OVERVIEW FOR AXIONS AND ALPS

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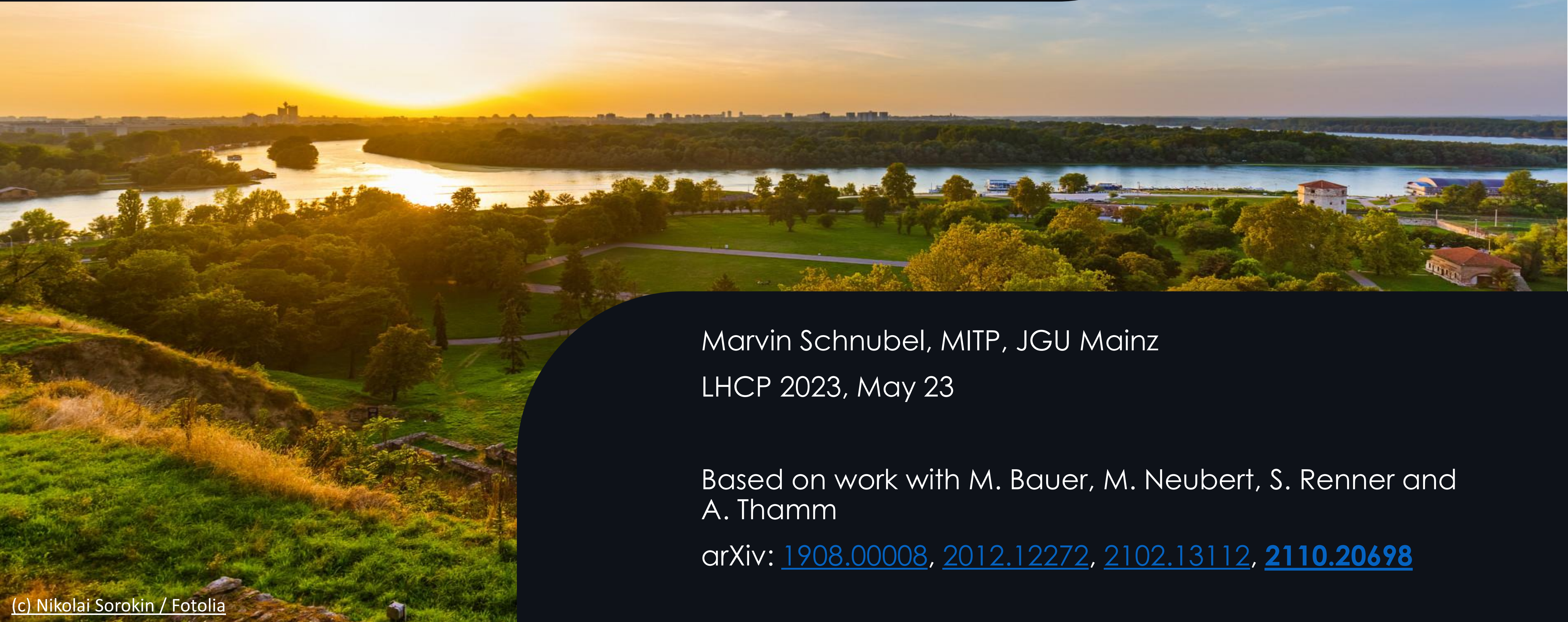
LHCP 2023, May 23

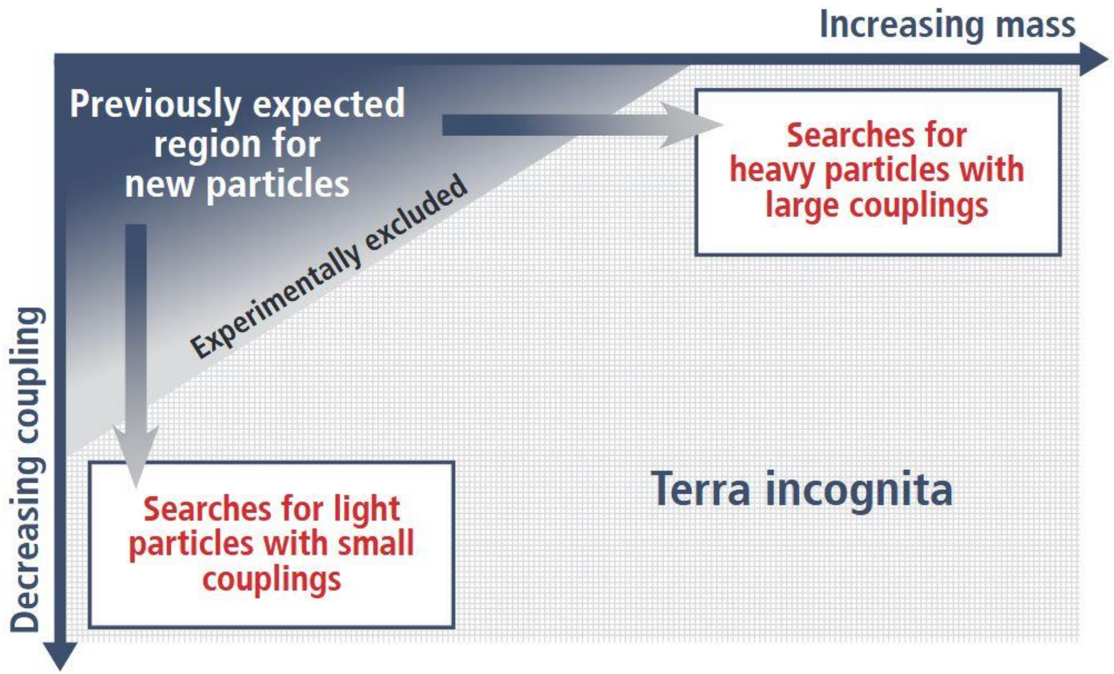
Based on work with M. Bauer, M. Neubert, S. Renner and A. Thamm

arXiv: 1908.00008, 2012.12272, 2102.13112, **2110.20698**



MOTIVATION

- Plenty of (in)direct hints for new physics: ν-oscillations, $(g-2)_\mu$, dark matter…
- Light and weakly coupled particles provide an interesting alternative to heavy new physics
- In this talk focus on ALPs, axions are retrieved in the small mass limit.



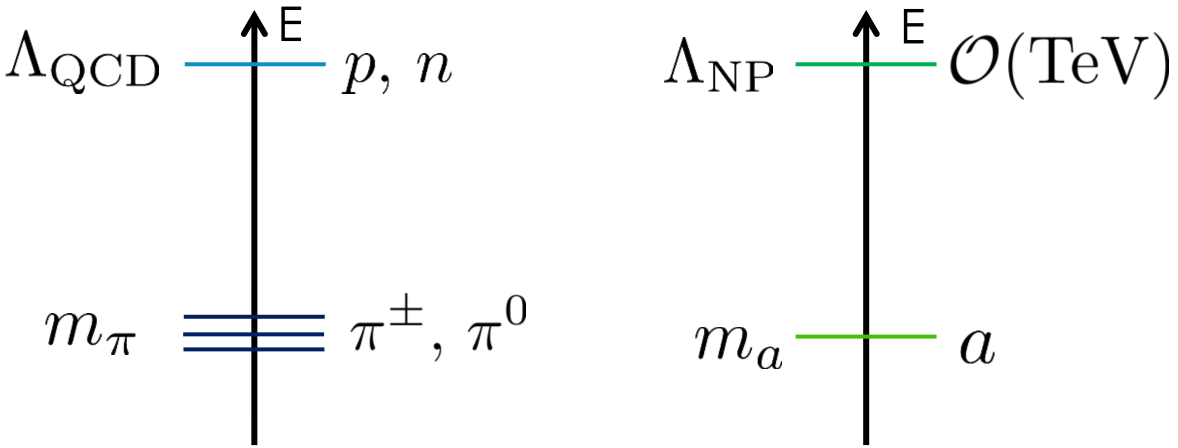
- Many explicit models for ALPs: QCD axion, flavon, familon, comp. Higgs

[Peccei, Quinn (1977)] [Alanne, Blasi, Goertz(2019)] [Gherghetta, Nguyen (2020)]

WHY AXIONS/ALPS?

Model building

- Any dynamics with a spontaneously broken (approximate) global symmetry will produce light, spinless particles (Goldstone theorem). Analogy with pions in QCD



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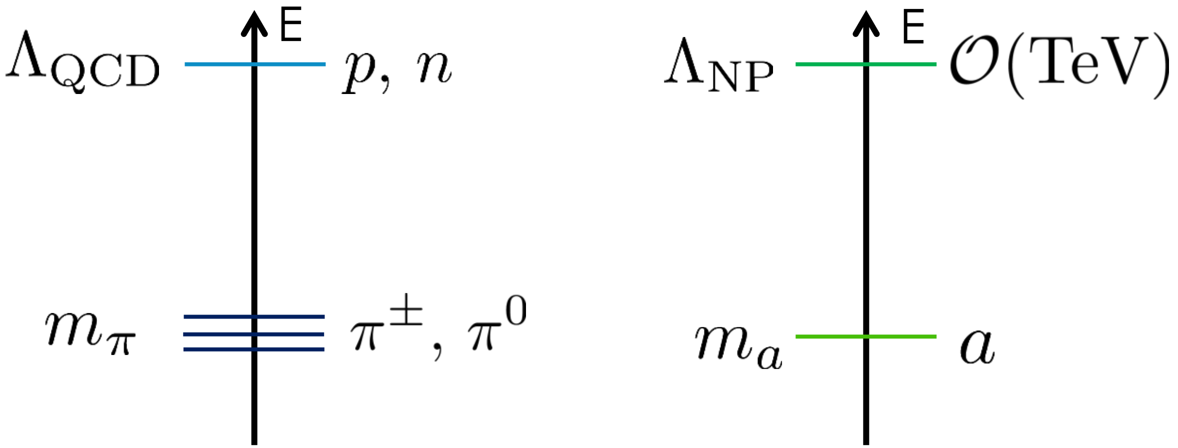
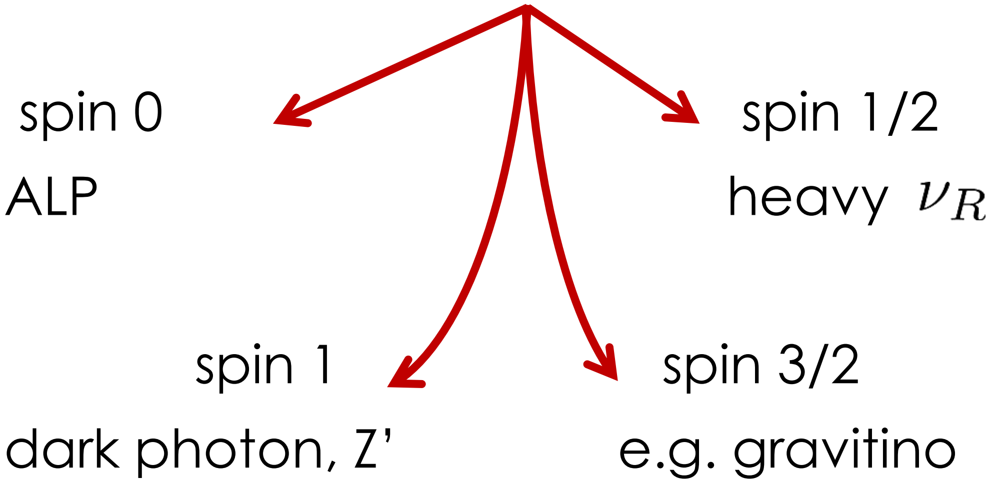


Model independent

- All new particles heavy: $m_{\rm NP} \gg \Lambda_{\rm NP}$
  - ➢ SMEFT (or similar)
- Light BSM particles:



THE ALP LAGRANGIAN

- Don't need to know the details of the UV physics to study ALPs
- Describe as an effective field theory (EFT) as SM+ALP
- Most general ALP Lagrangian:

ALPs: explicit mass term
axions: generated through instanton effects

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{f} \sum_F \bar{\psi}_F \mathbf{c}_F \gamma^\mu \psi_F$$

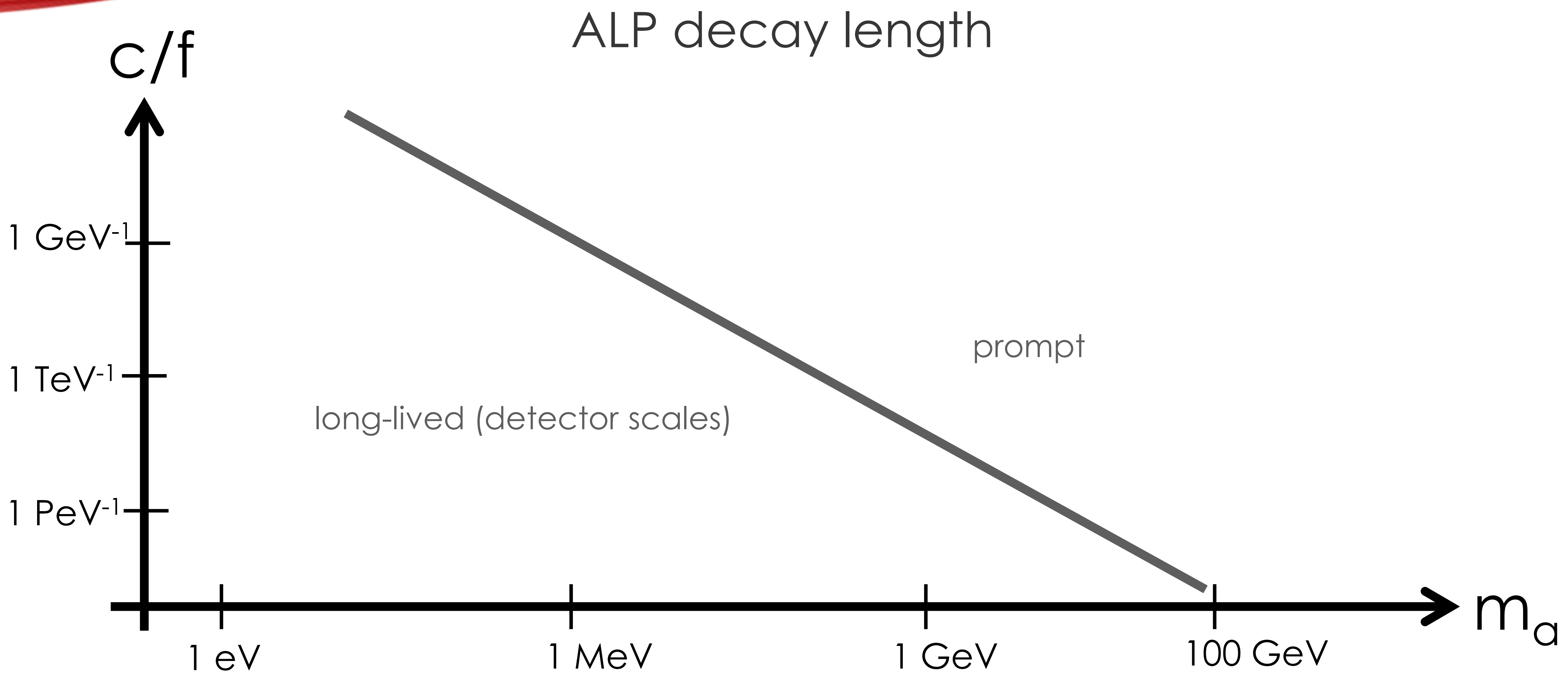
[Georgi, Kaplan, Randall (1986)]

$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

pre-factor ensures gauge couplings are scale independent

$$\tilde{V}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} V_{\alpha\beta}$$

ALP PHENO IN A NUTSHELL



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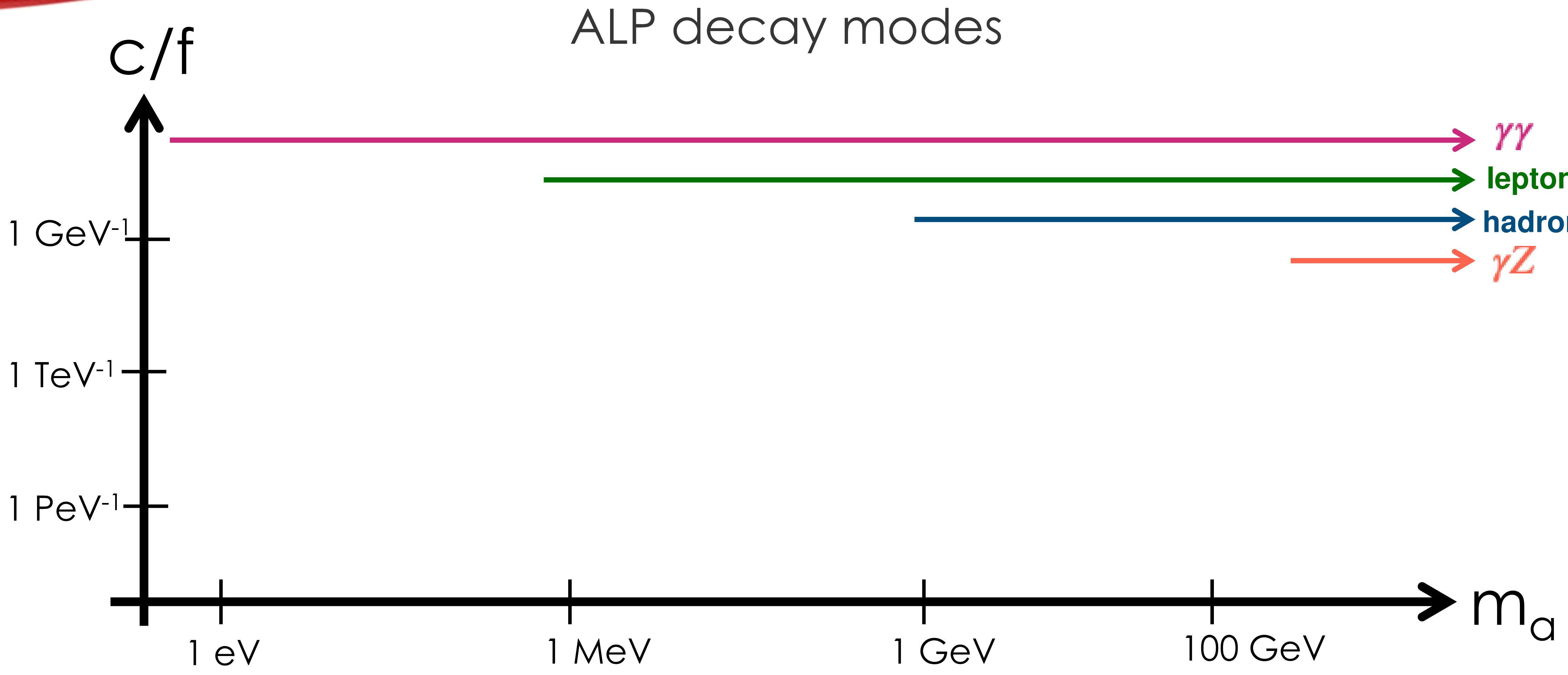

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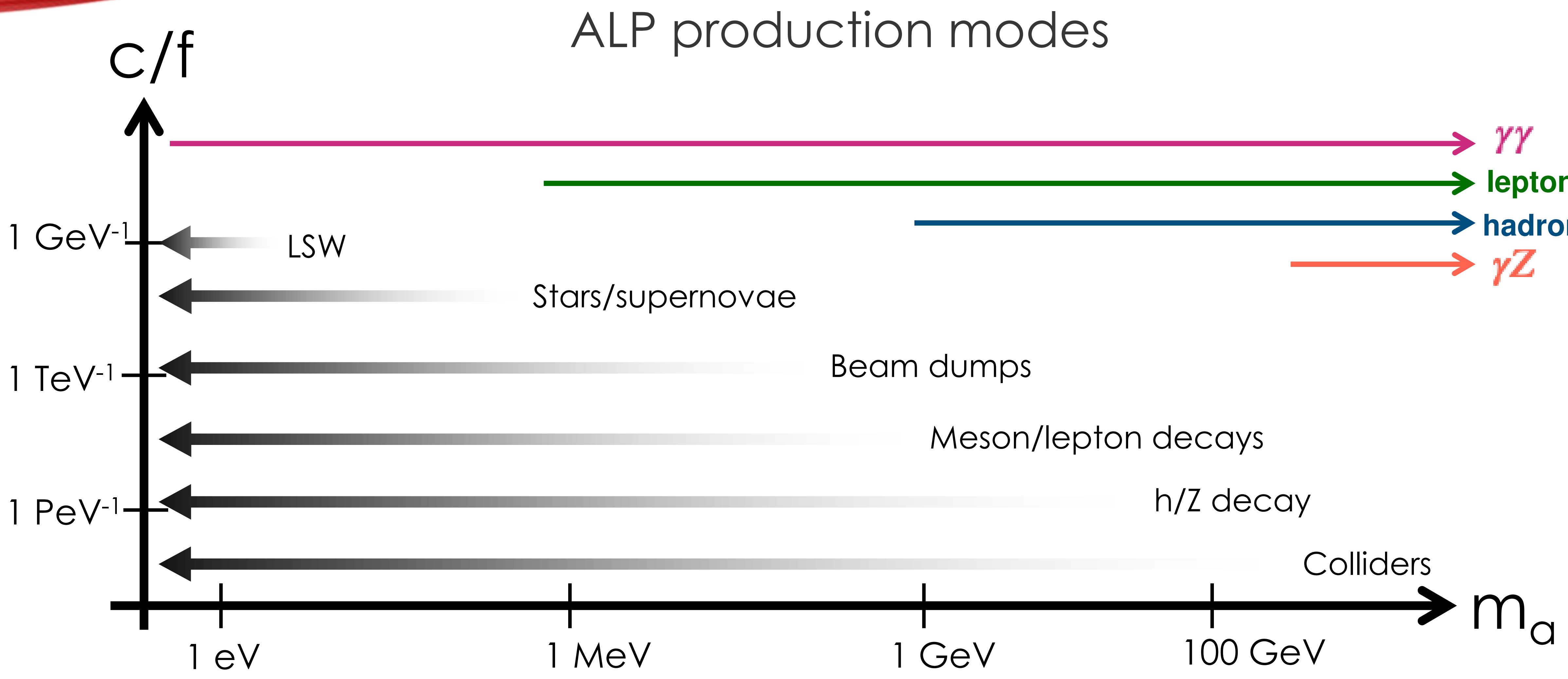

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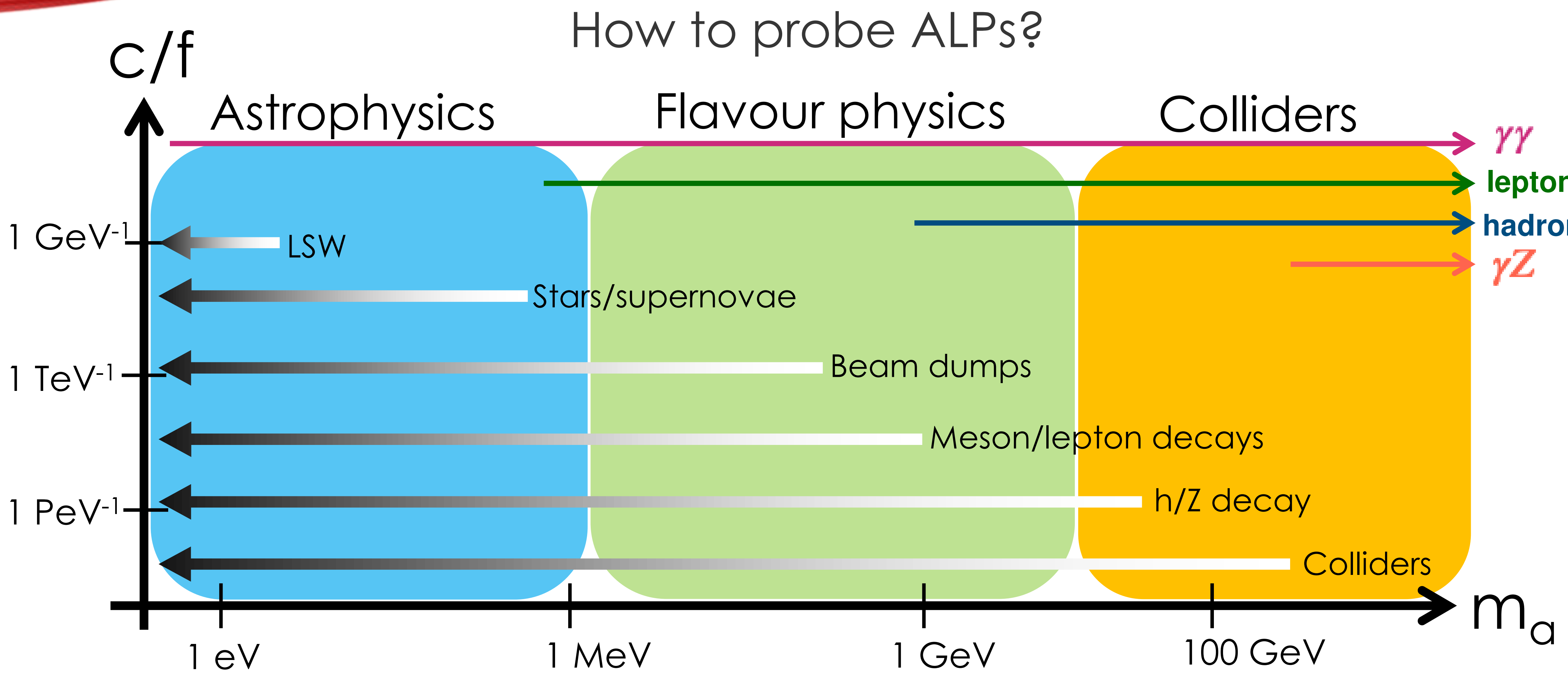
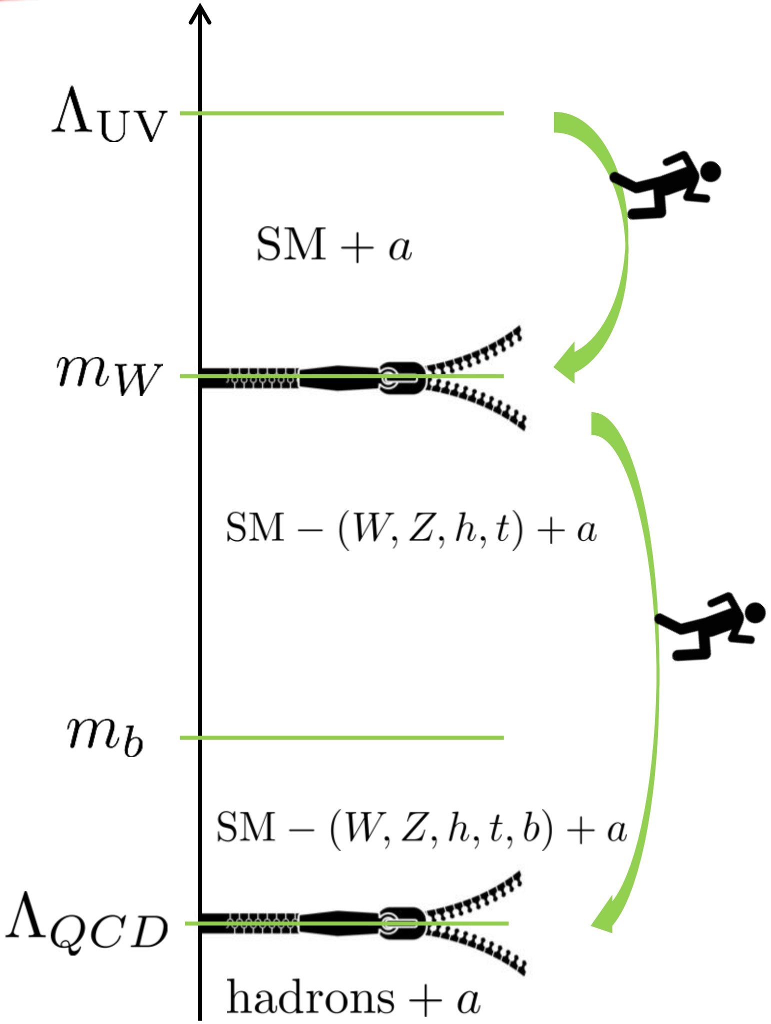


FLAVOUR EFFECTS



- ALP couplings determined by UV physics
- Connection to observables by running and matching to lower scales

See also [Choi, Im, Park, Yun (2017)
Chala, Guedes, Ramos, Santiago (2020)]

FLAVOUR EFFECTS

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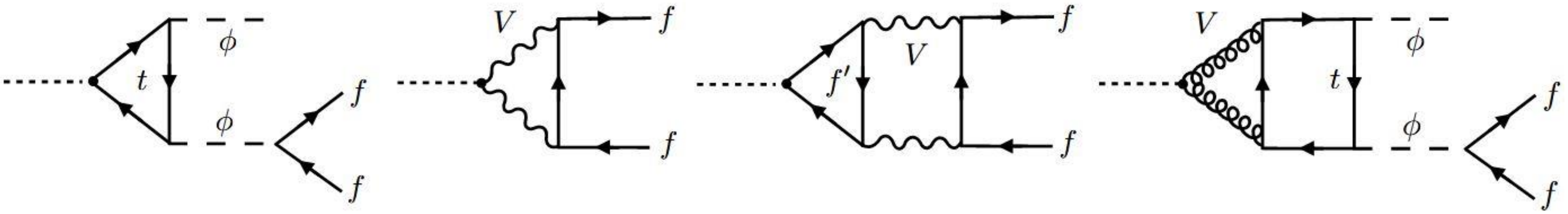
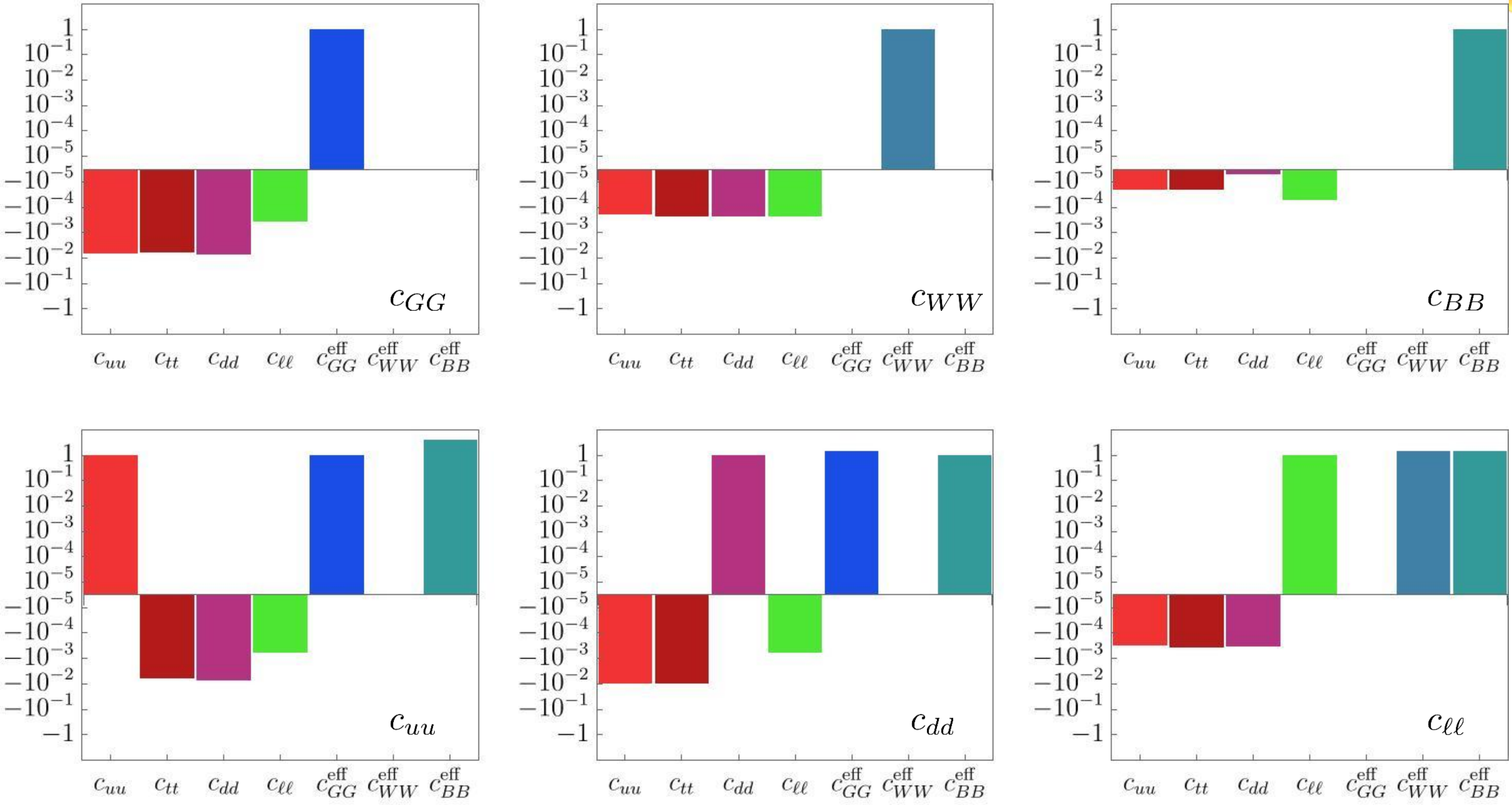
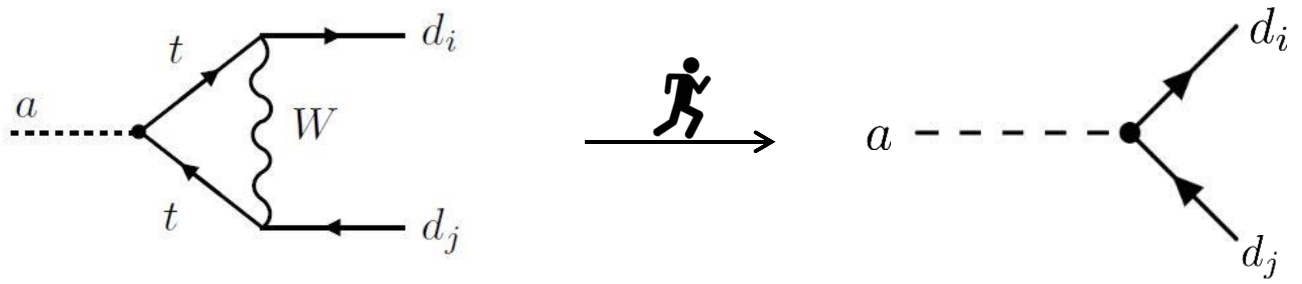
- Connection to observables by running and matching to lower scales See also [Choi, Im, Park, Yun (2017) Chala, Guedes, Ramos, Santiago (2020)]
- Generate ***flavour-conserving*** effects:




c_{GG}
c_{WW}
c_{BB}
c_{uu}
c_{dd}
$c_{\ell\ell}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
-10^{-5}
-10^{-4}
-10^{-3}
-10^{-2}
-10^{-1}
-1
c_{uu} c_{tt} c_{dd} $c_{\ell\ell}$ c_{GG}^{eff} c_{WW}^{eff} c_{BB}^{eff}

FLAVOUR EFFECTS

- ALP couplings determined by UV physics
- Connection to observables by running and matching to lower scales See also [Choi, Im, Park, Yun (2017) Chala, Guedes, Ramos, Santiago (2020)]
- Generate ***flavour-changing*** effects:



$$k_D(m_t)_{ij} \simeq 10^{-5} V_{ti}^* V_{tj} \Big[-6.1 c_{GG} - 2.8 c_{WW} - 0.02 c_{BB} - 1.9 \times 10^3 c_Q + 1.9 \times 10^3 c_u - 9.2 c_d + 4.2 c_L - 0.05 c_e \Big]$$

fermion couplings evaluated at Λ_{NP}

FLAVOUR EFFECTS

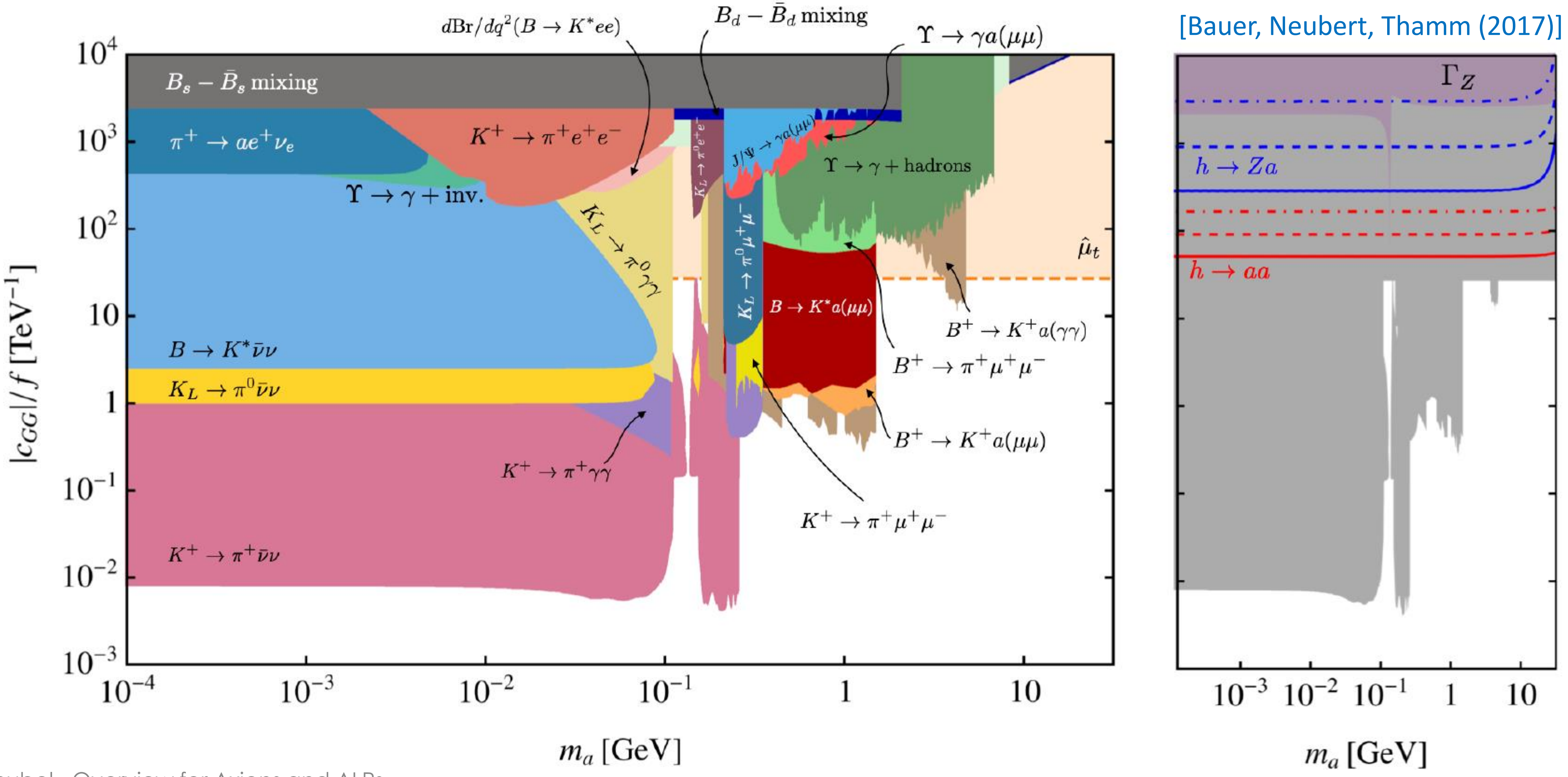
- ALP couplings determined by UV physics
- Connection to observables by running and matching to lower scales See also [Choi, Im, Park, Yun (2017) Chala, Guedes, Ramos, Santiago (2020)]

An ALP coupling to any particle in the UV will generate an effective coupling to **all** SM particles (including flavour-changing ones)!

BENCHMARK SCENARIOS

- Simplified scenario: only coupling to gluons $c_{GG} \neq 0$

[Bauer, Neubert, Thamm (2017)]



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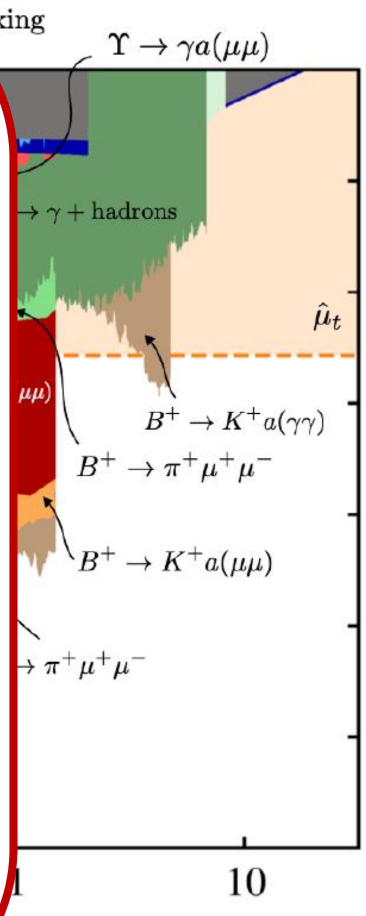

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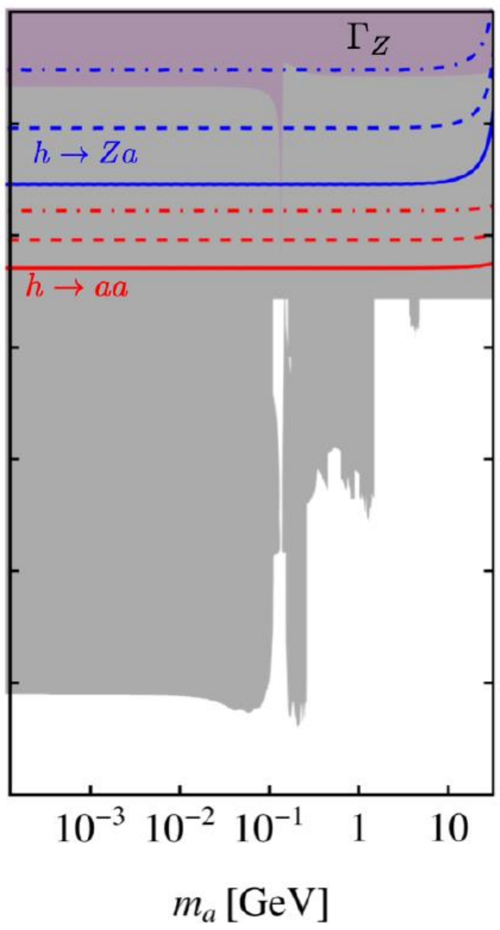

- Chromomagnetic moment constraint relies on the fact that the ALP doesn't contribute to underlying top production process

- Comparison with astrophysics difficult, because c_{GG} induces both large $c_{\gamma\gamma}$ and nucleon coupling

BENCHMARK SCENARIOS

- Simplified scenario: only coupling to weak gauge bosons $c_{WW} \neq 0$

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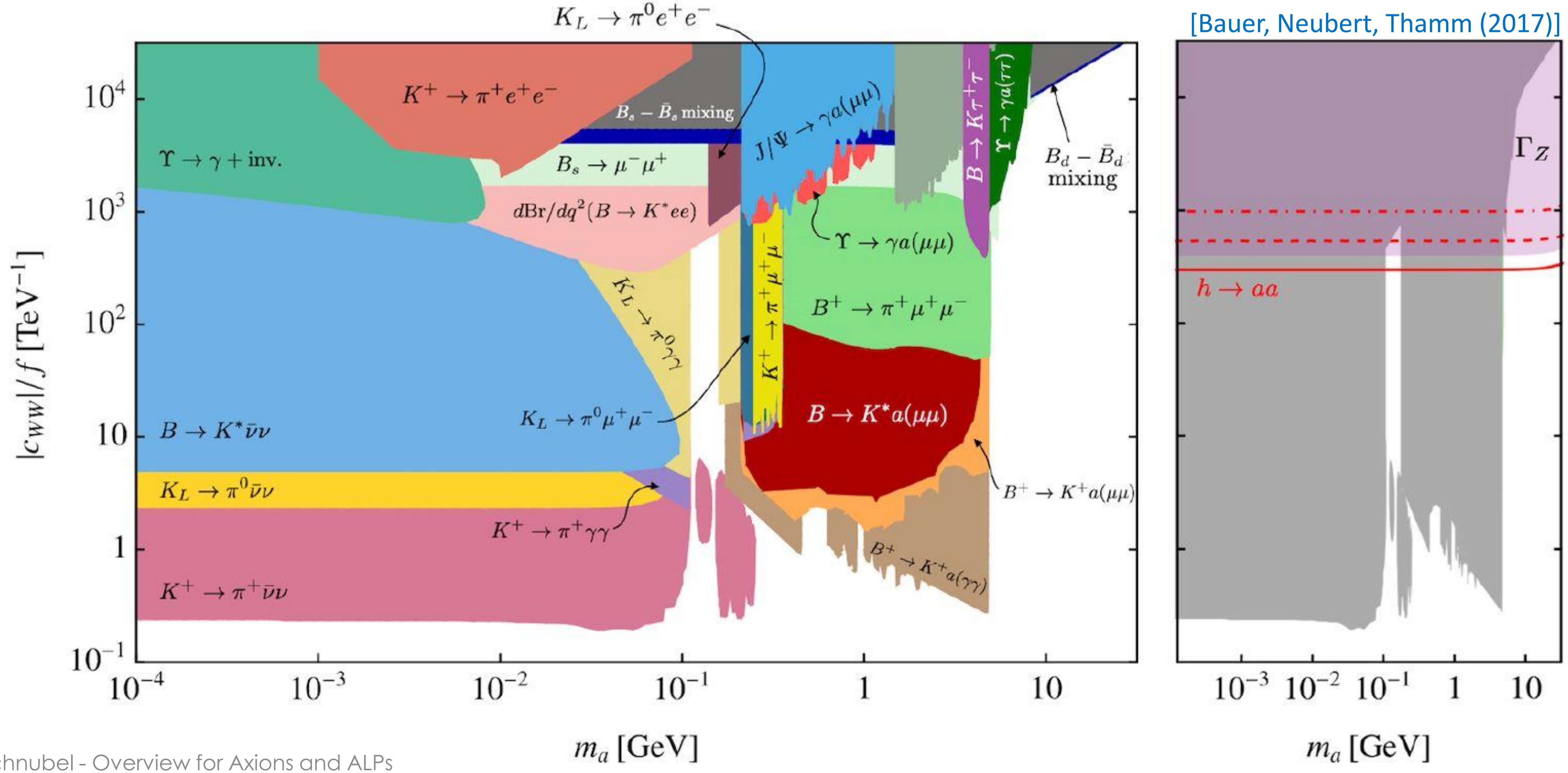

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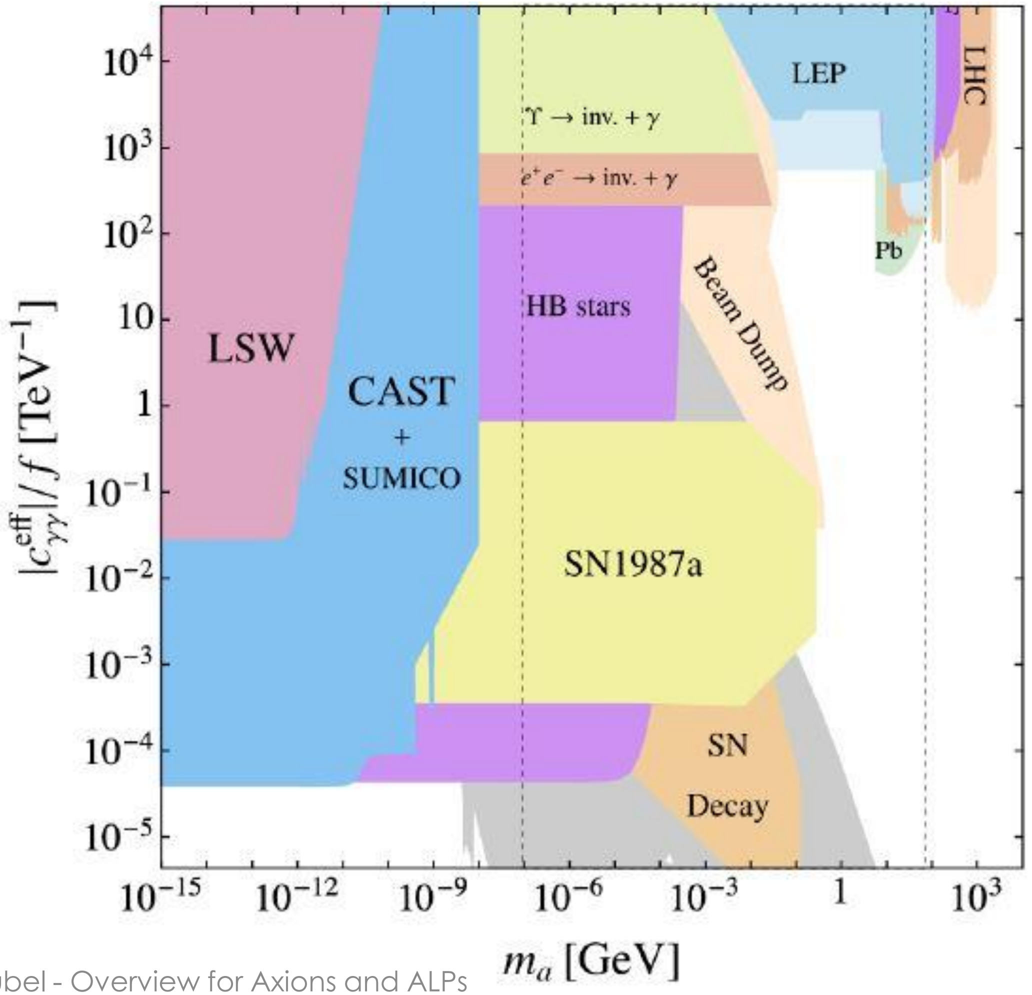
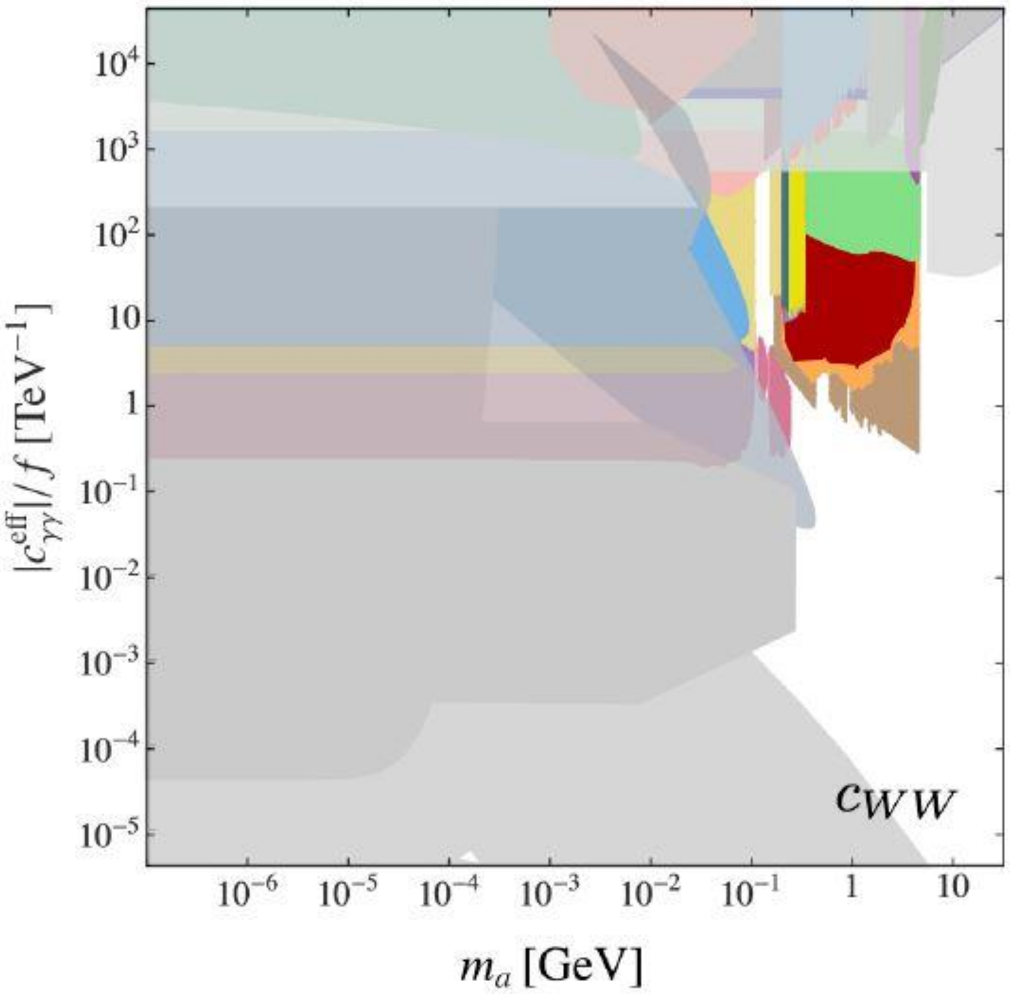
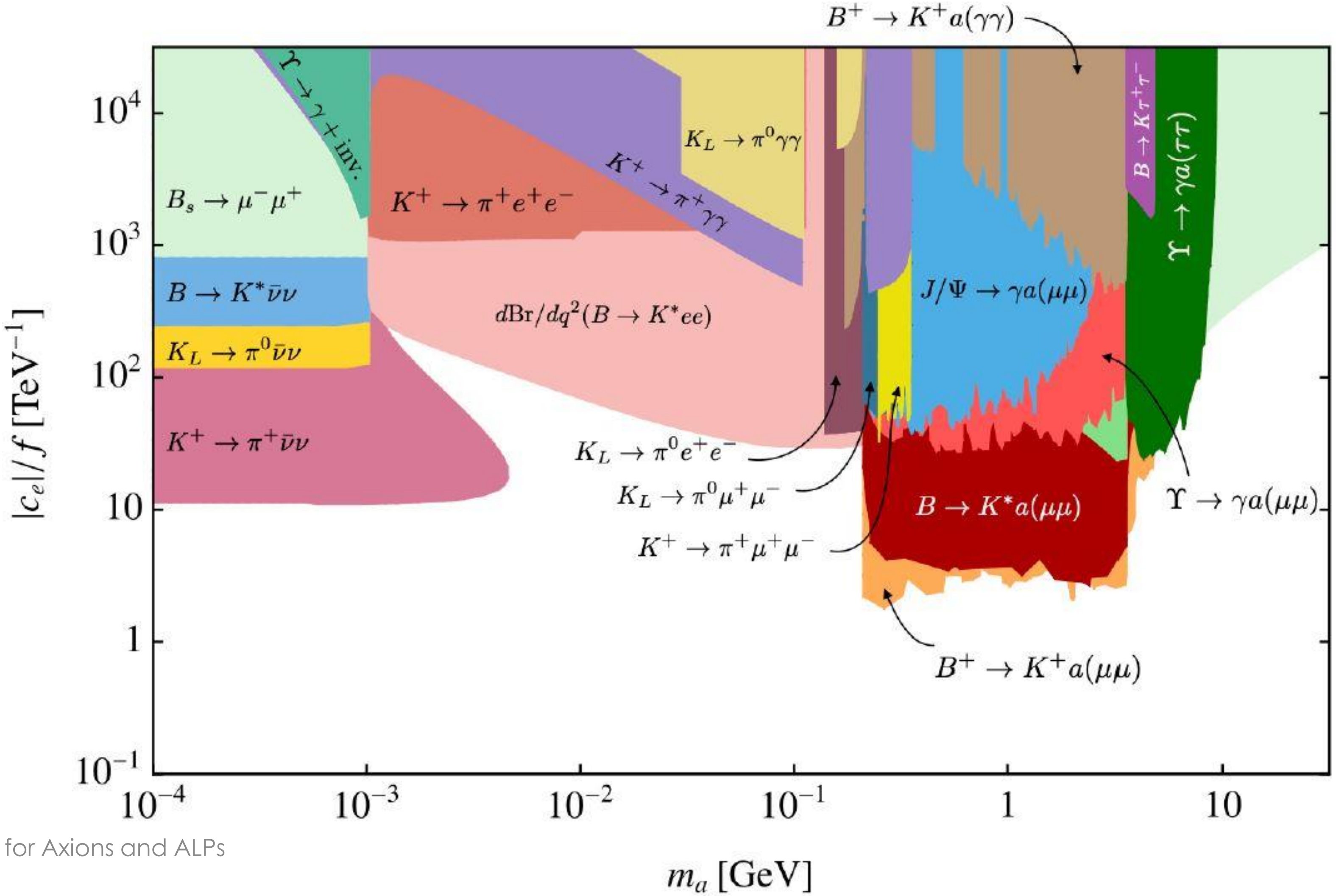




BENCHMARK SCENARIOS

- Simplified scenario: only coupling to leptons $c_L \neq 0$



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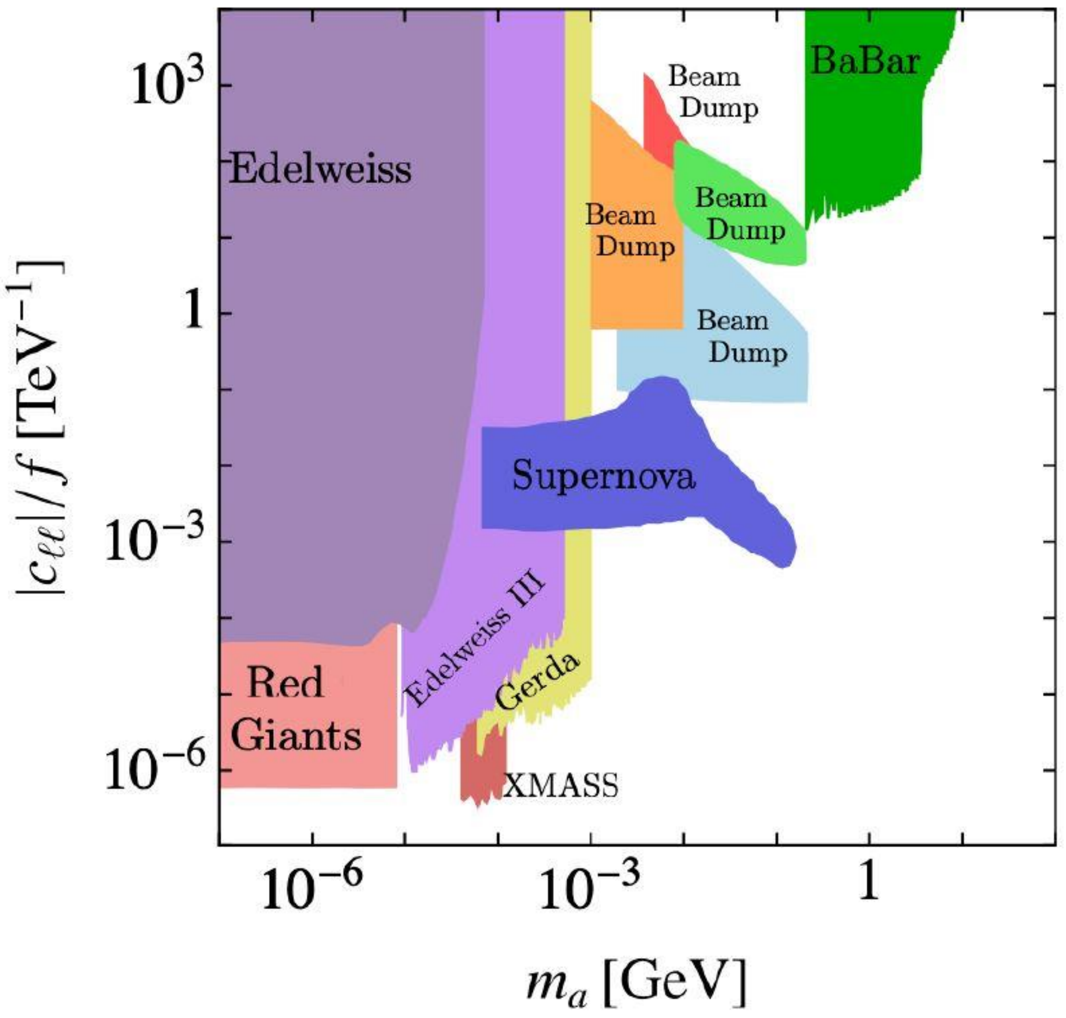

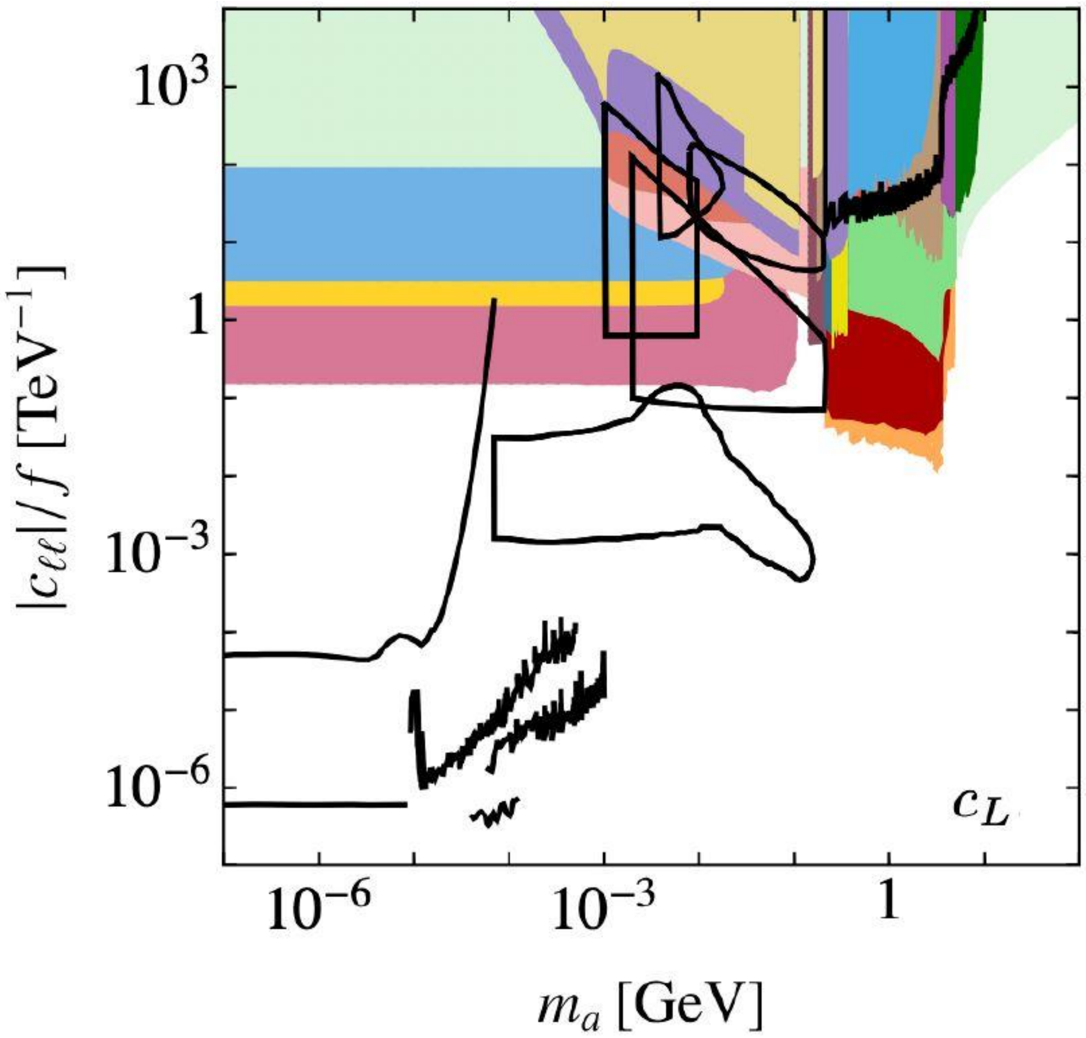

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CONCLUSIONS

- Axions and ALPs are well-motivated BSM particles
- Flavour physics can probe ALP parameter space that is complementary to collider and/or astro-physics
- RG running can have major effects and inevitably generates quark flavour changes

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Thank you for your attention!

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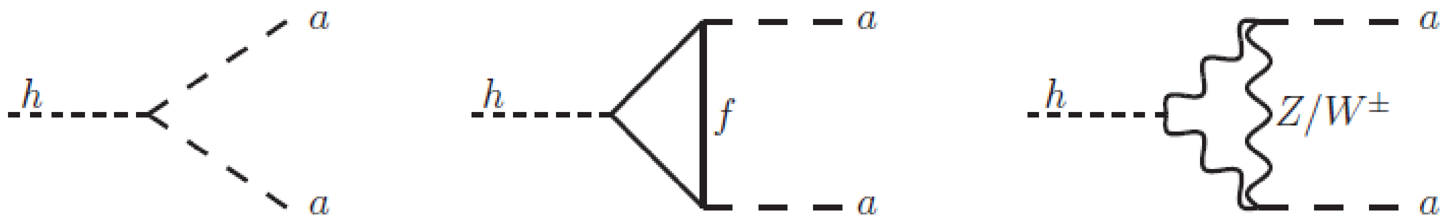
BACKUP

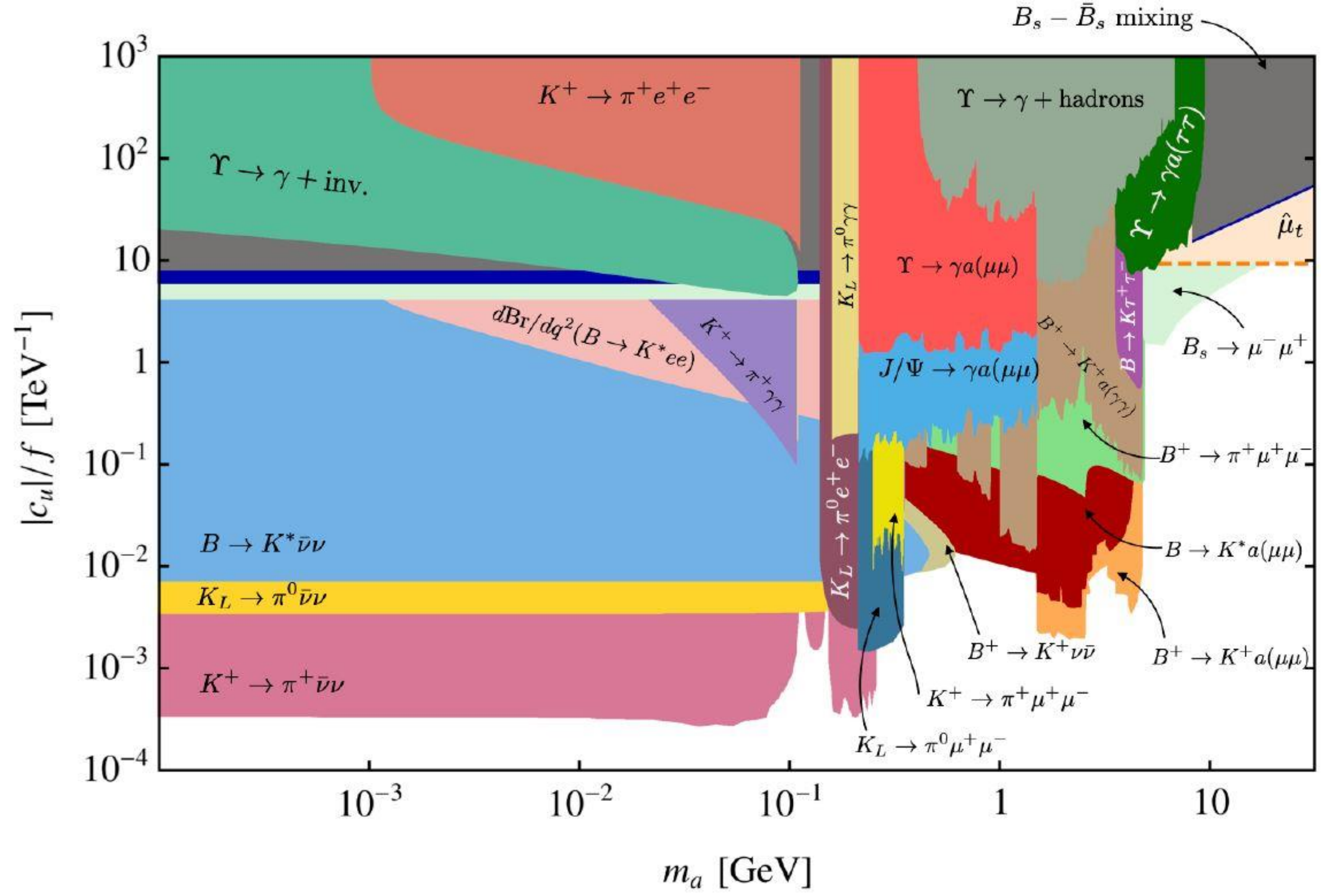
DETAILS ON COLLIDER SEARCHES

- ALP could show up in rare Higgs decays:



- Constraints from Z from EW precision tests

CONSTRAINTS FROM RH UP-TYPE QUARKS



FORMER ANOMALIES IN RARE B-DECAYS

- Anomalies seeming to indicate lepton flavour universality violation

$$R_K = \frac{\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{Br}\left(B^+ \to K^+e^+e^-\right)} = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012} \qquad \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2, \quad [$$

[LHCb (2017 and ongoing)]

$$R_{K^*} = \frac{\mathrm{Br}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\mathrm{Br}\left(B^0 \to K^{*0}e^+e^-\right)} = \begin{cases} 0.66\,^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045\,\mathrm{GeV}^2 < q^2 < 1.1\,\mathrm{GeV}^2 \\ 0.69\,^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2 \end{cases}$$

- In principle, ALPs could address these issues as they naturally couple non-universally to different lepton flavours

- Explanation by heavy ALP is ruled out by a combination of $\mathrm{Br}(B_s \to e^+e^-)$, $B_s - \bar{B}_s$ mixing, and $(g-2)_e$

THE ATOMKI ANOMALIES

- Transition amplitudes of excited Berillium and Helium to respective ground states deviate from SM prediction by ~7σ [ATOMKI (2016)]
- In principle, a $\sim 17\,\mathrm{MeV}$ ALP has all properties needed for simultaneous explanation
- ALP explanation (mostly) ruled out by Kaon measurements

THE WEAK DECAY K→ΠA

- Strongest particle-physics constraint on ALP couplings for masses below

$$m_a < m_K - m_\pi \approx 354\text{MeV}$$

- Despite a 35 year history, we find that most recent works are based on inconsistent equations [Georgi, Kaplan, Randall (1986)]

- Chiral implementation of leading SU(3) octet weak interaction operator

$$\mathcal{L}_{\text{weak}} = \frac{-4G_F}{\sqrt{2}} V_{ud}^* V_{us} g_8 \left[L_\mu L^\mu\right]^{32}$$

Experimental constant (g_8)

s-d-transition ($[L_\mu L^\mu]^{32}$)

with L_μ^{ij} the chiral representation of left-handed current $\bar{q}_L^i \gamma_\mu q_L^j$

[Bernhard, Draper, Soni, Politzer, Weis (1985); Crewther (1986); Kambor, Missimer, Wyler (1990)]

THE WEAK DECAY K→ΠA

- Georgi, Kaplan, Randall used $L_\mu^{ij} = -\frac{i f_\pi^2}{4} e^{-i(\kappa_{q_j} - \kappa_{q_i}) c_{GG} a/f} \left[\Sigma \partial_\mu \Sigma^\dagger\right]^{ij}$

  $\Sigma(x) = \exp\left[\frac{i\sqrt{2}}{f_\pi} \lambda^a \pi^a(x)\right]$

Phase used in chiral rotation to eliminate ALP-gluon coupling, involves auxiliary parameters κ_q

- The Noether theorem gives instead:

$$L_\mu^{ji} = -\frac{i f_\pi^2}{4} e^{i(\kappa_{q_j} - \kappa_{q_i}) c_{GG} \frac{a}{f}} \left[\Sigma \left(D_\mu \Sigma\right)^\dagger\right]_{ji}$$

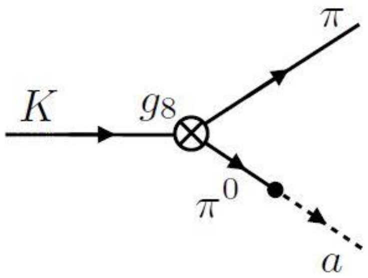
$$\ni -\frac{i f_\pi^2}{4} \left[1 + i\left(\kappa_{q_j} - \kappa_{q_i}\right) c_{GG} \frac{a}{f}\right] \left[\Sigma\, \partial_\mu \Sigma^\dagger\right]_{ji} + \frac{f_\pi^2}{4} \frac{\partial^\mu a}{f} \left[\hat{k}_Q - \Sigma\, \hat{k}_q \Sigma^\dagger\right]_{ji}$$

Contains also derivative ALP interactions

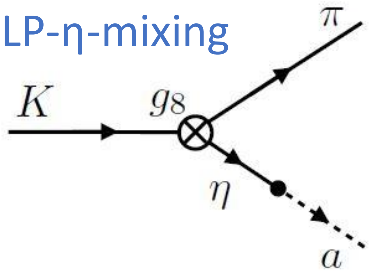
Extra terms from Noether-procedure!

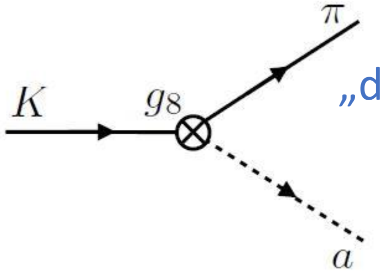
THE WEAK DECAY K→ΠA

ALP-π-mixing



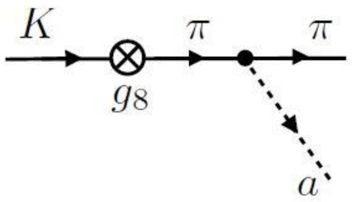
ALP-η-mixing

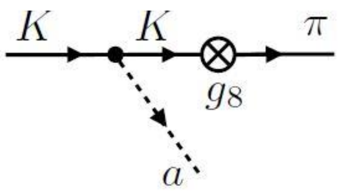




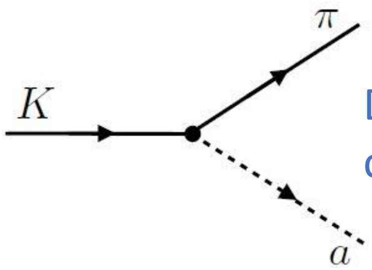
„direct“ contribution

Final state radiation





Initial state radiation



Direct flavour changing contribution

- Only in the sum of all diagrams the auxiliary parameters cancel
- Including only the first diagrams (kinetic mixing) gives in general an uncontrolled approximation (except for special cases)

THE WEAK DECAY K→ΠA

- Decay amplitude

$$
\begin{aligned}
i\mathcal{A}_{K^-\to\pi^-a} = \frac{N_8}{4f}\Bigg[& 16c_{GG}\frac{(m_K^2-m_\pi^2)(m_K^2-m_a^2)}{4m_K^2-m_\pi^2-3m_a^2} \\
& + 6(c_{uu}+c_{dd}-2c_{ss})m_a^2\frac{m_K^2-m_a^2}{4m_K^2-m_\pi^2-3m_a^2} \\
& + (2c_{uu}+c_{dd}+c_{ss})(m_K^2-m_\pi^2-m_a^2)+4c_{ss}m_a^2 \\
& + (k_d+k_D-k_s-k_S)(m_K^2+m_\pi^2-m_a^2)\Bigg] \\
& - \frac{m_K^2-m_\pi^2}{2f}[k_q+k_Q]^{23}.
\end{aligned}
$$

UV flavour changing coupling

Previously used:

$$\mathcal{A}_{K^-\to\pi^-a} \approx \frac{iN_8 m_K^2}{4f_a}\frac{m_u}{m_u+m_d}.$$

underestimates amplitude by factor $\frac{m_u}{m_u+m_d} \approx 0.16$

leading to factor ≈40 in BR

CONSTRAINTS FROM LEPTONS

- Flavour change can‘t be generated by loops → no mixing with SM
- Some observables only generated at loop level
- Heavy leptons in internal loops can magnify ALP effects
- Assume one LFV coupling to be dominant, include diagonal couplings, no tree-level coupling to gauge bosons
- Focus on muons, results can easily be translated to tau-sector

CONSTRAINTS FROM LFV