

Tackling ALP searches in meson decays with ALPaca

A phenomenological approach

Marta Fuentes Zamoro

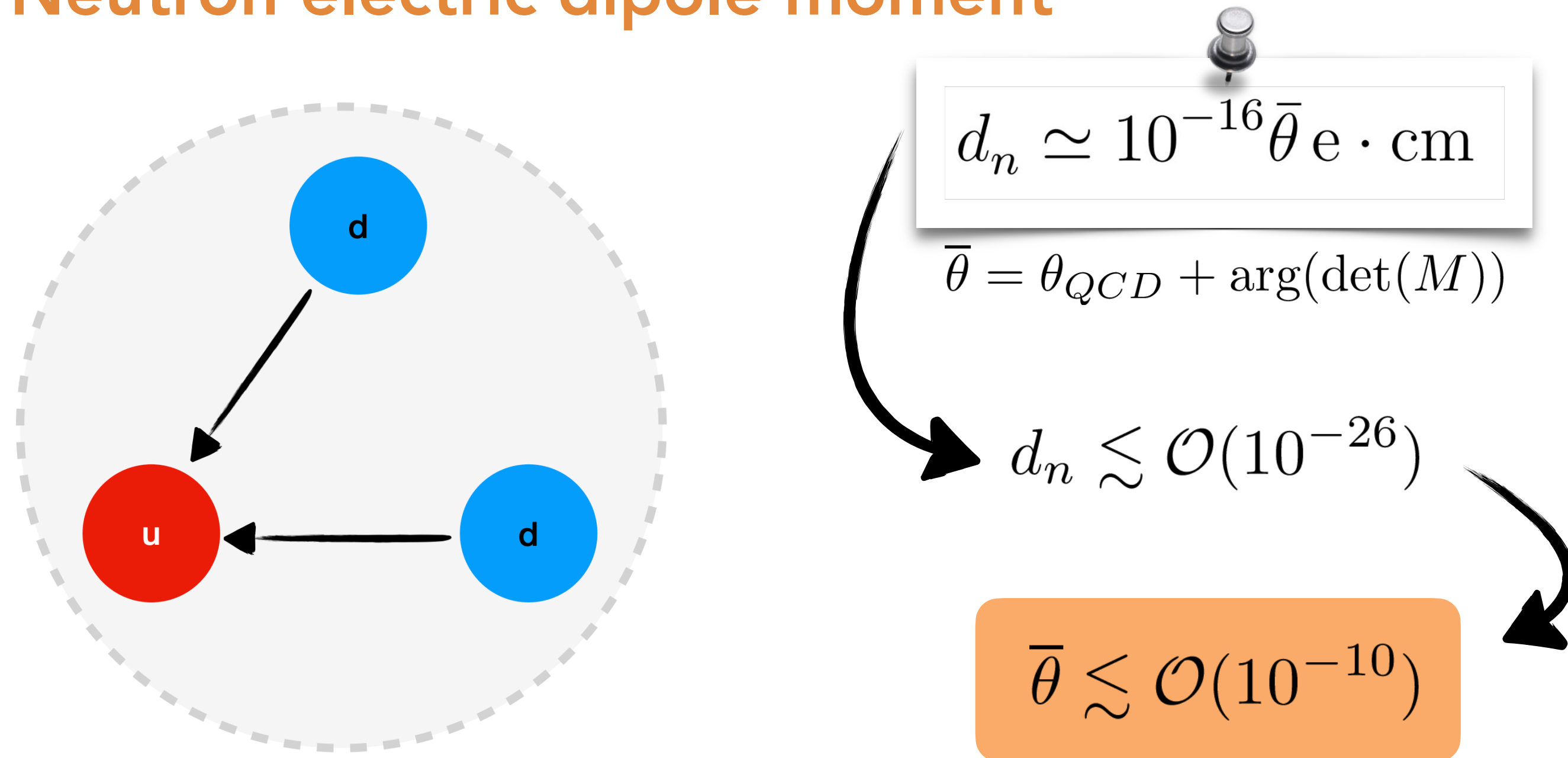
Based on 2506.XXXXX, in collaboration with Jorge Alda, Luca Merlo, Xavier Ponce Díaz and Stefano Rigolin



Strong CP problem and ALPs

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

Neutron electric dipole moment

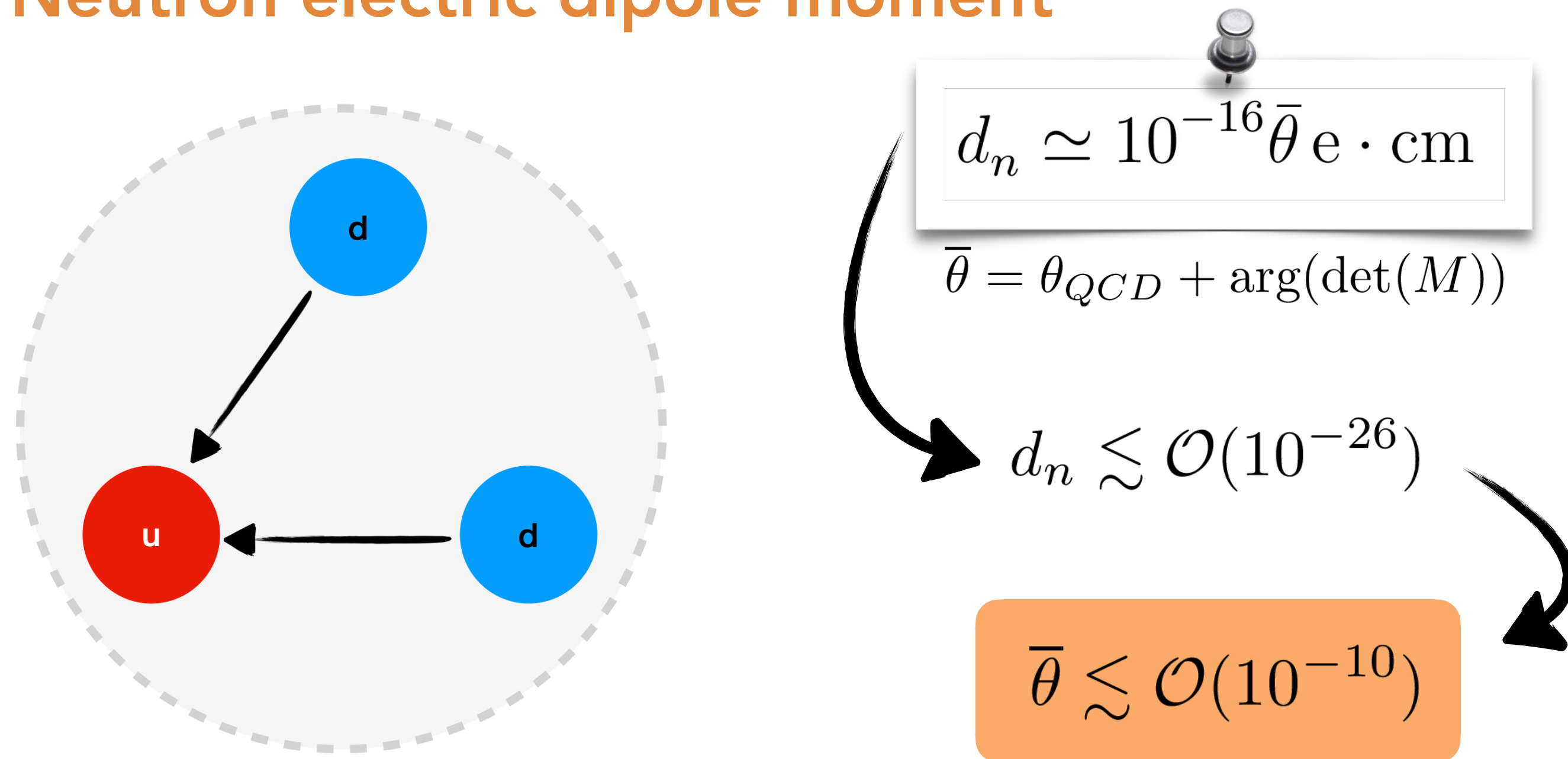


[C. Abel et al., Phys. Rev. Lett., vol. 124, no.8, p. 081803, 2020]

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Neutron electric dipole moment



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

Solution

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

SSB

Axion

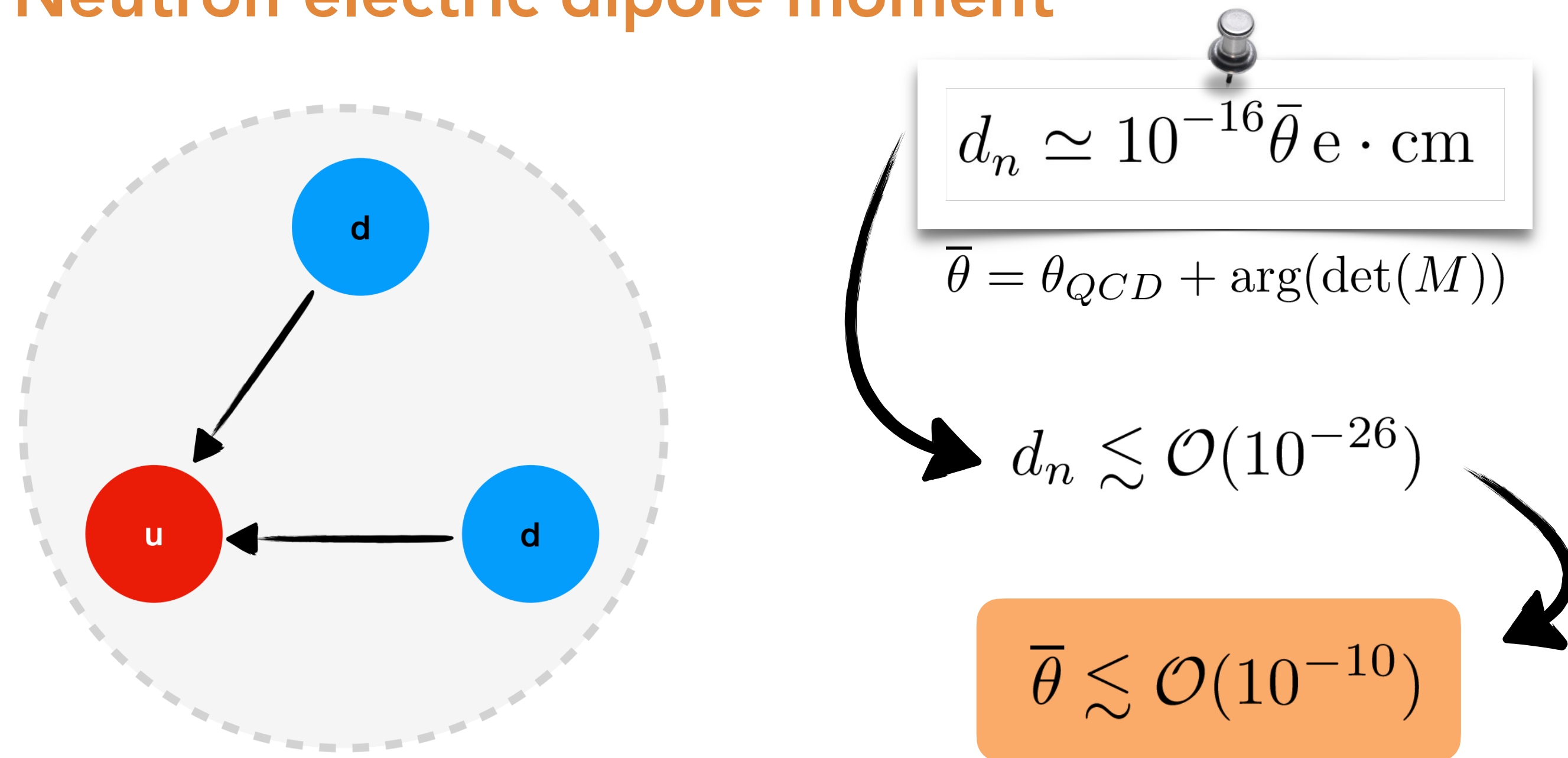
[R. D. Peccei, H. R. Quinn, Phys. Rev. Lett., vol. 38, pp. 1440-1443, 1977]

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

Strong CP problem and ALPs

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Neutron electric dipole moment



Solution

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

ALP $\rightarrow$ Free parameters

Possible to work with
lower scales for ALPs $\Rightarrow$
Not solve Strong CP

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

ALP EFT

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

$$\begin{aligned}O_{\tilde{B}} &= \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}, \\ O_{\tilde{W}} &= \frac{a}{f_a} W_{\mu\nu}^i \tilde{W}^{i\mu\nu}, & O_{f,ij} &= \frac{\partial^\mu a}{f_a} (\bar{f}_i \gamma_\mu f_j) \\ O_{\tilde{G}} &= \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu},\end{aligned}$$

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

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Pure ALP



Gauge fields



Fermions

$$\begin{aligned}O_{\tilde{B}} &= \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}, \\ O_{\tilde{W}} &= \frac{a}{f_a} W_{\mu\nu}^i \tilde{W}^{i\mu\nu}, \\ O_{\tilde{G}} &= \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu},\end{aligned} \quad \left| \quad O_{f,ij} = \frac{\partial^\mu a}{f_a} (\bar{f}_i \gamma_\mu f_j)\right.$$

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Pure ALP



Gauge fields



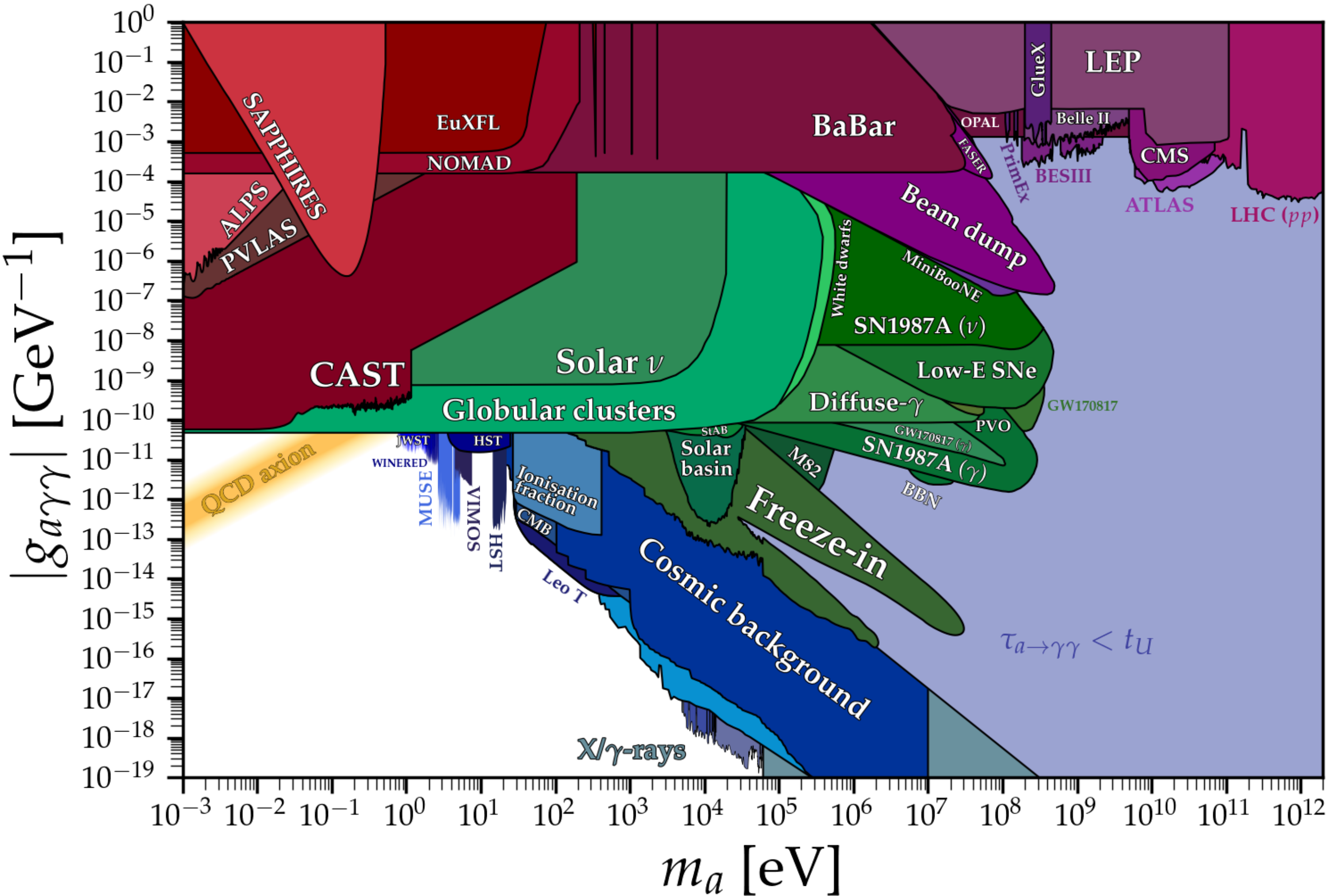
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Shift-invariant $a \rightarrow a + C$

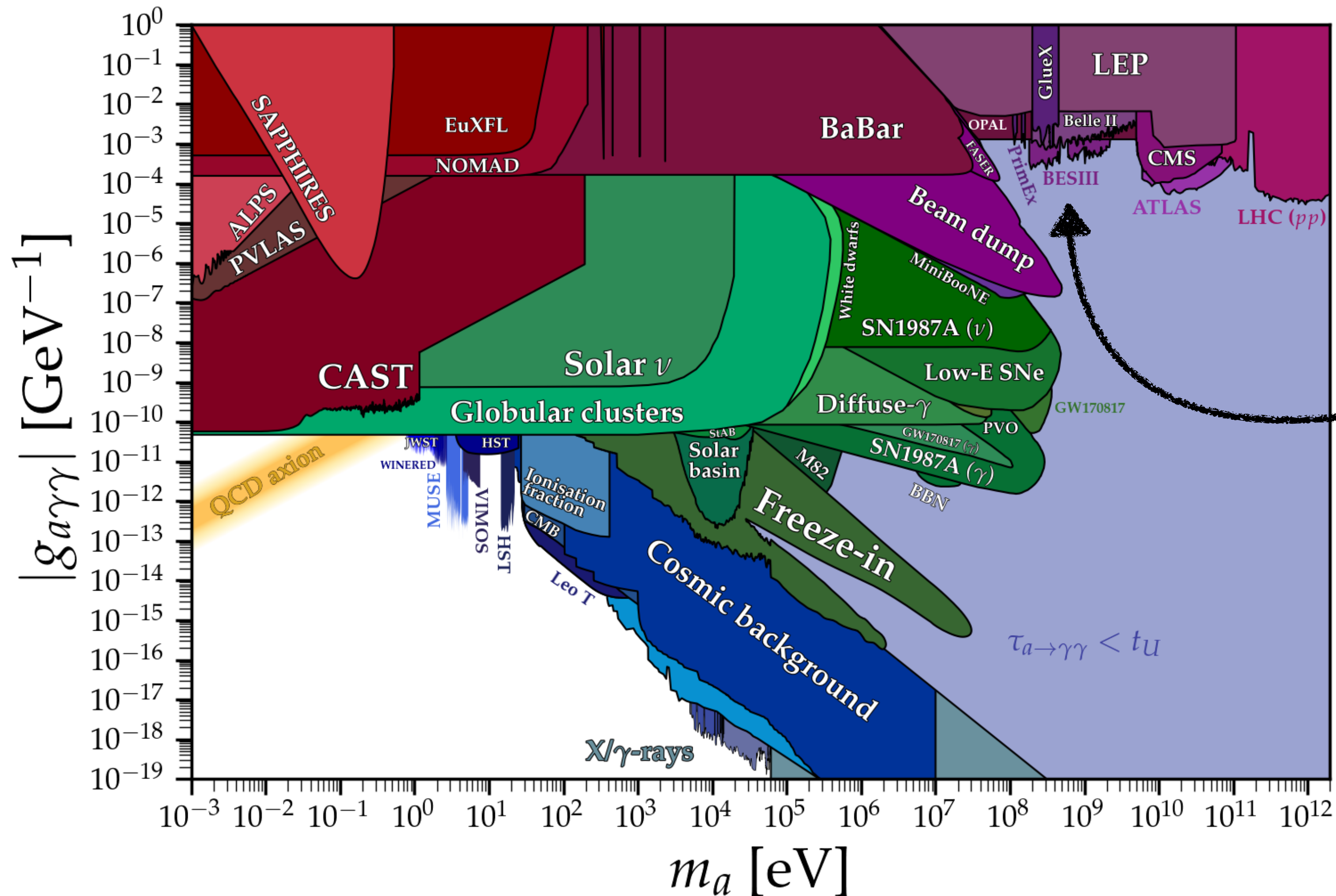
[H. Georgi, D. Kaplan, L. Randall, PLB 169B(1986)73]

Why meson searches?



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

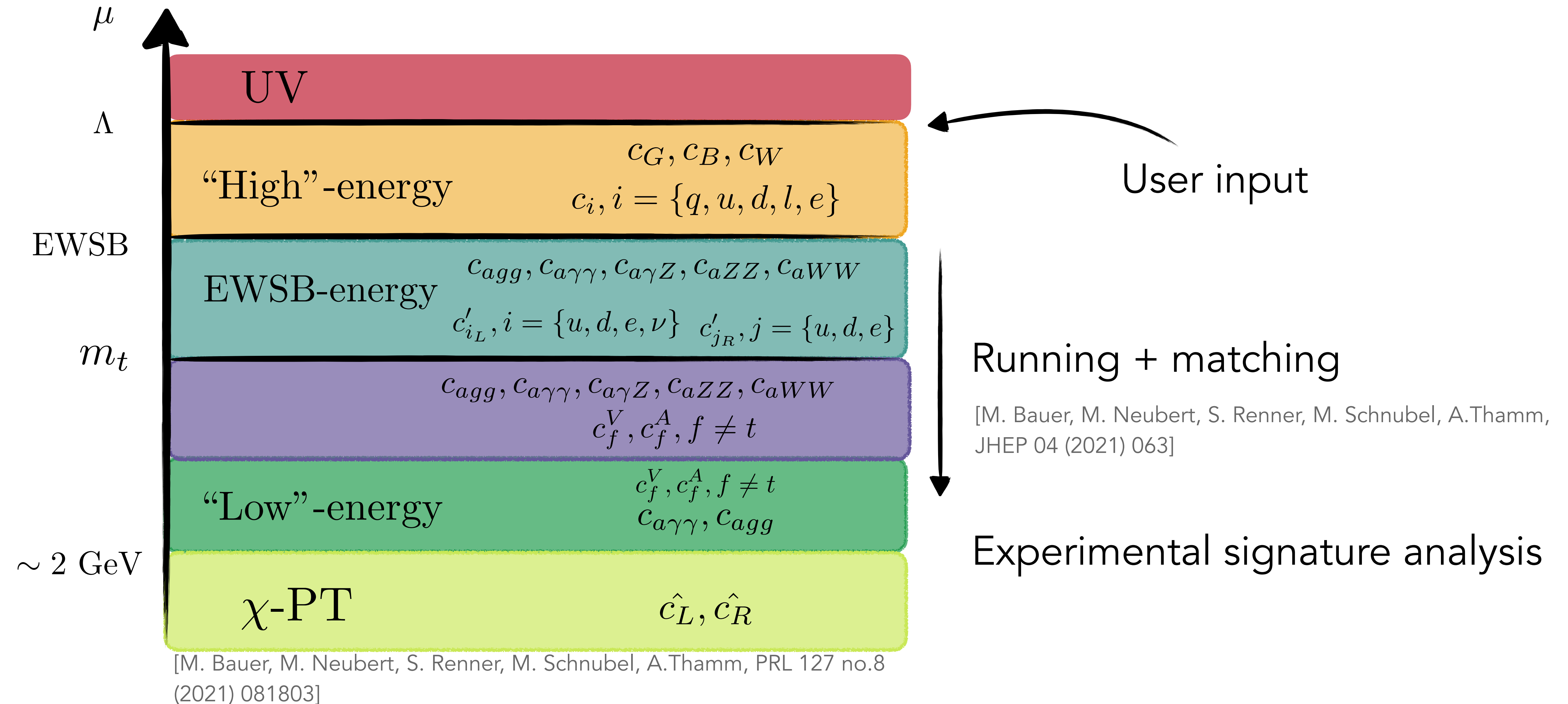
Why meson searches?



Too heavy for
astrophysics,
too light for
colliders

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

From theory (UV) to experiment (IR)



ALPaca



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

ALP-automated computing algorithm



ALP-automated computing algorithm

Benchmark models or
coefficients at High scale

User input:



```
1 couplings_1000 = alpaca.ALPCouplings(  
2   {'cqL': 1.0},  
3   scale=1000,  
4   basis='derivative_above'  
5 )
```

Fed with



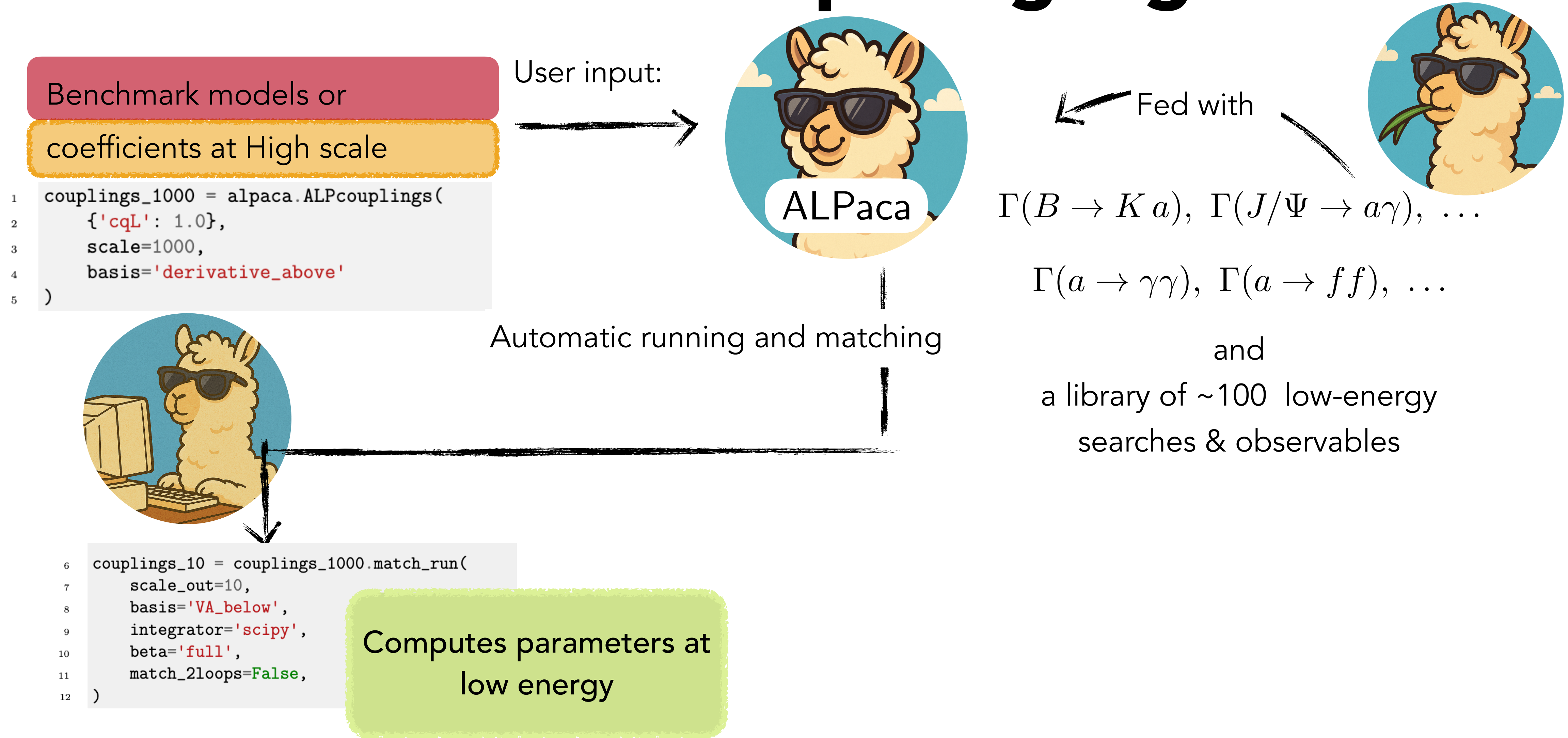
$\Gamma(B \rightarrow K a), \Gamma(J/\Psi \rightarrow a\gamma), \dots$

$\Gamma(a \rightarrow \gamma\gamma), \Gamma(a \rightarrow ff), \dots$

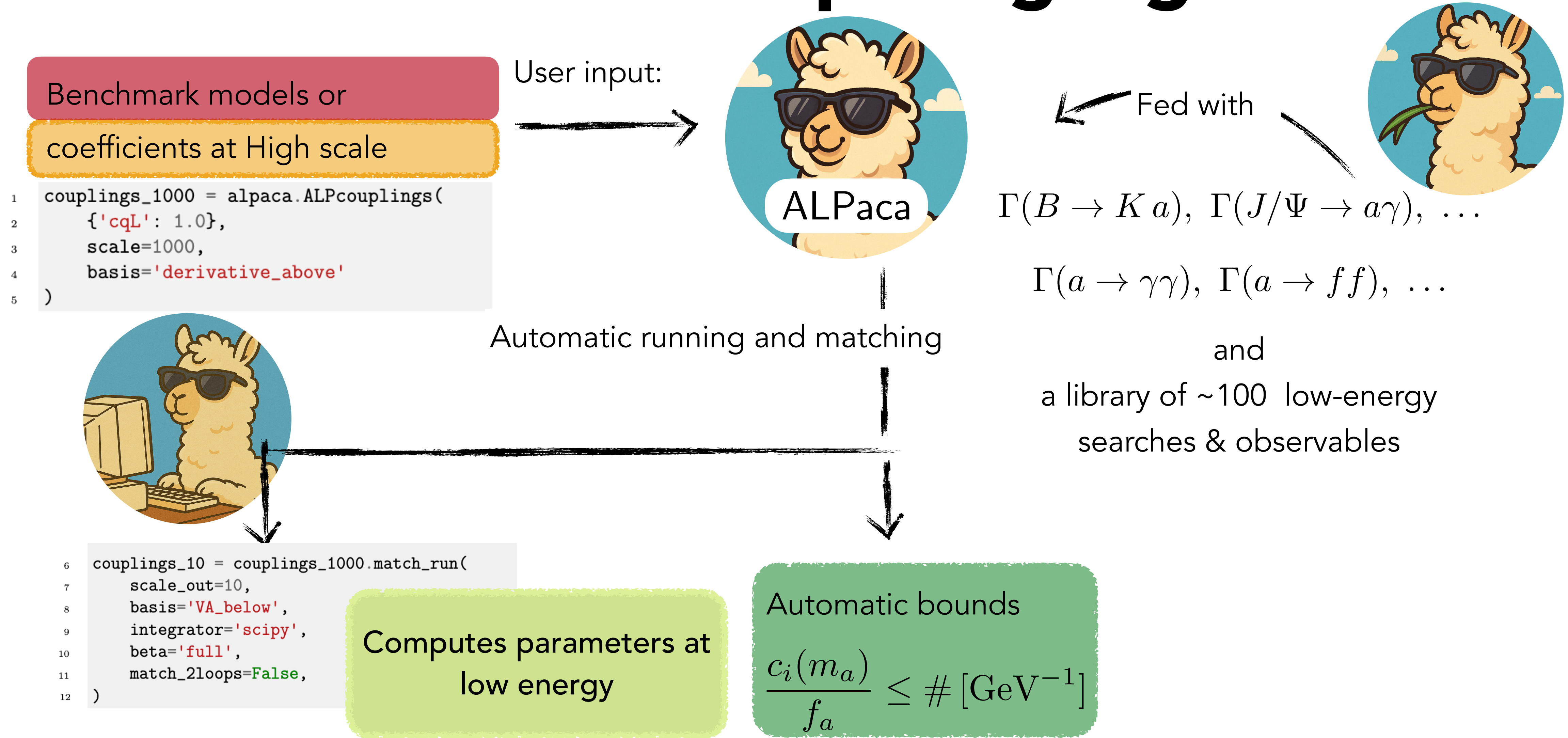
and

a library of ~ 100 low-energy
searches & observables

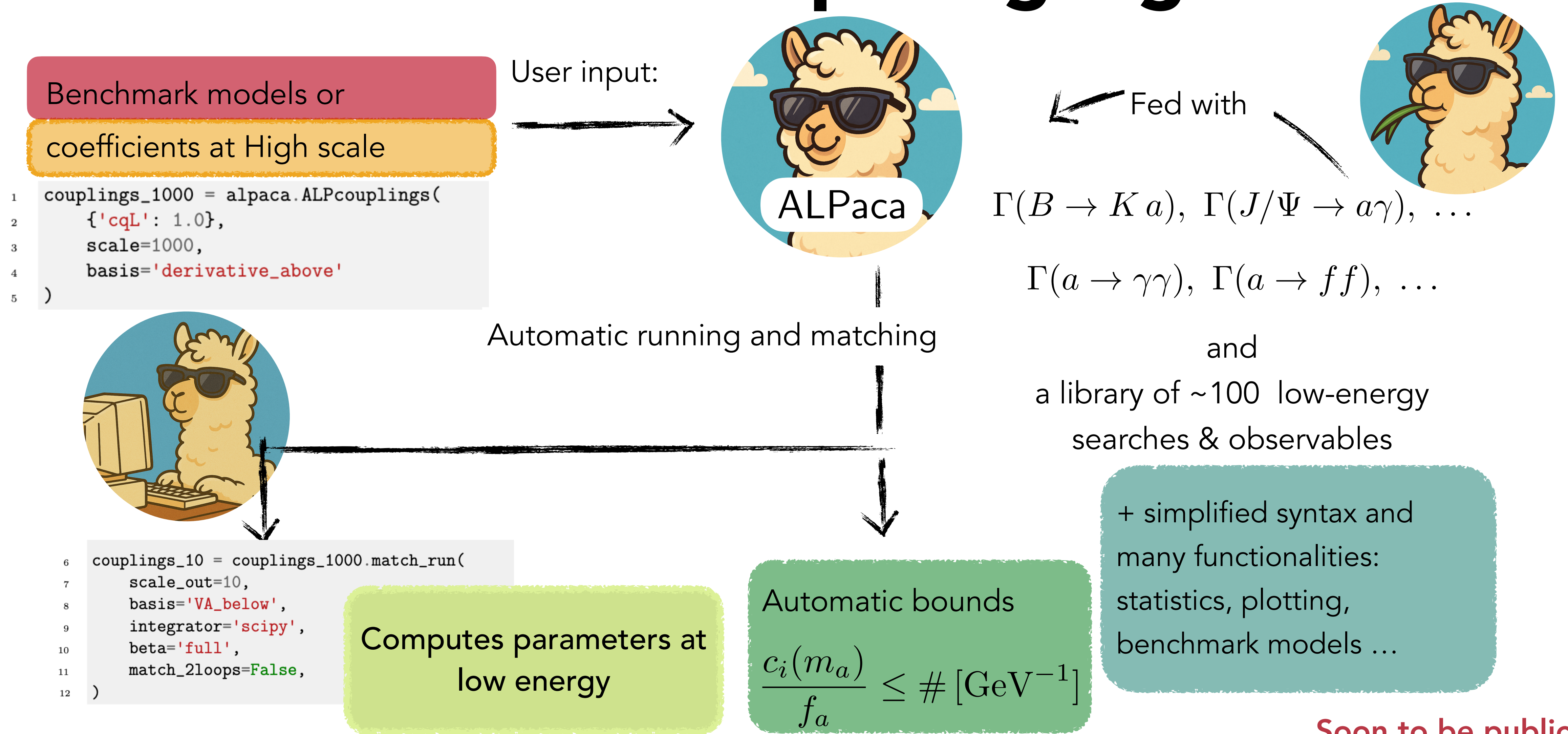
ALP-automated computing algorithm



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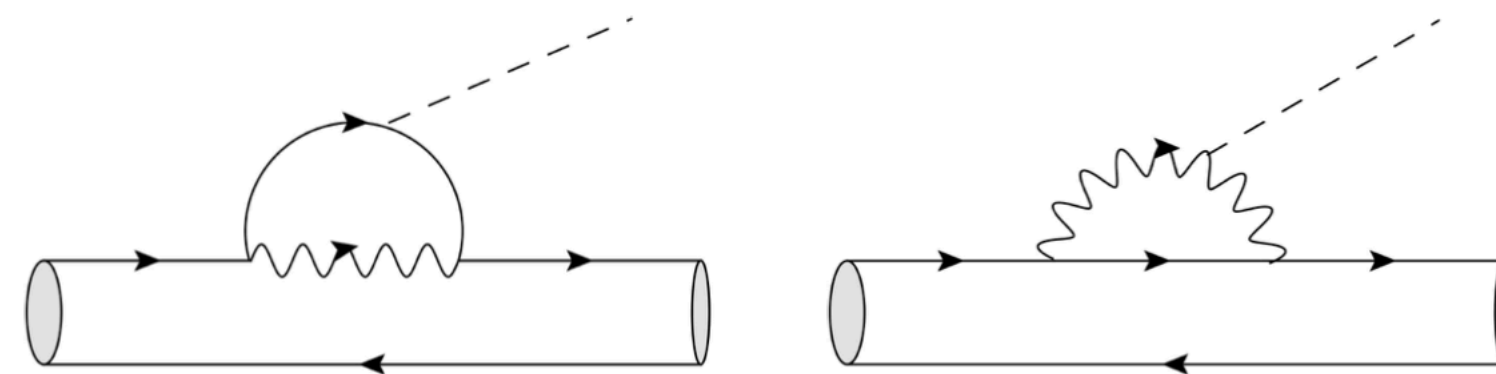
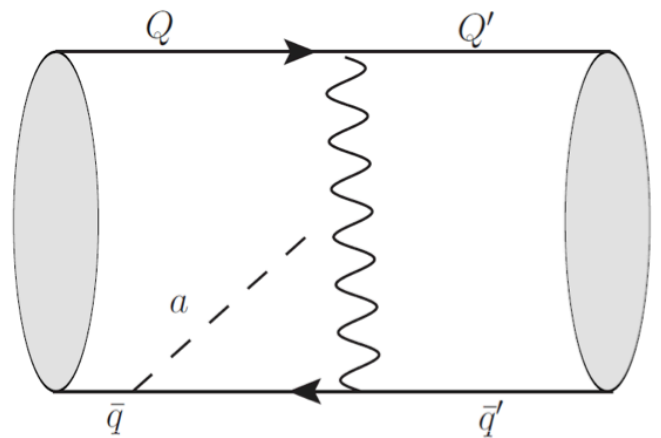
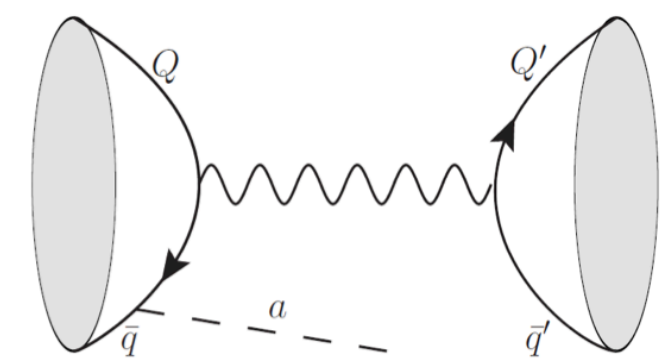
ALP-automated computing algorithm



ALP production

FCNC meson decays

Tree level vs Loop level



Form factor

$$P \rightarrow P(V)$$
$$V \rightarrow V(P)$$

$$R_{T/L} = \left| \frac{\mathcal{M}_T^{(s,t)}}{\mathcal{M}_L} \right| \approx 2 \pi^2 \frac{f_I f_F}{m_f^2} \left| \frac{V_T^{\text{CKM}}}{V_L^{\text{CKM}}} \right|$$

Need to consider both contributions

Lepage-Brodsky, χ PT

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

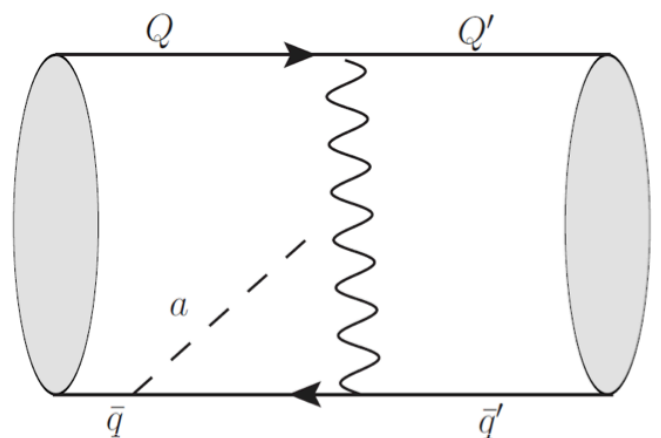
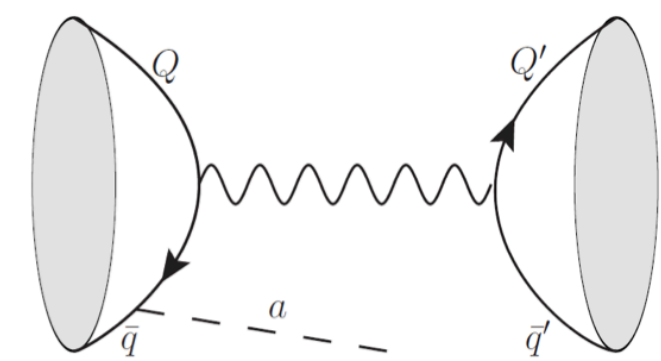
[A. Guerrera, S. Rigolin, Fortsch.Phys. 71 (2023) 2-3, 2200192]

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

ALP production

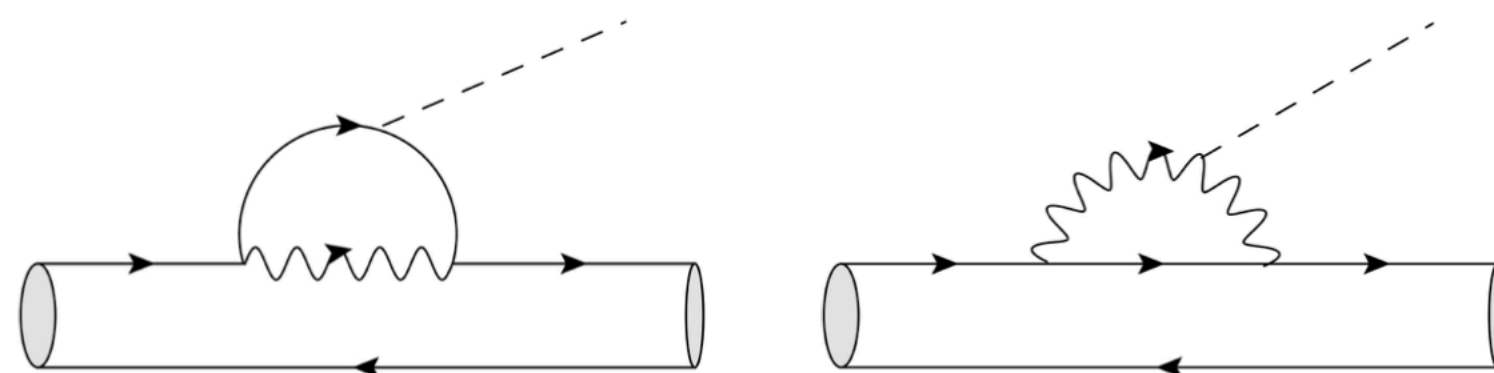
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Tree level vs Loop level



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Need to consider both contributions

Other observables:

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

ALP decays

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

Photons $\Gamma(a \rightarrow \gamma\gamma) = \frac{\alpha_{\text{EM}}^2 m_a^3}{(4\pi)^3 f_a^2} \left| \underset{\text{Tree level}}{c_\gamma} + \underset{\text{Loop level}}{c_\gamma^\ell} + \underset{\text{Hadronic}}{c_\gamma^X} + \underset{\text{Hadronic}}{c_\gamma^{\text{VMD}}} + \underset{\text{Hadronic}}{c_\gamma^{\text{pQCD}}} + \underset{\text{Loop level}}{c_\gamma^W} \right|^2$

[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: $\pi, \eta, \eta' \dots \rightarrow$ Mixing matrix with pseudo scalar and vector mesons relevant

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

[M. Ovchinnikov, A. Zaporozhchenko, 2501.04525]

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

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Possible decay to DM

 Tree level

 Loop level

 Hadronic

ALP decays

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

ALP decay length + experiment characteristics

ALP decays

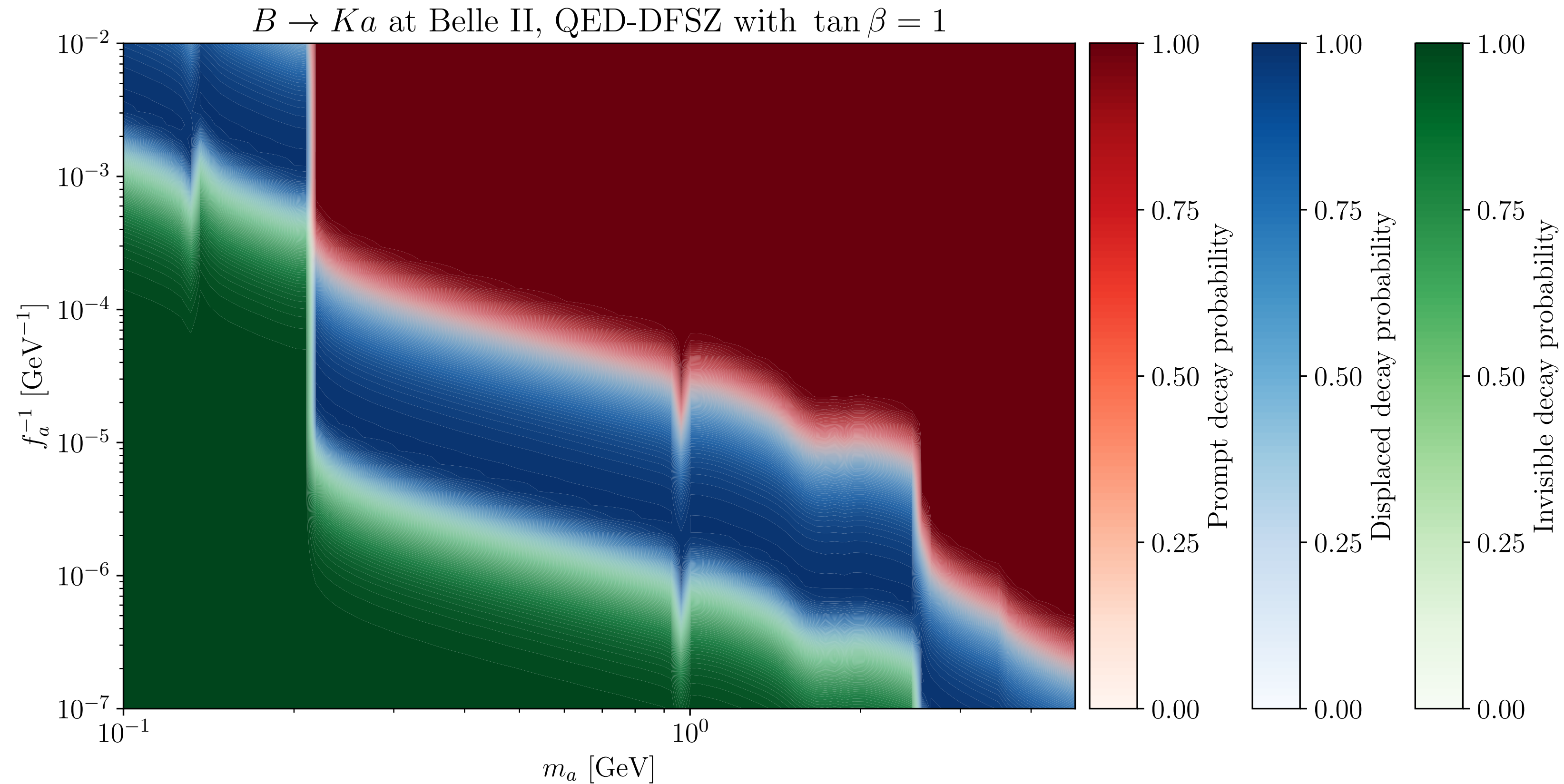
$$\text{BR}(X \rightarrow YZ)_{\text{NWA}} \approx \text{BR}(X \rightarrow Ya) \times \text{BR}(a \rightarrow Z)$$

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 detector → 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

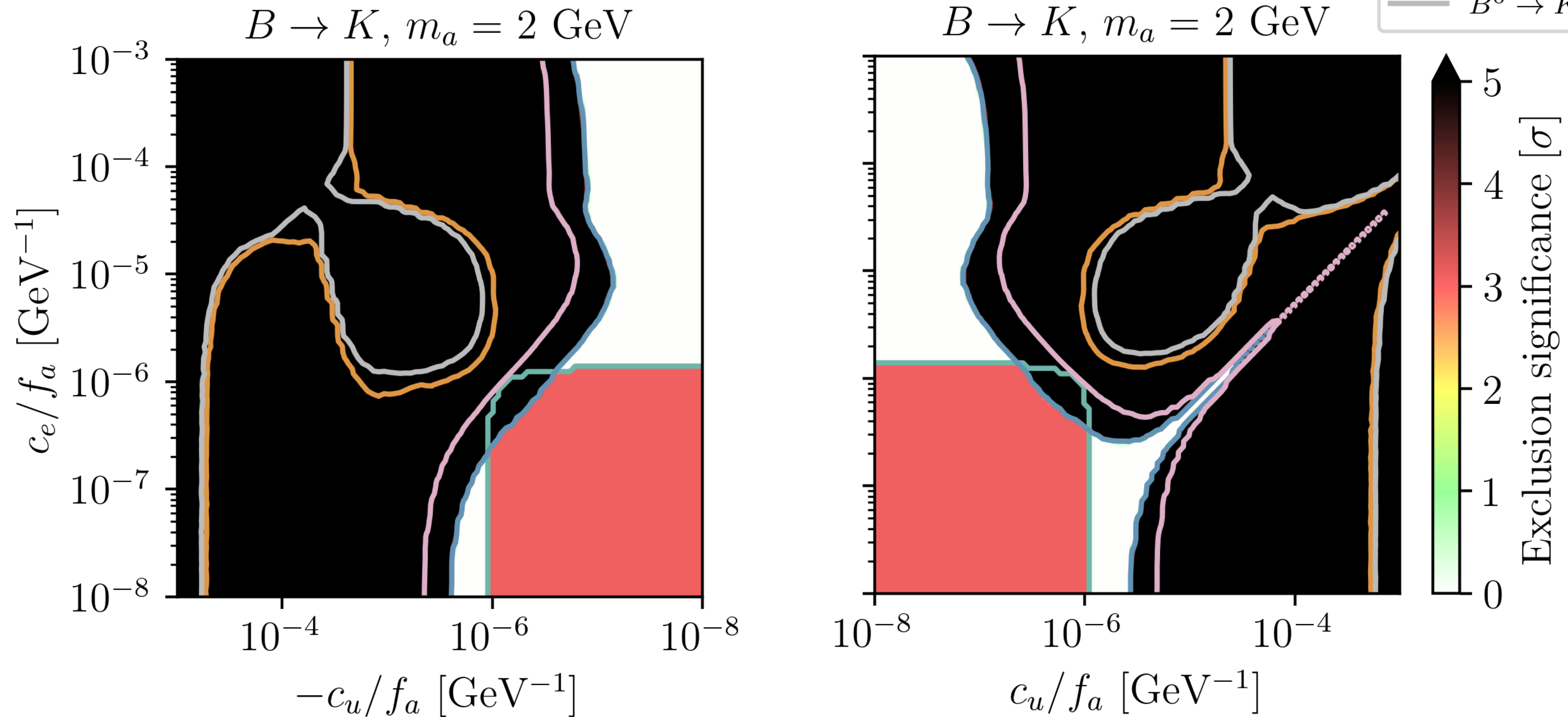
β_a, γ_a : determined by the kinematics

Phenomenology

B physics

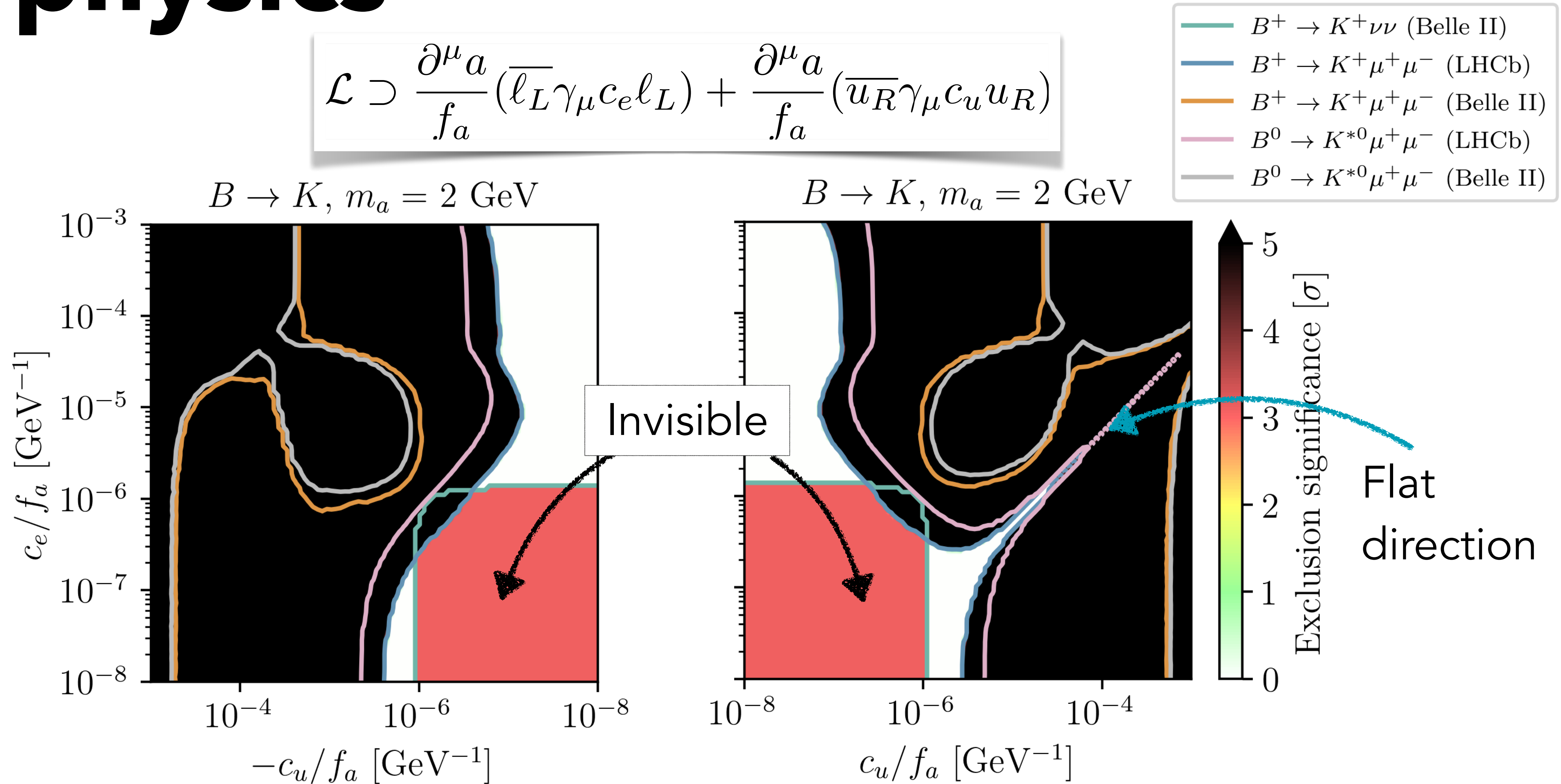
$$\mathcal{L} \supset \frac{\partial^\mu a}{f_a} (\bar{\ell}_L \gamma_\mu c_e \ell_L) + \frac{\partial^\mu a}{f_a} (\bar{u}_R \gamma_\mu c_u u_R)$$

- $B^+ \rightarrow K^+ \nu \nu$ (Belle II)
- $B^+ \rightarrow K^+ \mu^+ \mu^-$ (LHCb)
- $B^+ \rightarrow K^+ \mu^+ \mu^-$ (Belle II)
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (LHCb)
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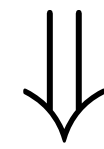
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Belle II anomaly

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



2.7 σ discrepancy!

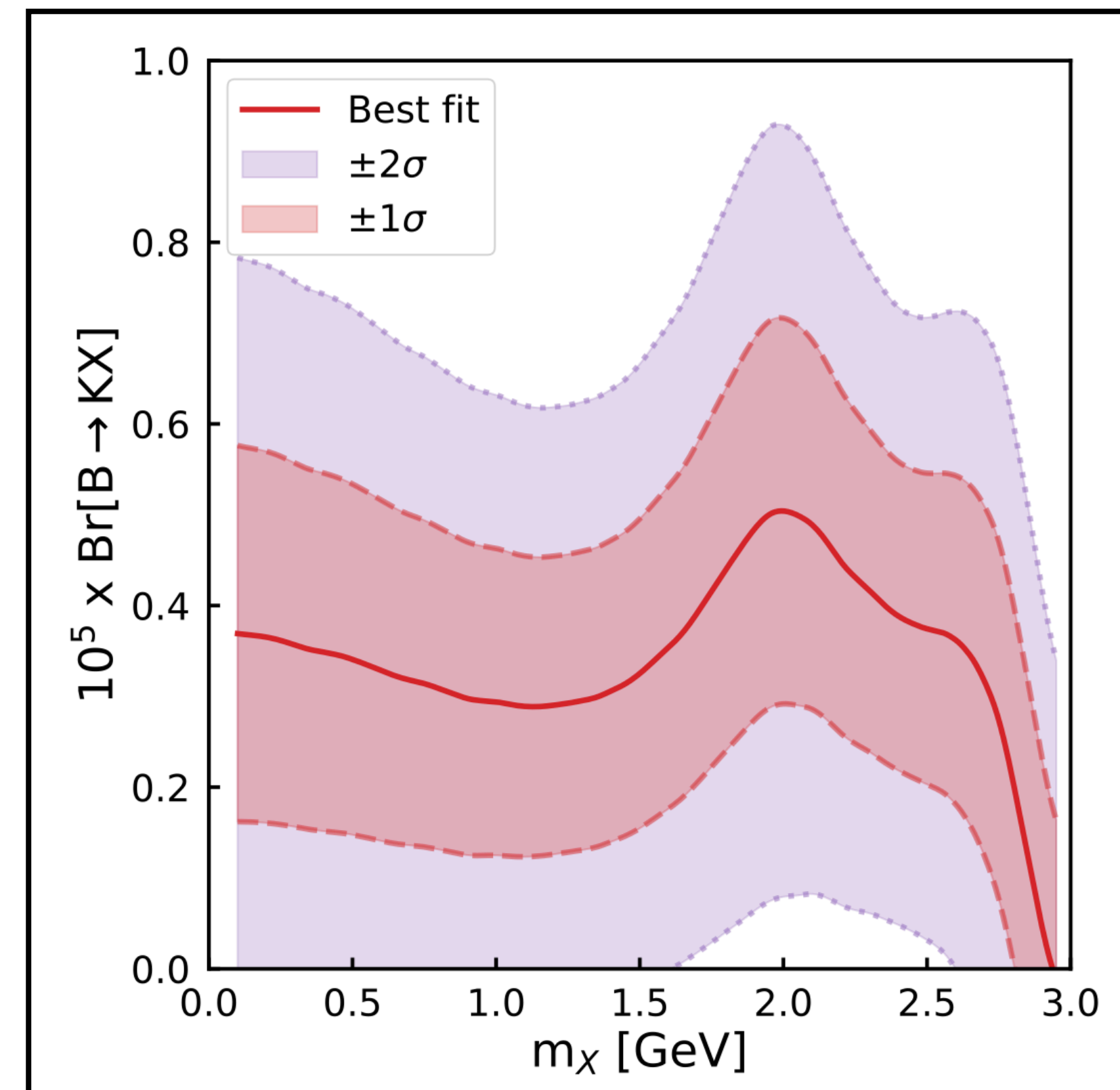
Possible solution:

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

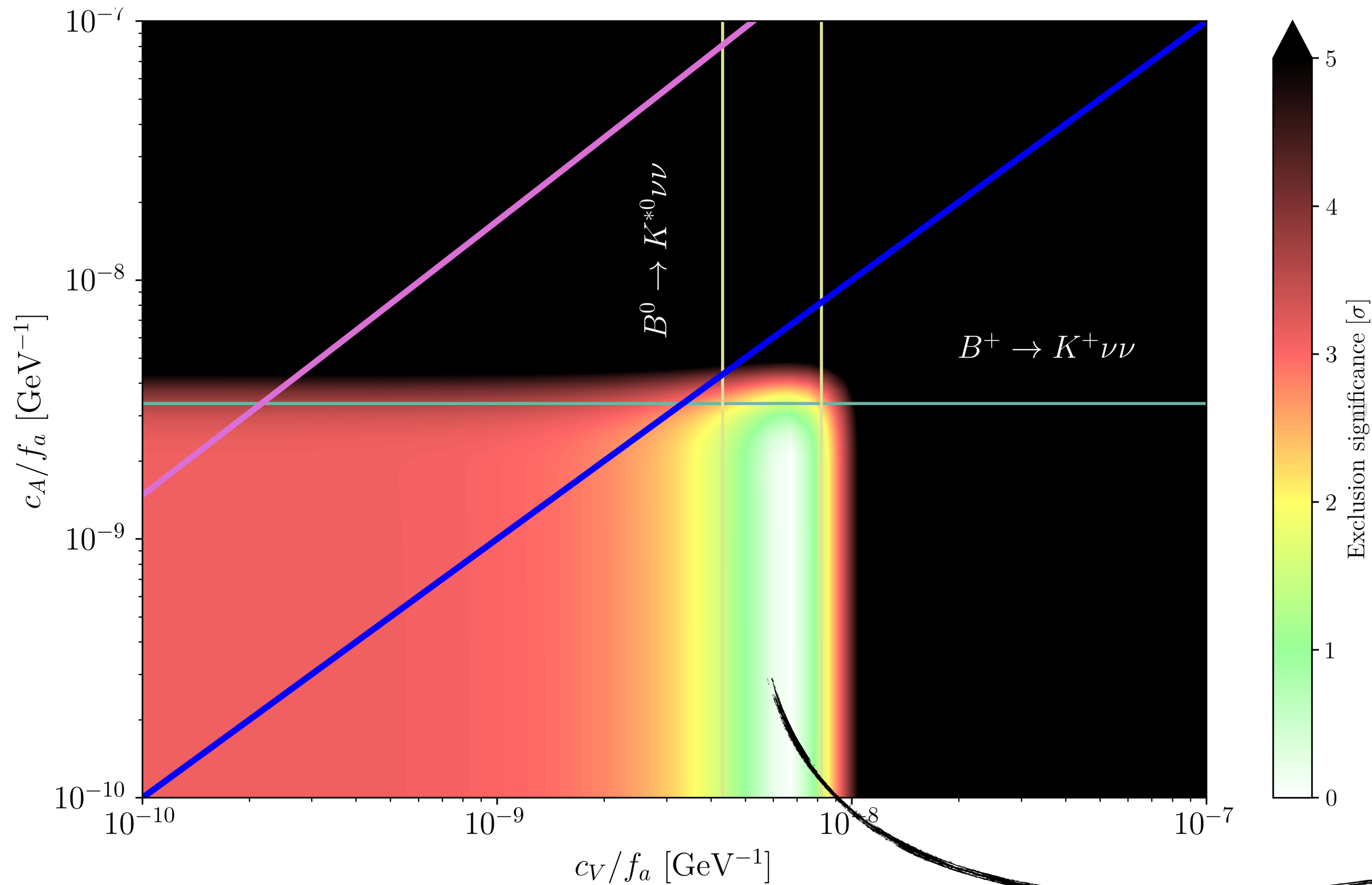
ALP mass $m_a = 2 \text{ GeV}$

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

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

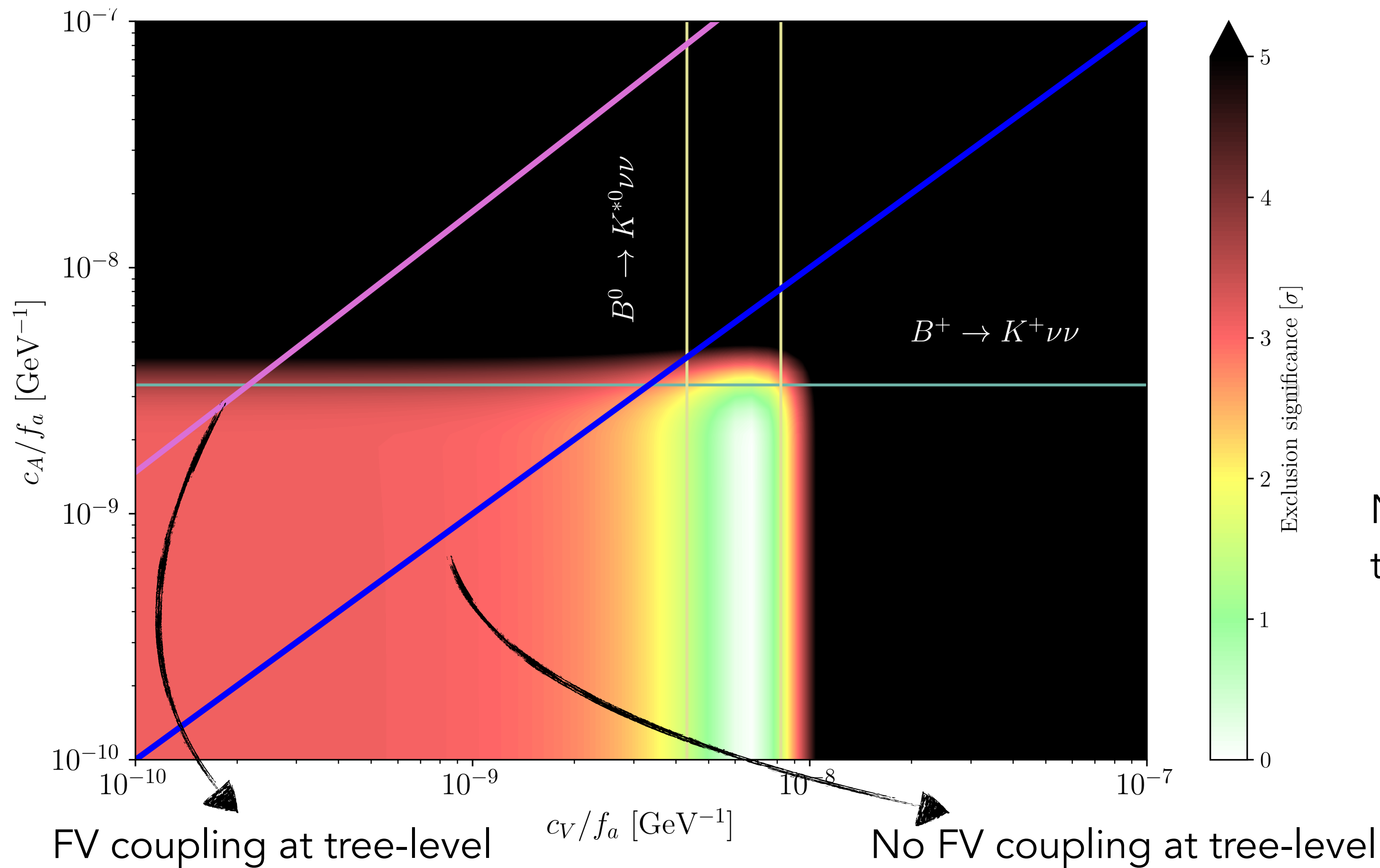


Belle II anomaly



Agreement with
Altmannshofer et al.

Belle II anomaly



Flaxion: tree-level
flavour violation

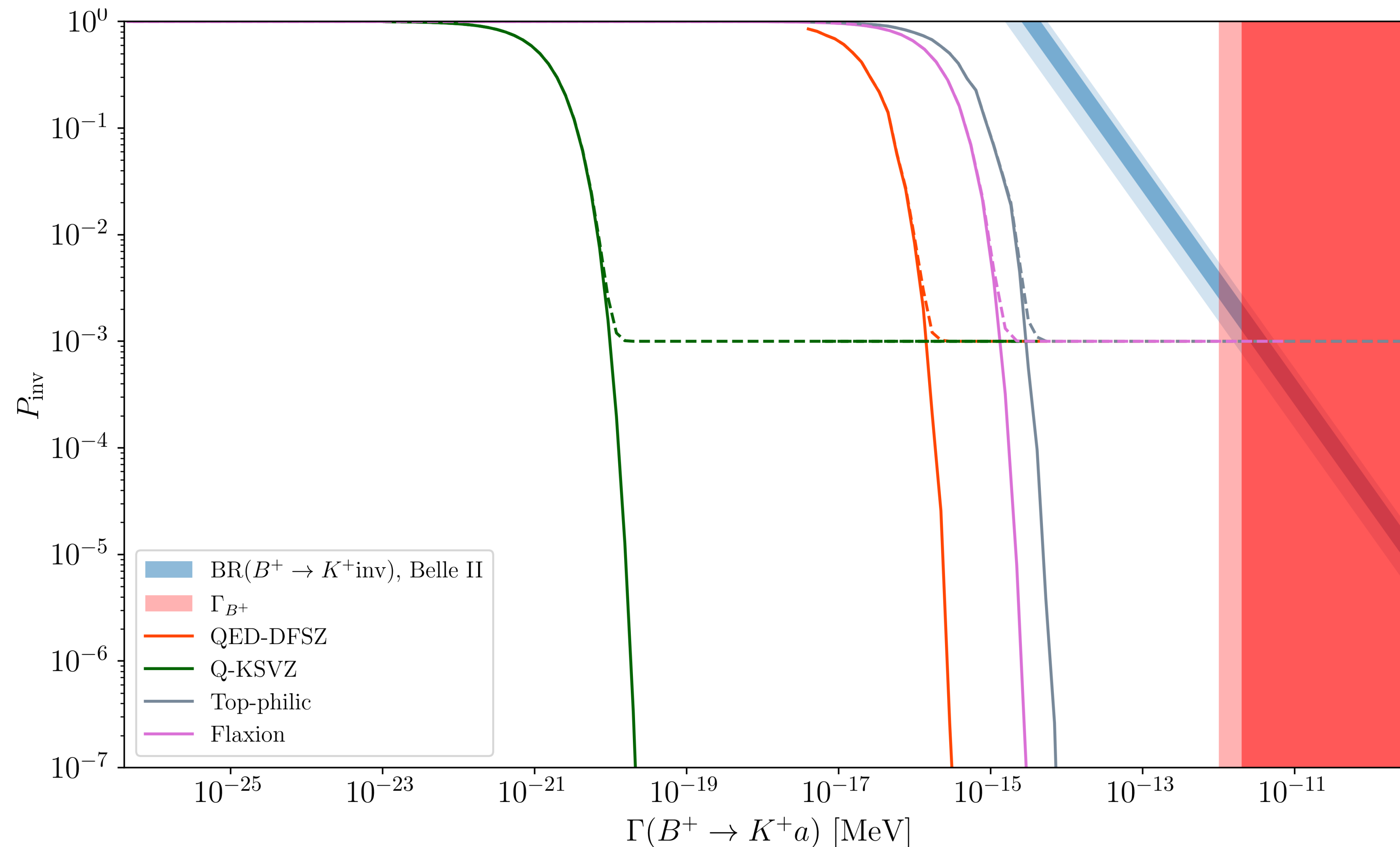
[Y. Ema, K. Hamaguchi, T. Moroi, and K. Nakayama, JHEP 01 (2017) 096]

Top-philic: only
coupling to c_{t_R}

QED-DFSZ: order
one coupling to
fermions

Q-KSVZ: $c_g = 1$

Belle II anomaly



Flaxion: tree-level
flavour violation

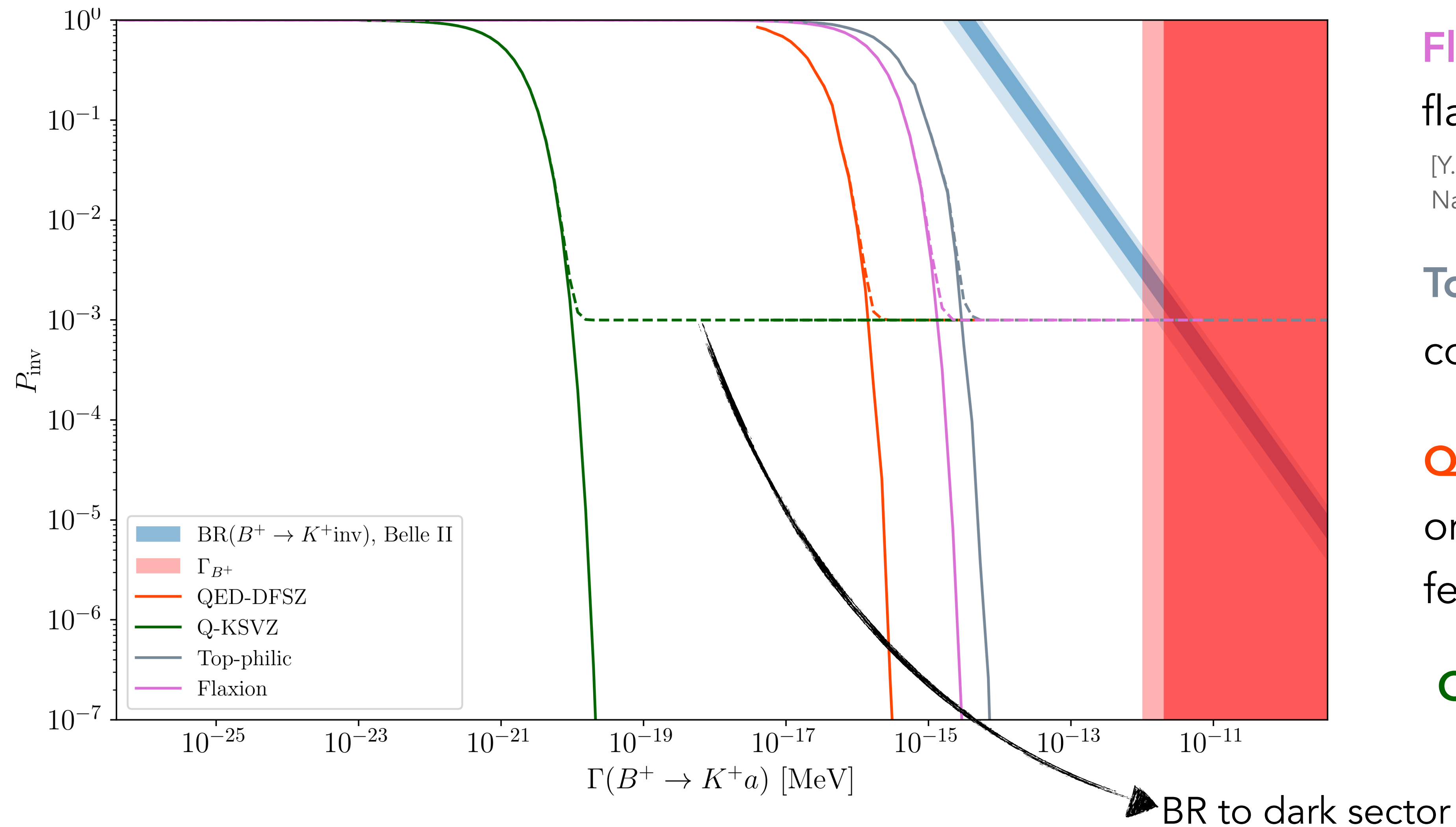
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Conclusions

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

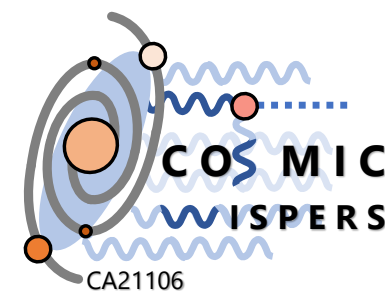
Work supported by:

PID2019-108892RB-I00, PID2022-137127NB-I00,
CEX2020-001007-S, COST Action COSMIC WISPers CA21106,
FPU22/03625

funded by

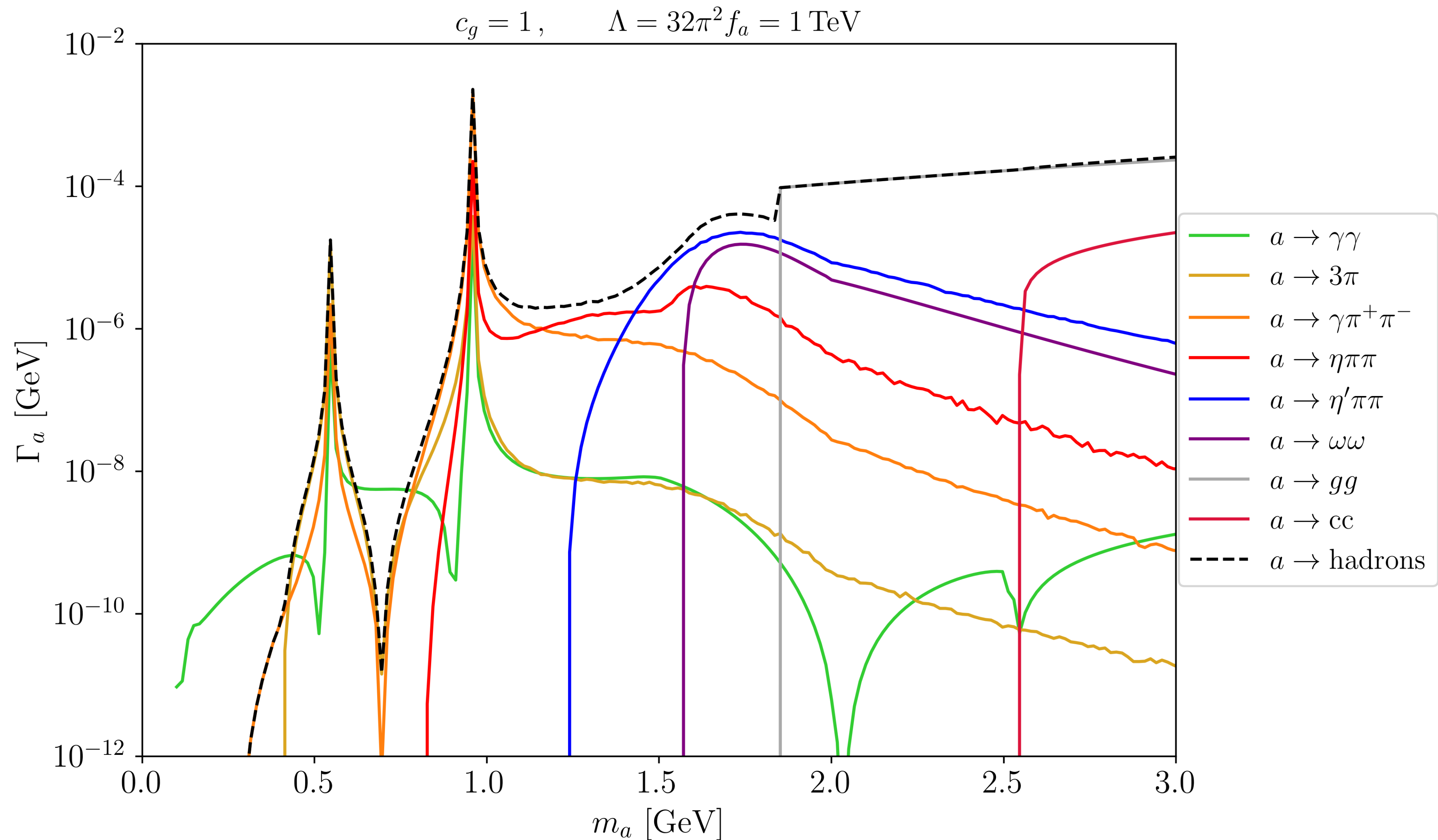


EXCELENCIA
SEVERO
OCHOA



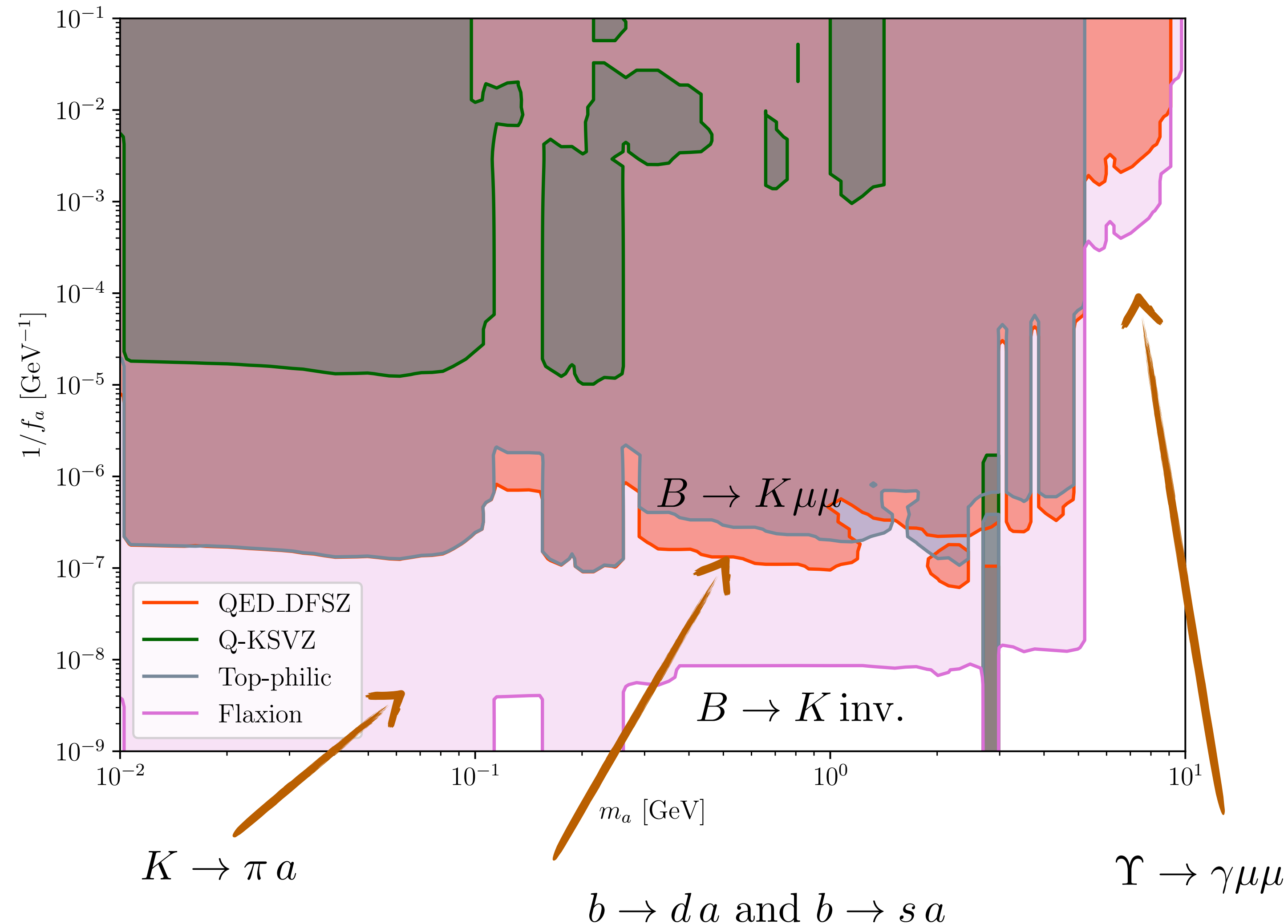
Back up slides

Hadronic decays



Benchmark models

JHEP 01 (2017) 096,



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