixing matrix with pseudo scalar and vector mesons relevant

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[M. Ovchynnikov, A. Zaporozhchenko, 2501.04525]

$a \to 3\pi$ $\quad a \to VV(VV = \omega\omega, \pi\pi\gamma)$ $\quad a \to PPP(PPP = \eta\pi\pi, \eta'\pi\pi)$

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Tree level — Loop level — Hadronic

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Possible decay to DM

Tree level

Loop level

Hadronic

ALP decays

$$\mathrm{BR}(X \to YZ)_{\mathrm{NWA}} \approx \mathrm{BR}(X \to Ya) \times \mathrm{BR}(a \to Z)$$

ALP decay length + experiment characteristics

ALP decays

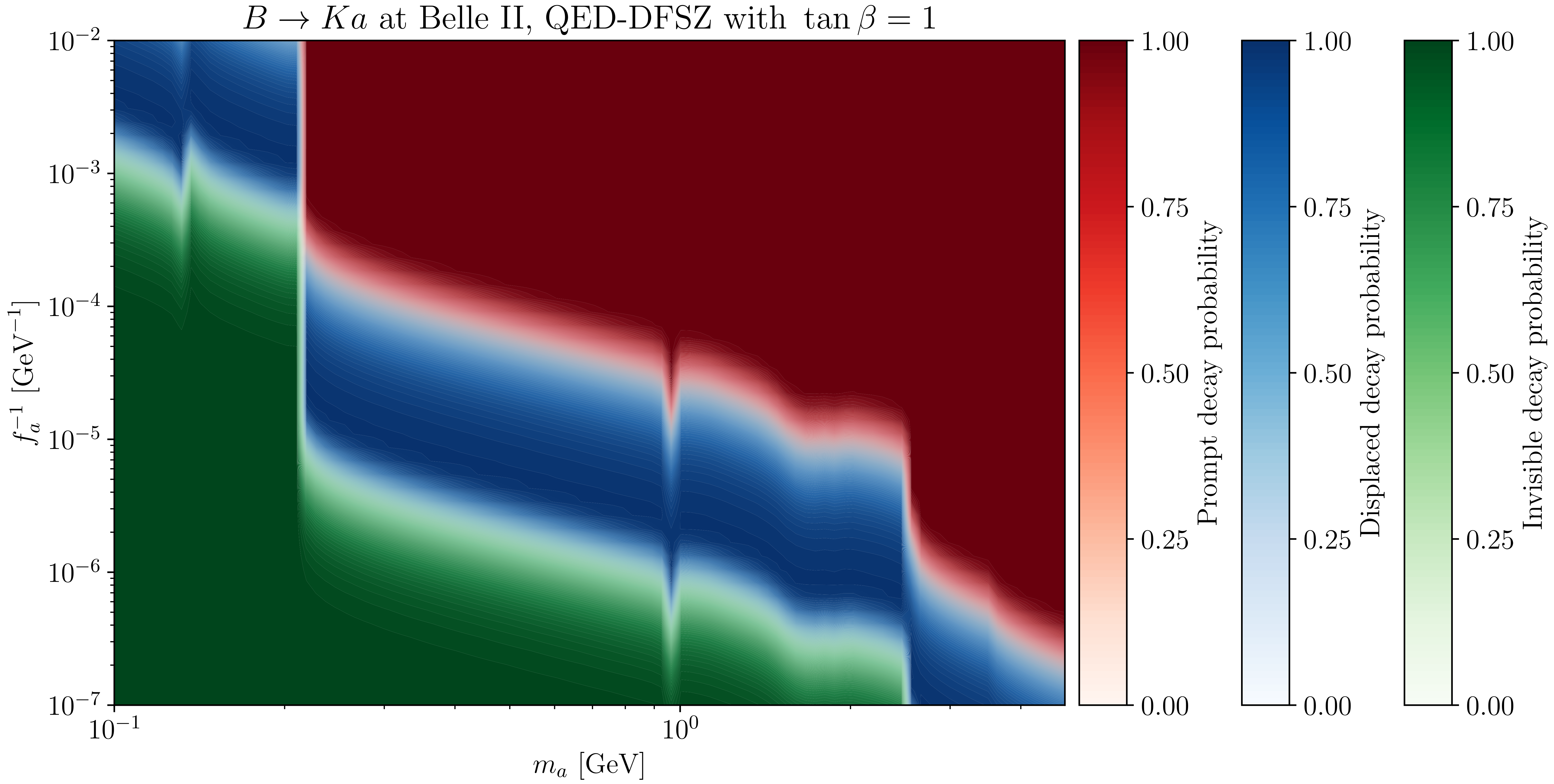
$$\mathrm{BR}(X \to YZ)_{\mathrm{NWA}} \approx \mathrm{BR}(X \to Ya) \times \mathrm{BR}(a \to Z)$$

ALP decay length + experiment characteristics

Prompt	Displaced	Invisible
Short-lived ALP	Decay length comparable resolution	Long-lived ALP
Decay products "originate" at IP	Displaced vertex	Escape dectector → Missing energy

Study the probability of each case

Type of signal: prompt, displaced, invisible?



$$P(r_1, r_2) = \exp\left(-\frac{r_1}{c\tau_a\beta_a\gamma_a}\right) - \exp\left(-\frac{r_2}{c\tau_a\beta_a\gamma_a}\right)$$

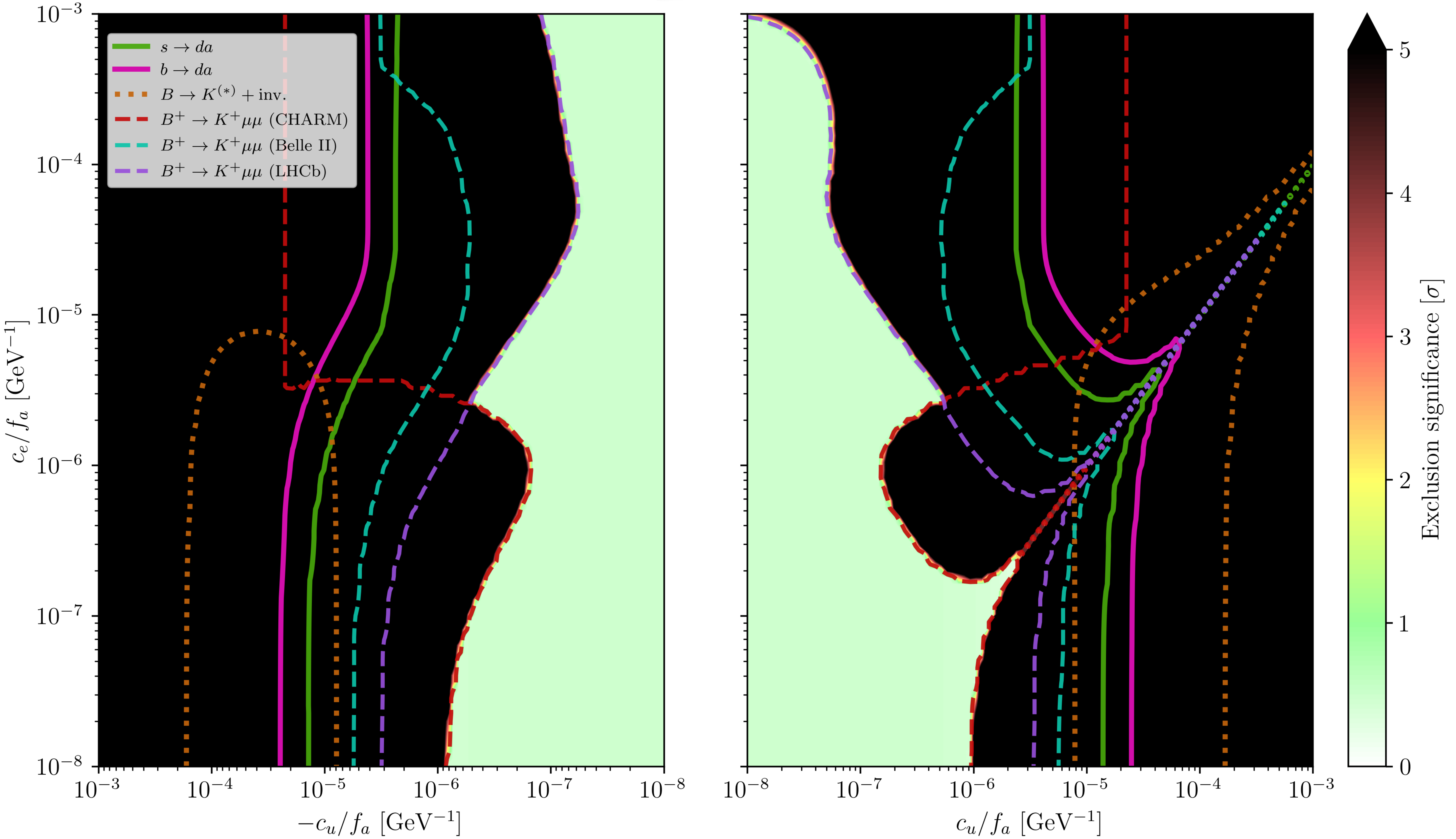
$r_1,\ r_2$: characteristic lengths of the detector

$\beta_a,\ \gamma_a$: determined by the kinematics

Phenomenology

B physics

$$\mathcal{L} \supset \frac{\partial^\mu a}{f_a}(\overline{\ell_L}\gamma_\mu c_e \ell_L) + \frac{\partial^\mu a}{f_a}(\overline{u_R}\gamma_\mu c_u u_R)$$



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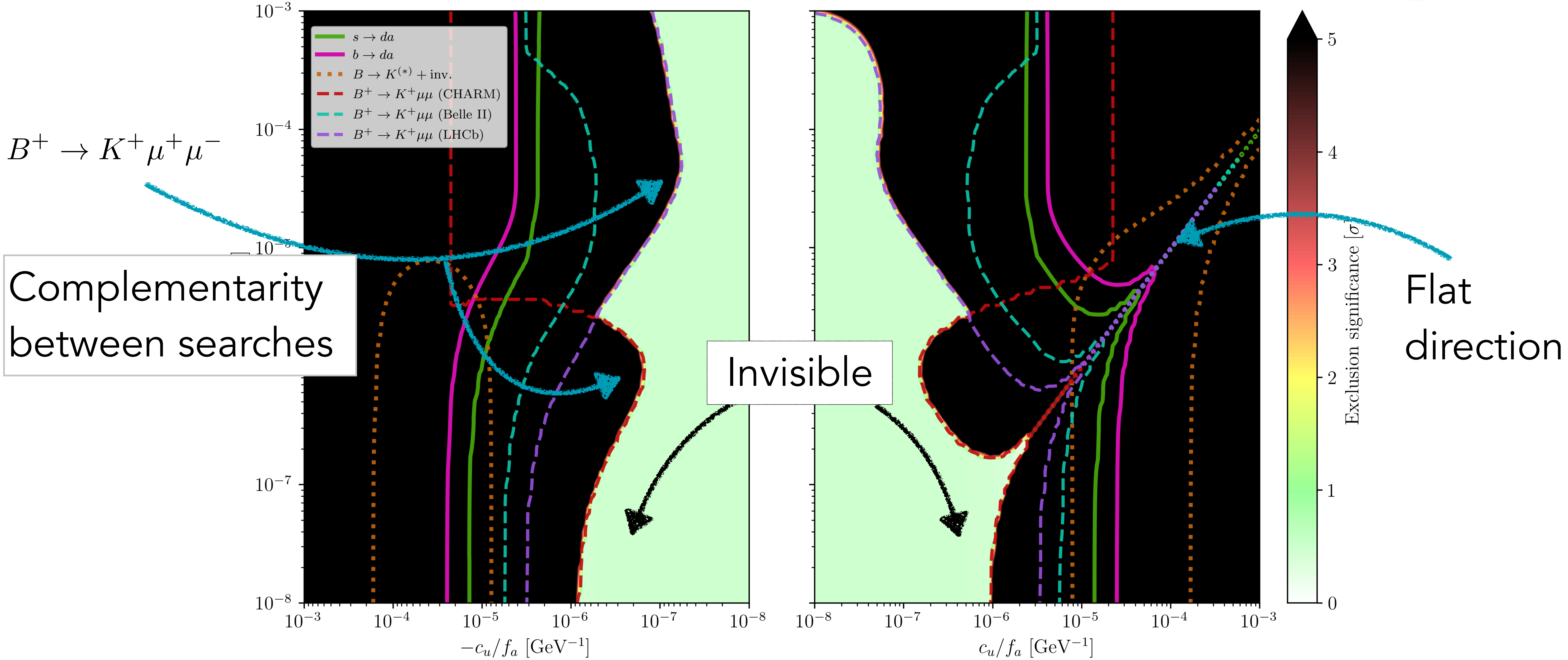


Belle II anomaly

$$\mathcal{BR}(B^+ \to K^+ \overline{\nu} \nu) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \cdot 10^{-5}$$

[Belle II, *Phys.Rev.D* 109 (2024) 11, 112006]

$$\Downarrow$$

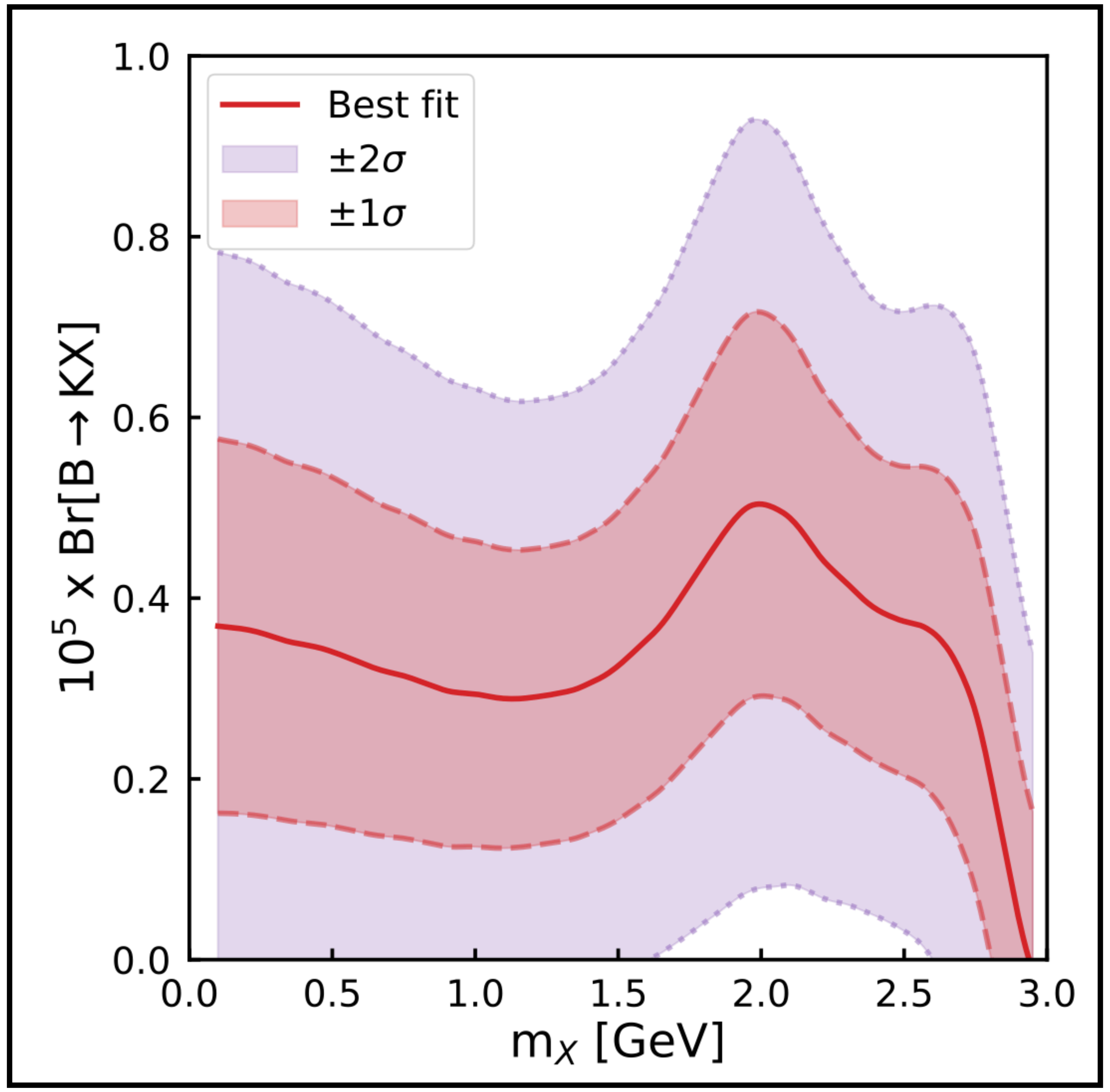
2.7σ discrepancy!

Possible solution:

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \left(c_{sb}^V \overline{s} \gamma^\mu b + c_{sb}^A \overline{s} \gamma^\mu \gamma_5 b \right) + \text{h.c}$$

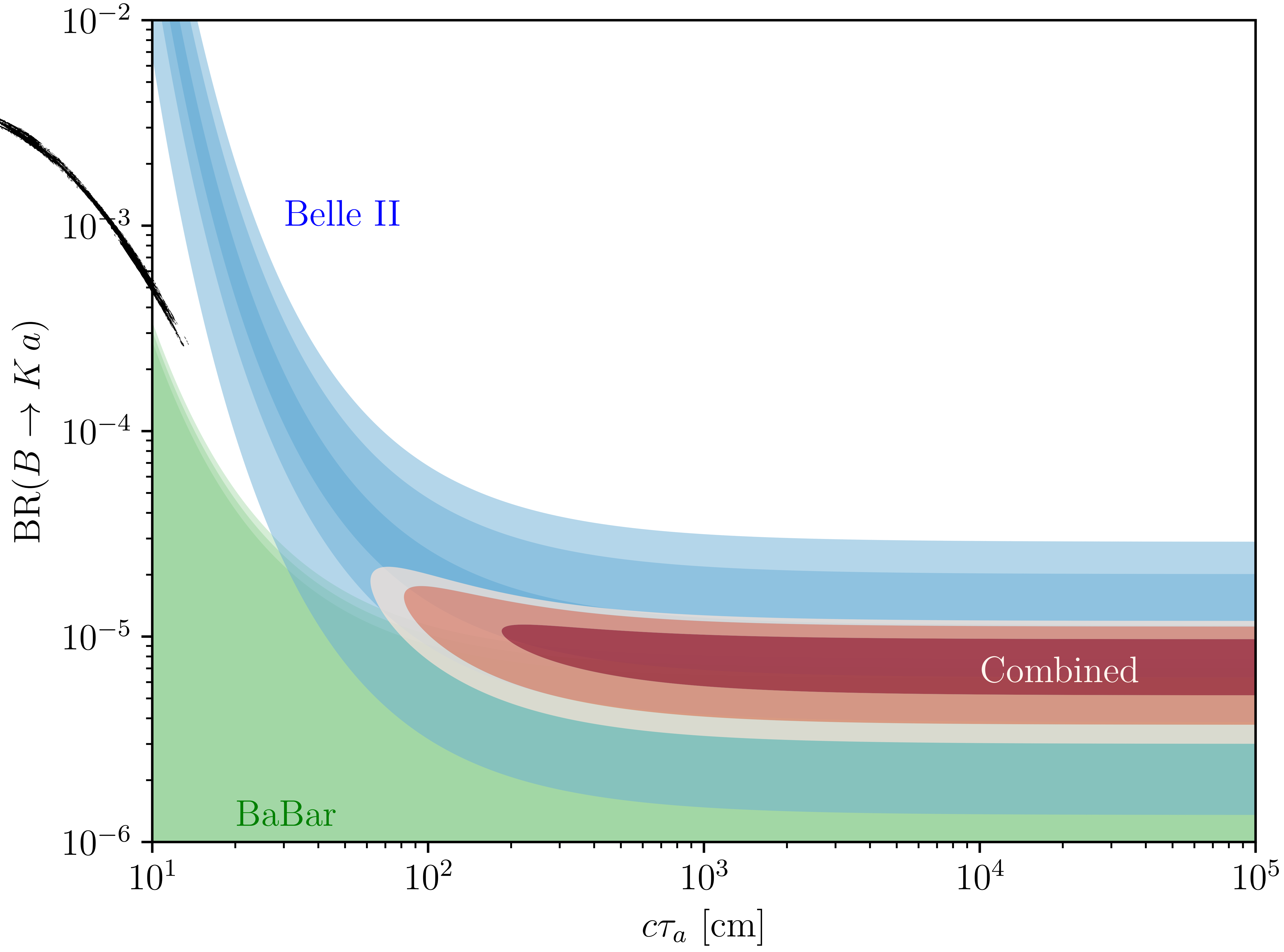
ALP mass $m_a = 2$ GeV

[W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia, J. Martin Camalich, *Phys.Rev.D* 109 (2024) 7, 075008]



Belle II anomaly

Different decay lengths allow to constrain ALP lifetime



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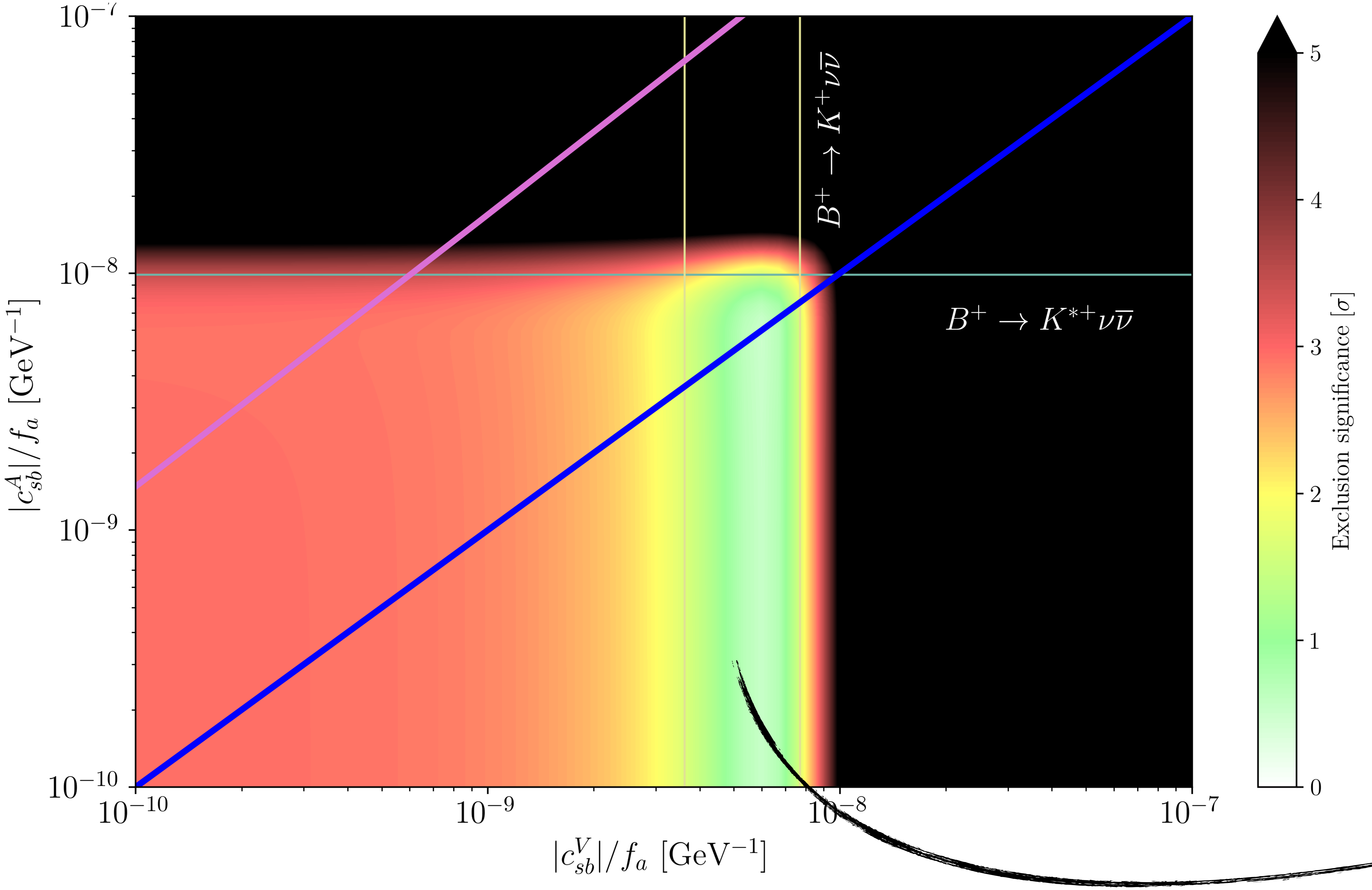
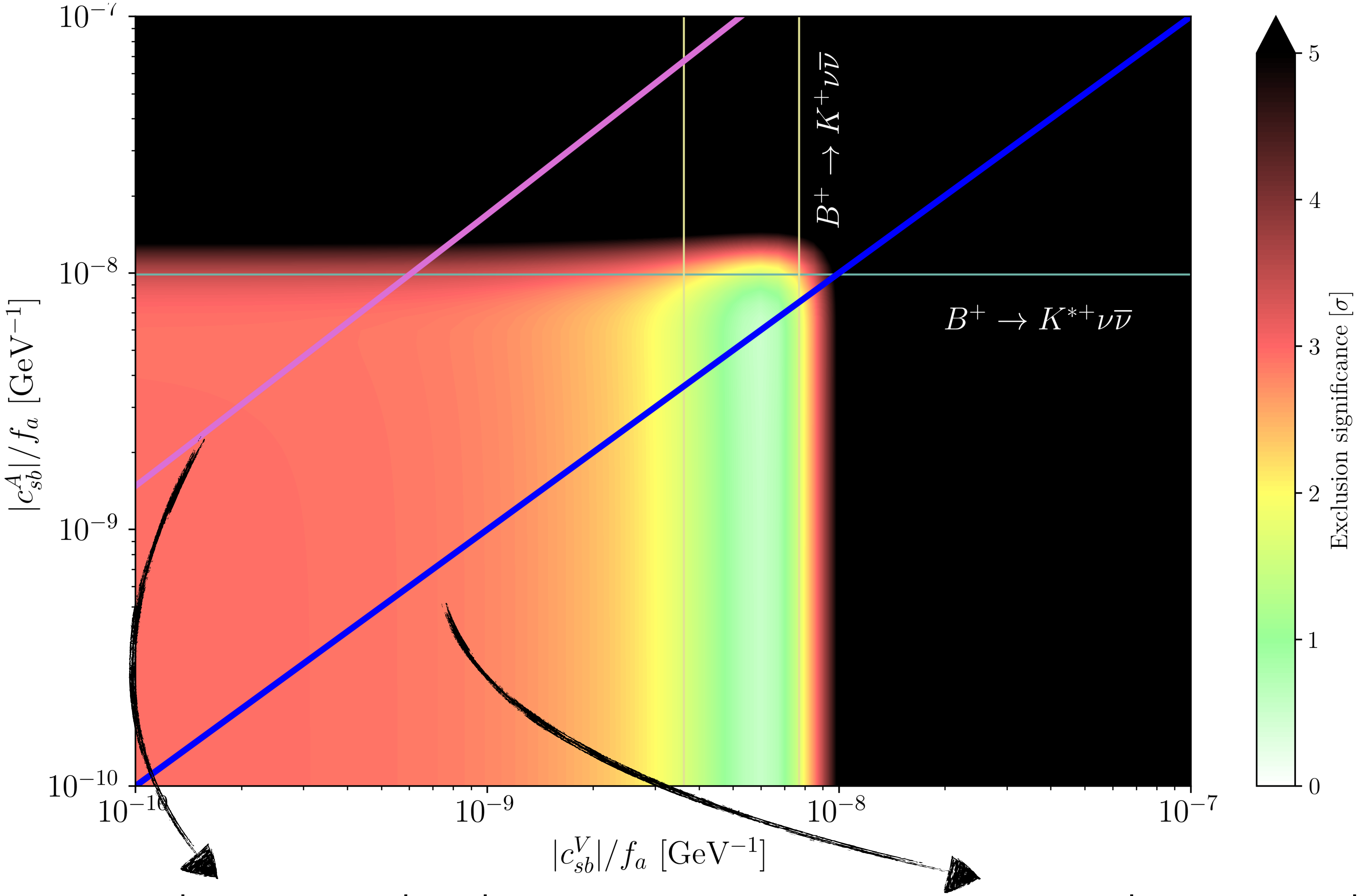


Agreement with Altmannshofer et al.

Belle II anomaly



FV coupling at tree-level

No FV coupling at tree-level

No FV at tree-level

Flaxion: tree-level flavour violation

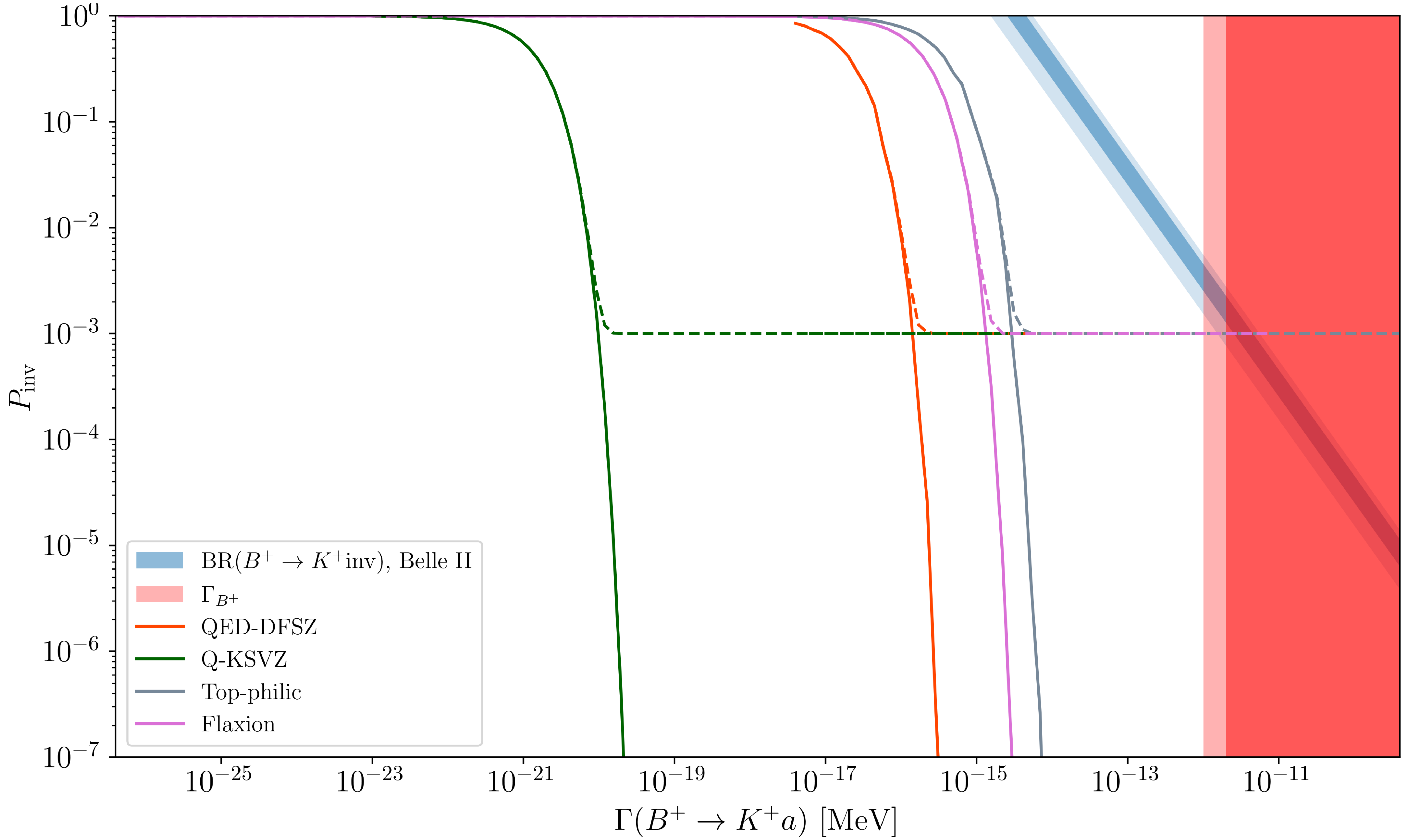
[Y. Ema, K. Hamaguchi, T. Moroi, and K. Nakayama, JHEP 01 (2017) 096]

Top-philic: only coupling to c_{t_R}

QED-DFSZ: order one coupling to fermions

Q-KSVZ: $c_g = 1$

Belle II anomaly



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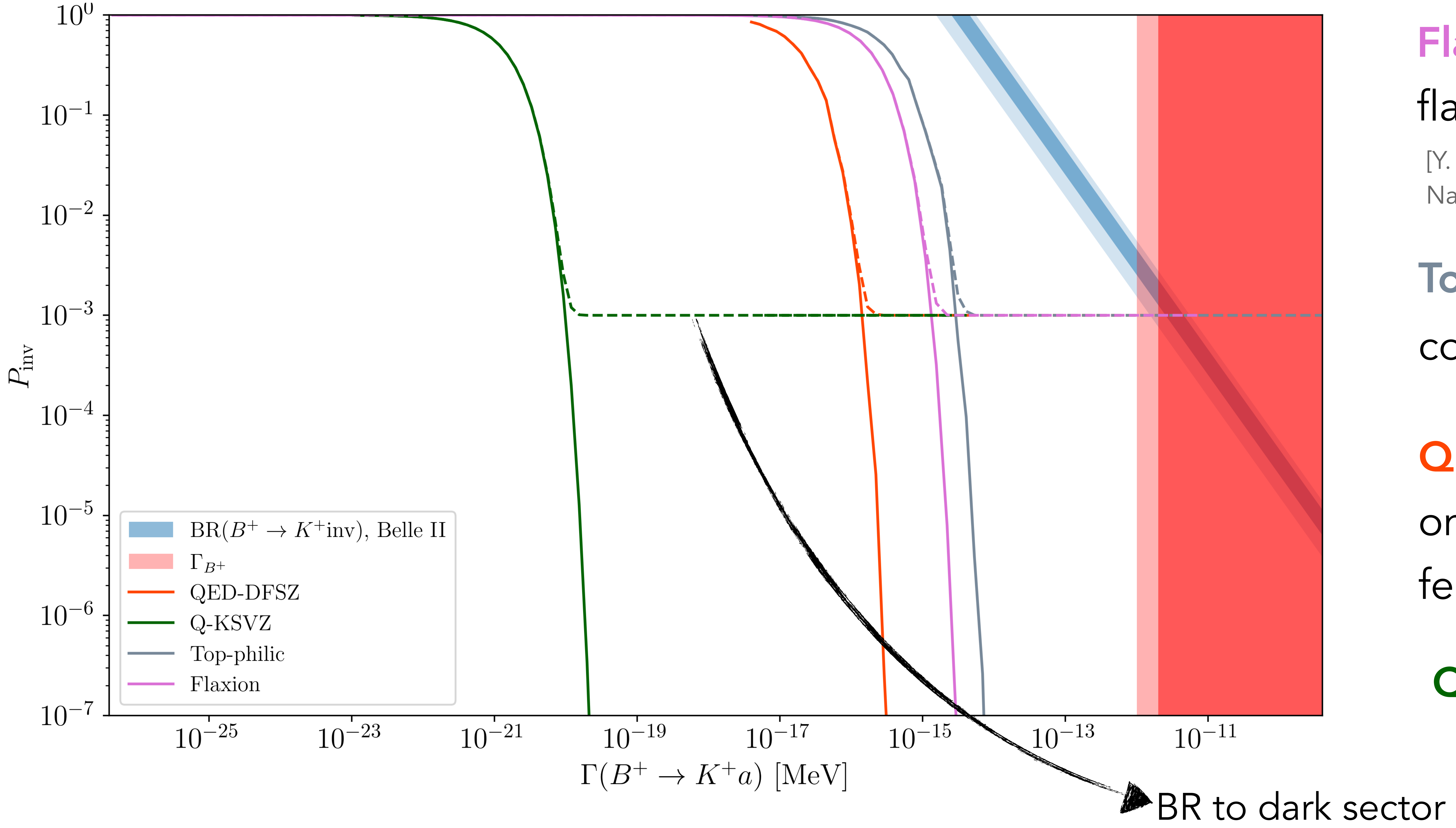

Flaxion: tree-level flavour violation

[Y. Ema, K. Hamaguchi, T. Moroi, and K. Nakayama, JHEP 01 (2017) 096]

Top-philic: only coupling to c_{t_R}

QED-DFSZ: order one coupling to fermions

Q-KSVZ: $c_g = 1$

Conclusions

ALPaca: ALP automated computing algorithm

- User-friendly Python package → Obtain bounds on ALP EFT in automatized way
- **Running** and **matching** of coefficients
- **Production** and **decay** of ALPs, including QCD effects
- **Library** of flavour observables and experimental searches

Phenomenological study on B physics

- Need for **dark sector** to explain Belle II with **benchmark models**

Thank you for your attention

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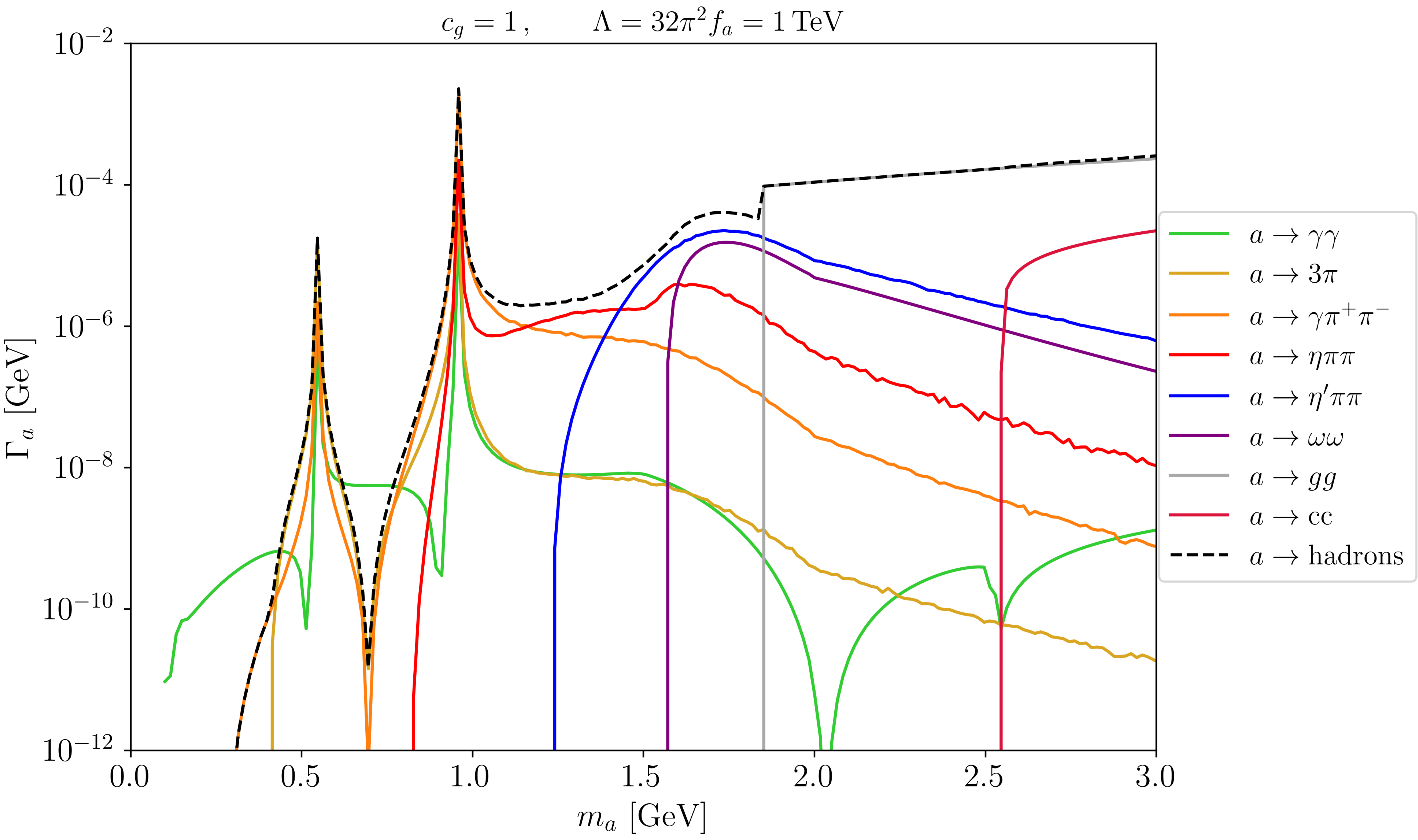
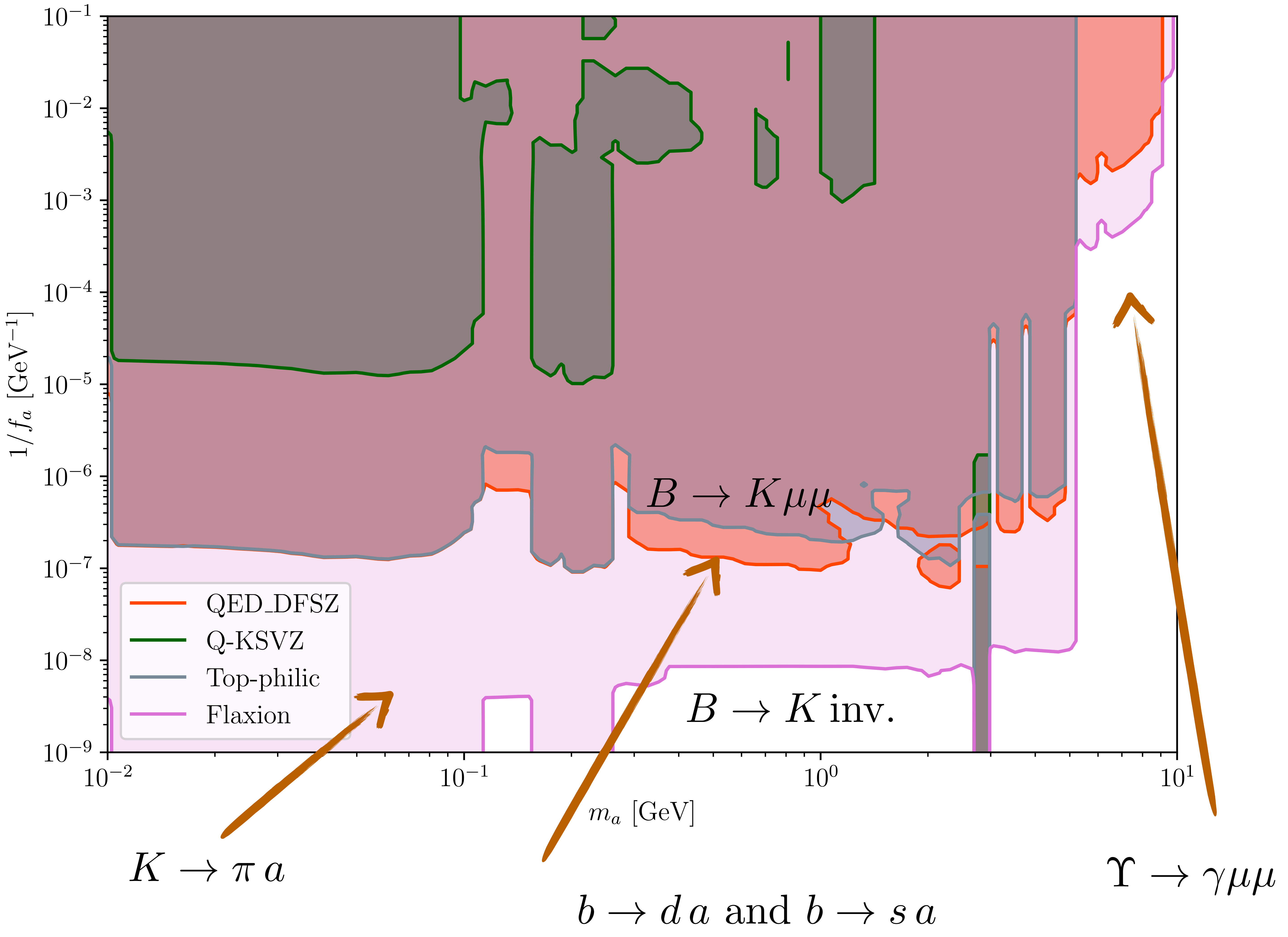
Back up slides

Hadronic decays



Benchmark models



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Future searches