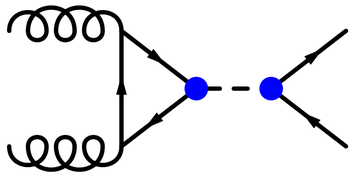
Axion-like particles at colliders

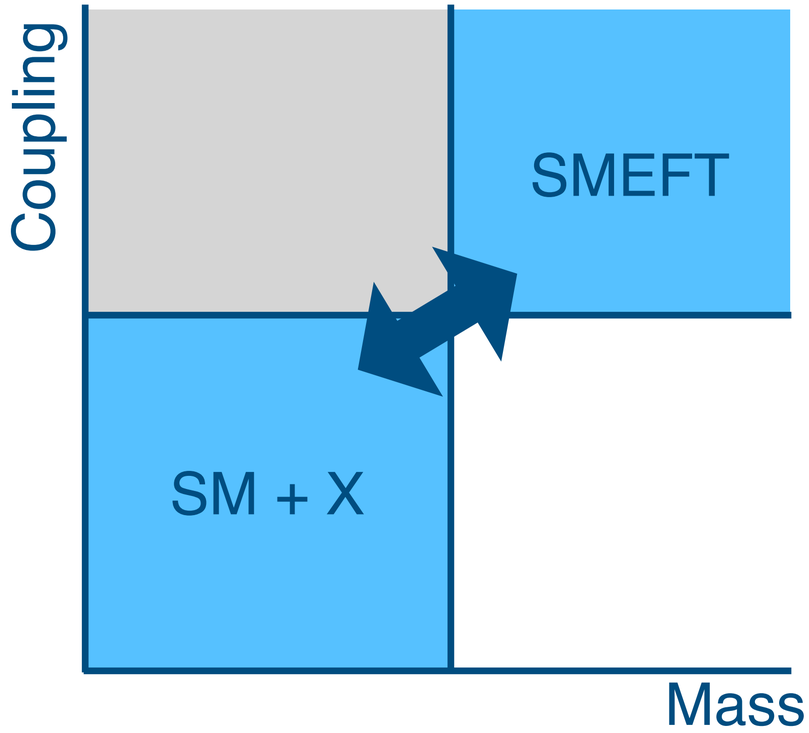
Anke Biekötter - JGU Mainz

LFC24 - Fundamental Interactions at Future Colliders, Sep 18, 2024

Outline

- Axion-like particle (ALP) Effective Field Theory
  - ALP parameter space and colliders
- ALP couplings to top quarks
  - $t\bar{t}$ production
- Indirect bounds on ALP couplings from the SMEFT
  - FCC-ee limits





Axions

$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

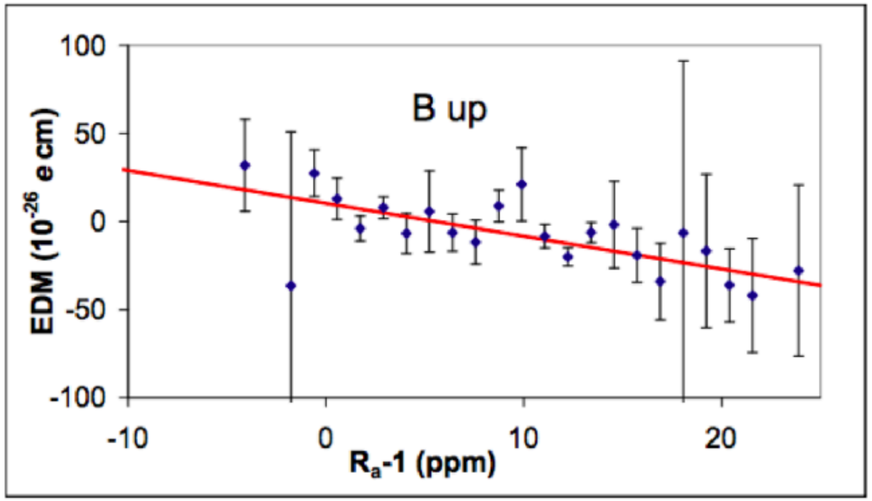
Why is the theta term so small?

$$\mathcal{L} = \left(\theta - \frac{a}{f_a} \right) \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Dynamical solution to the strong CP problem

$$m_a f_a = \text{const.}$$

[Baker et al. (hep-ex/0602020)]



Electric dipole moment of the neutron

[Peccei, Quinn (ref1, ref2)]
[Weinberg] [Wilczek]

Axions

This talk is NOT about the QCD axion.

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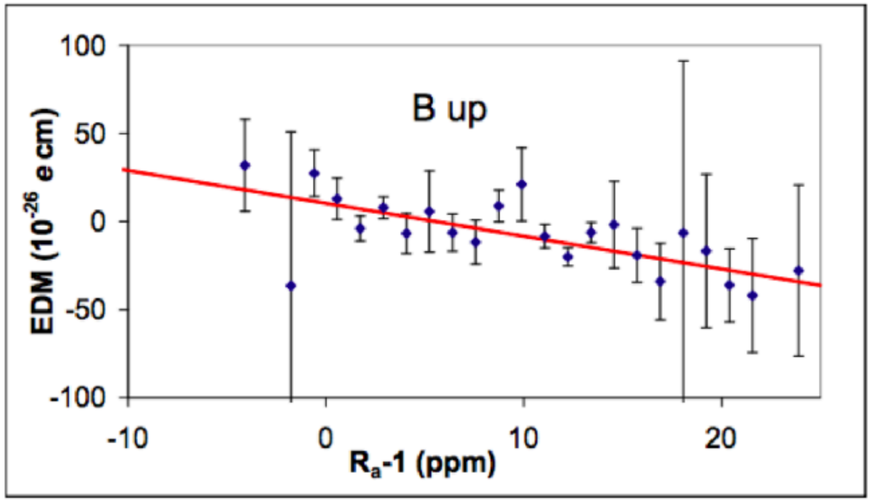

Electric dipole moment of the neutron

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Axion-like particles

EFT with an additional light d.o.f. and at dimension 5

- Featured in many BSM scenarios: “Higgs portal” dark matter, composite Higgs models, …

[Peccei, Quinn (ref1, ref2)] [Weinberg] [Wilczek]

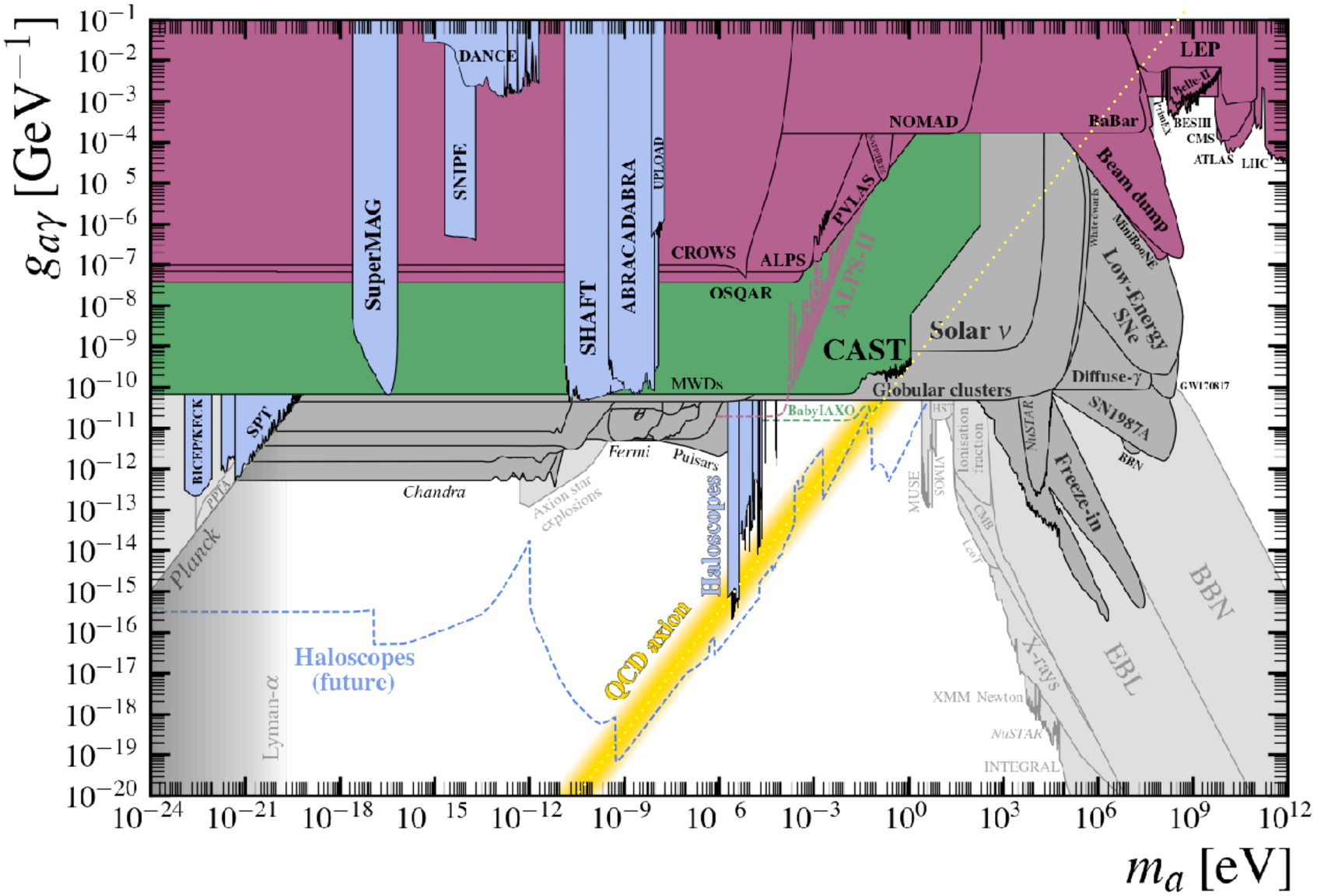
- Consider a generic ALP with effective Lagrangian

[Brivio et al. (1701.05379)] [Bauer et al. (1708.00443)]

- Shift symmetry $a \to a + a_0$, Lagrangian terms: $\dfrac{\partial_\mu a}{f_a}\,(\mathrm{SM})^\mu$

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\, c_F\, \gamma_\mu \psi_F + c_\phi\,\frac{\partial^\mu a}{f}\left(\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi\right)$$
$$+ c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}\,.$$

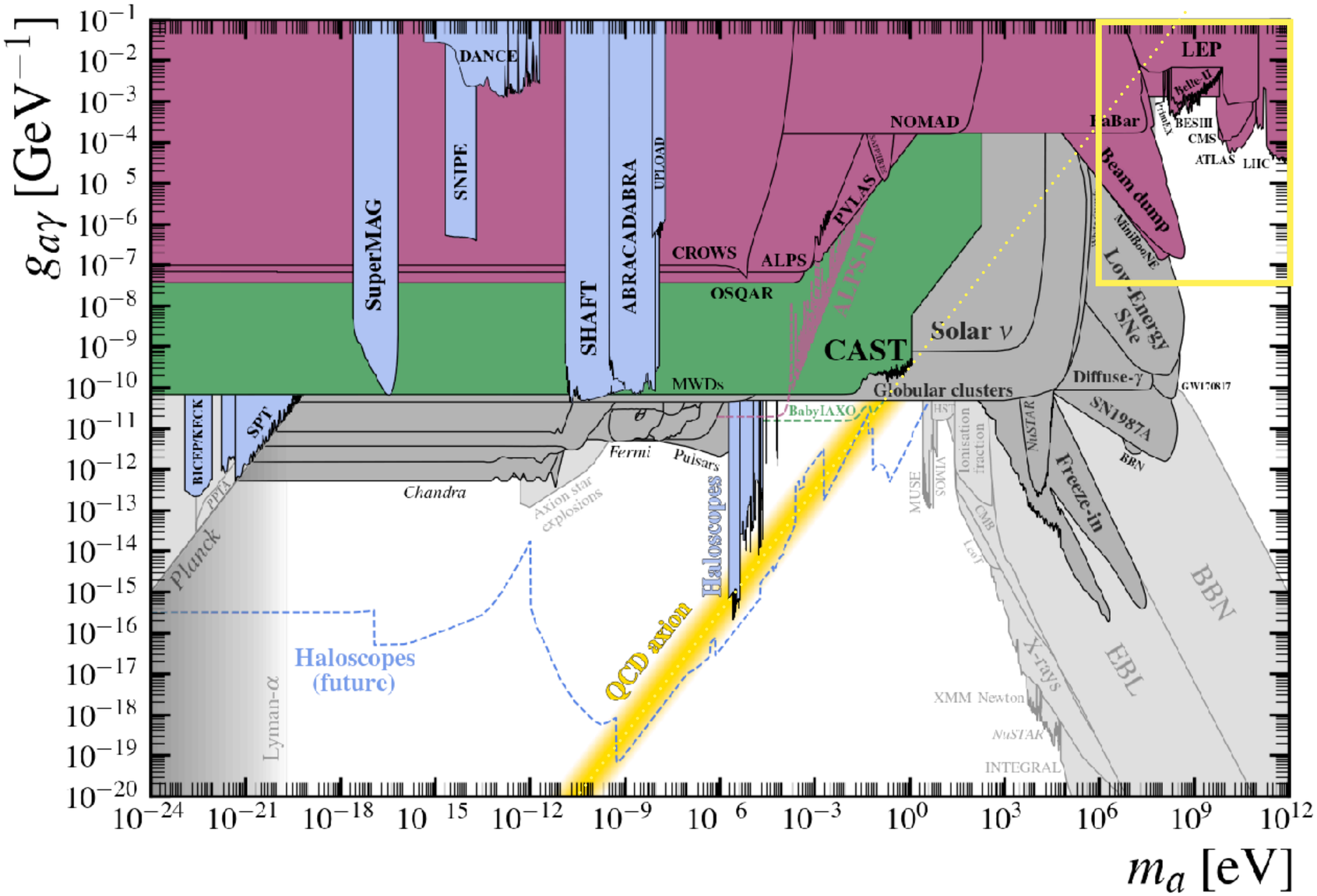
ALP phenomenology



Interplay of experiments/ observations crucial

[O'Hare (axion limits)]

ALP phenomenology



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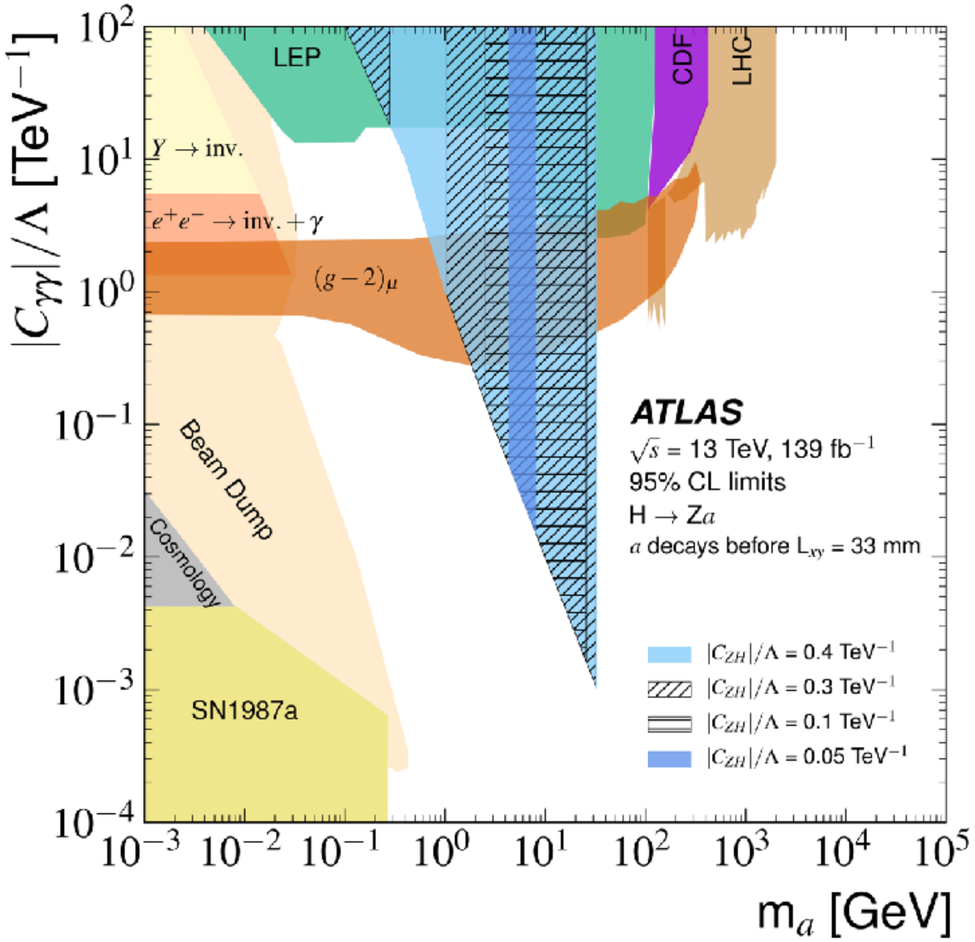
ALPs at colliders



[ATLAS (2312.01942)]

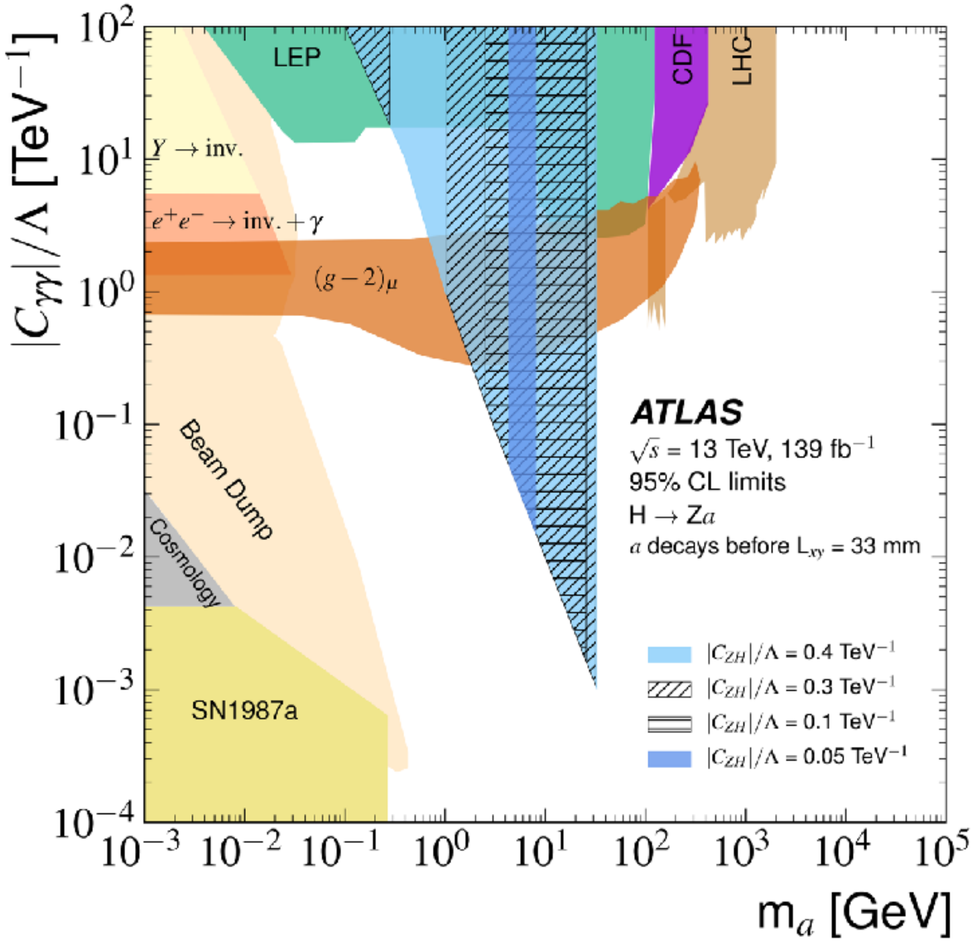
g_{aXX}

Prompt

Long lived

m_a

ALPs at colliders



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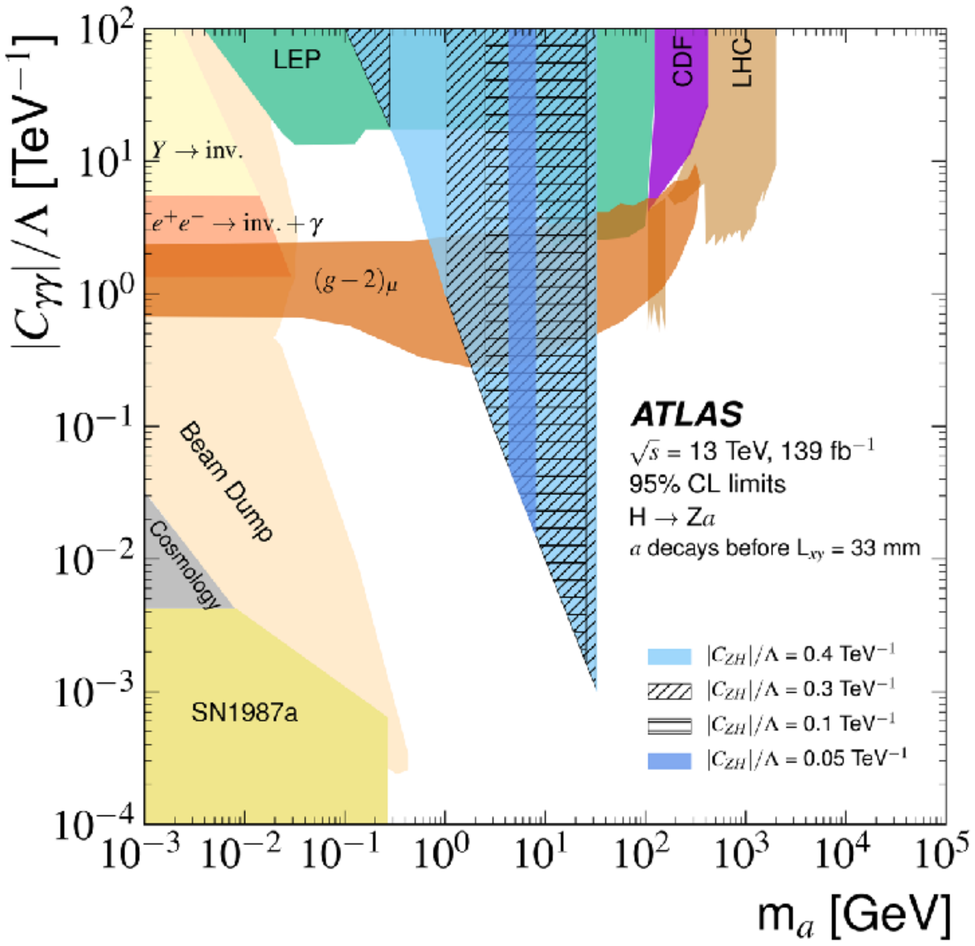

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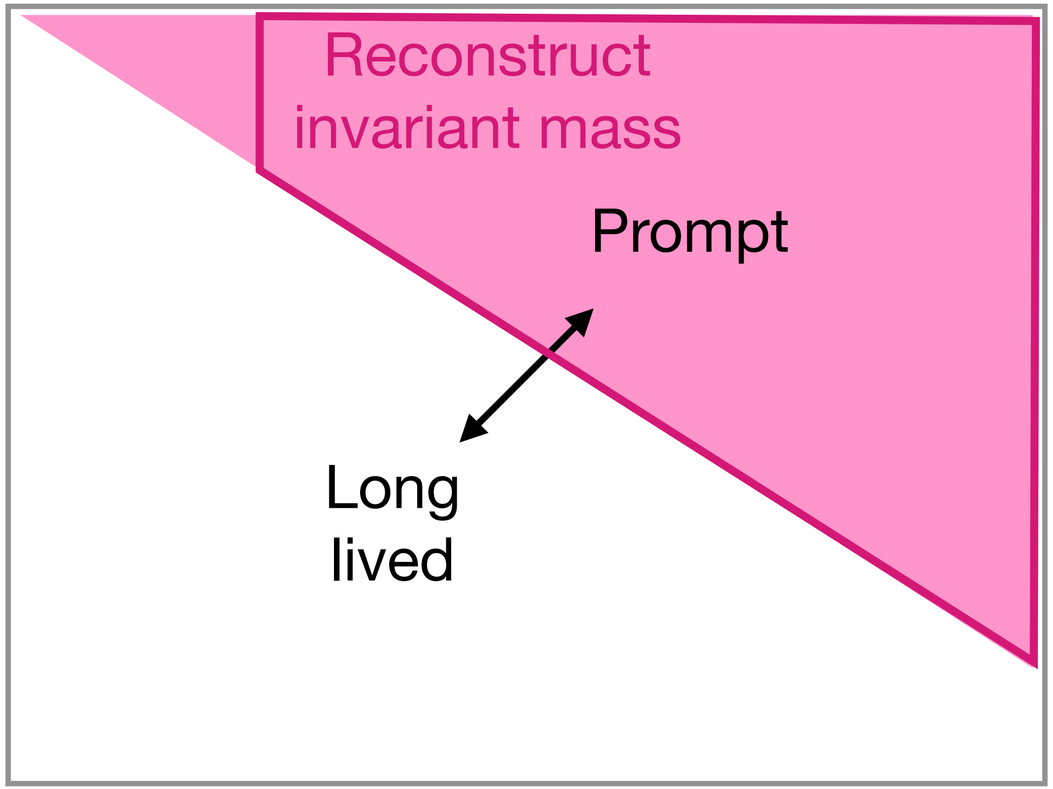

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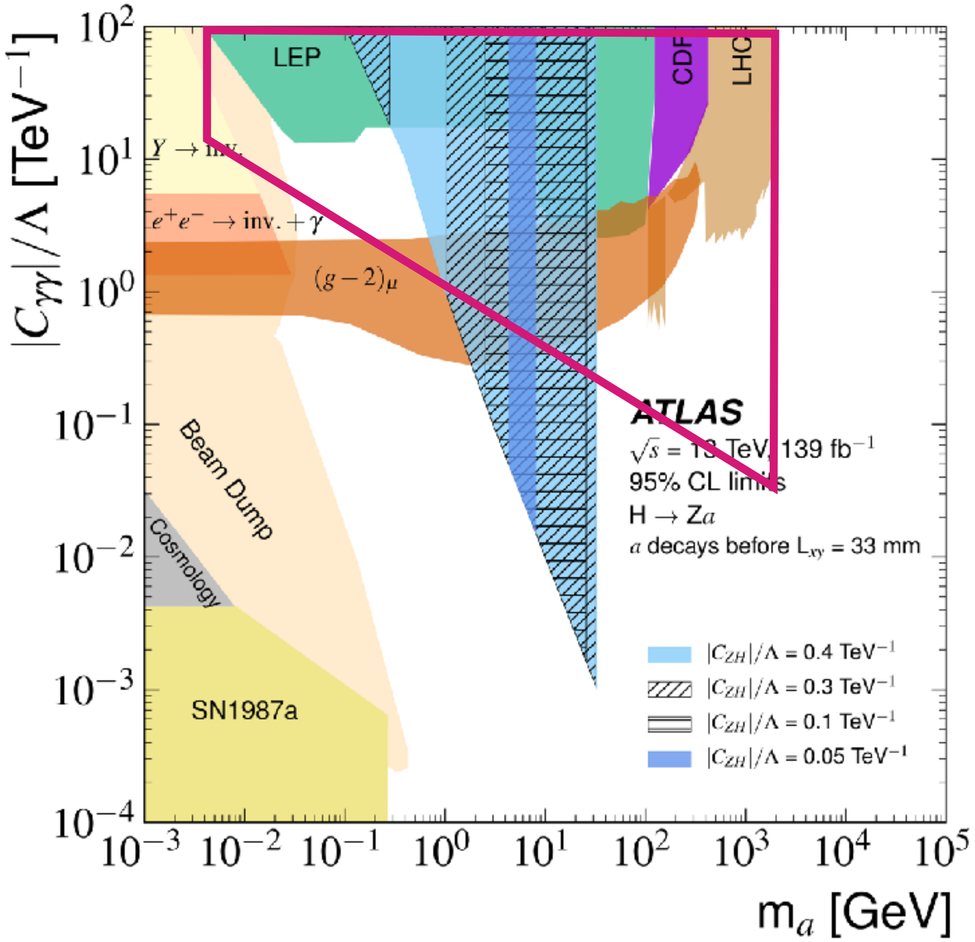

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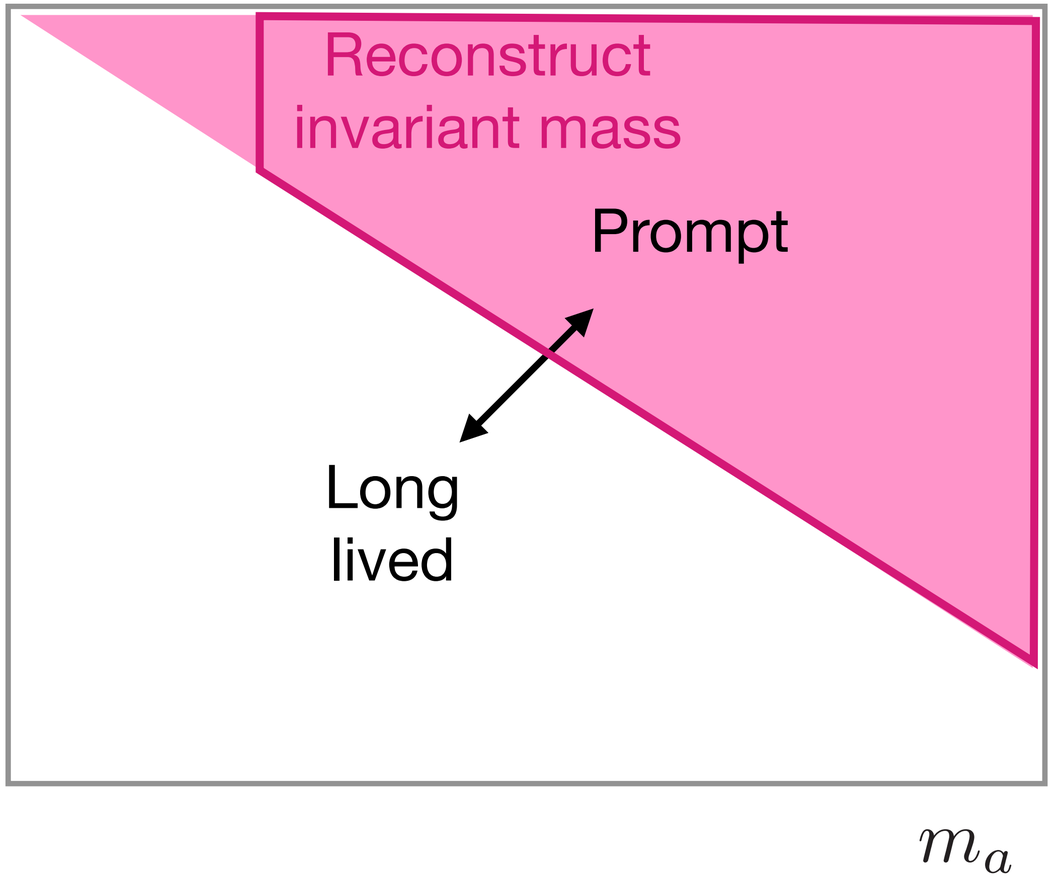

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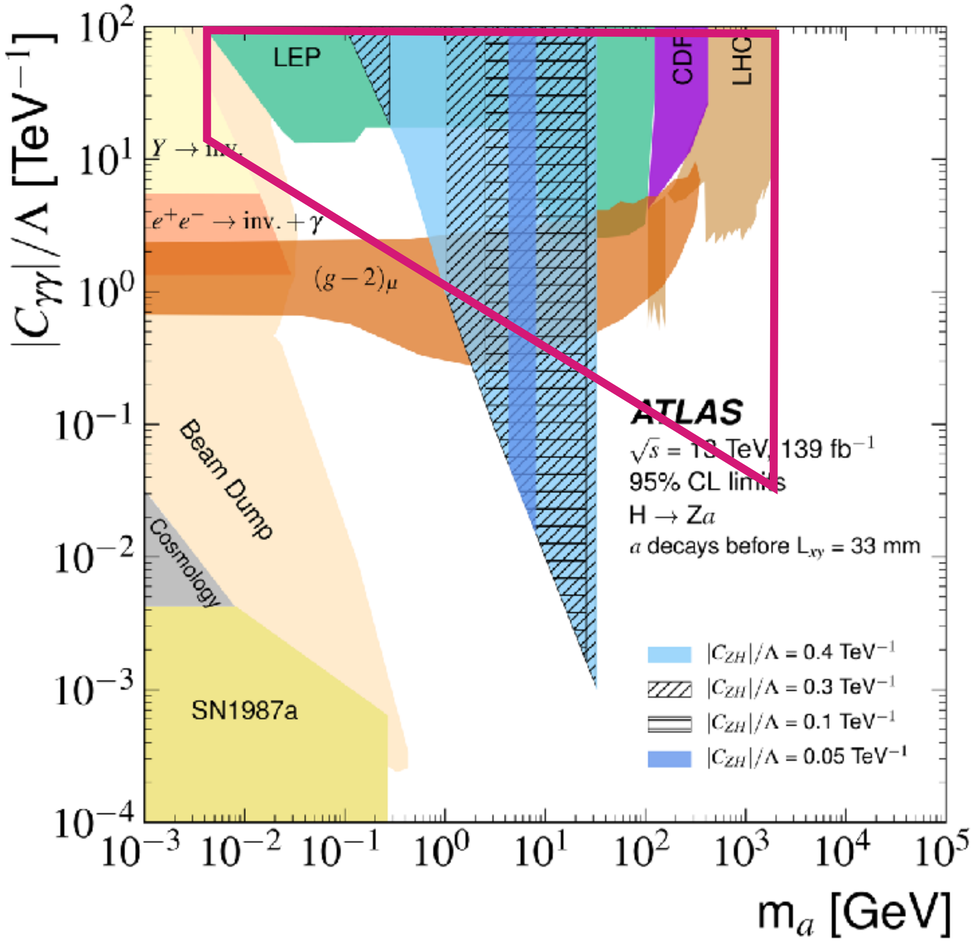

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Beam dumps

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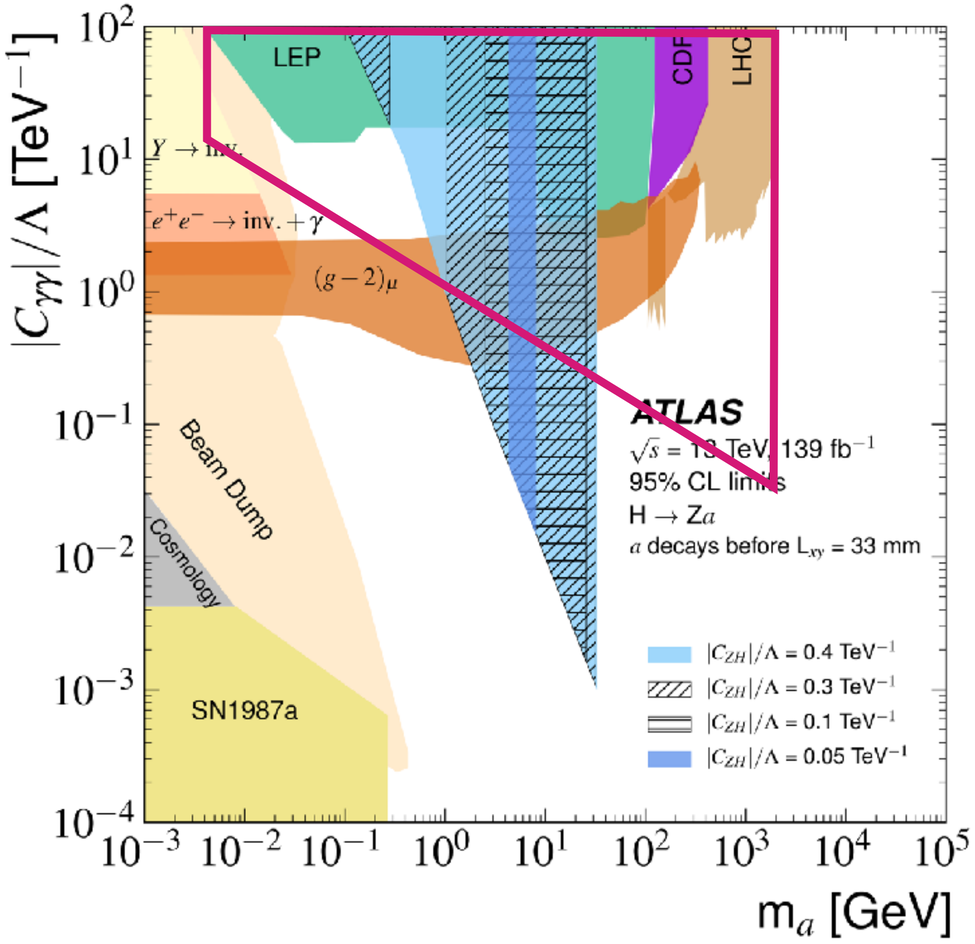

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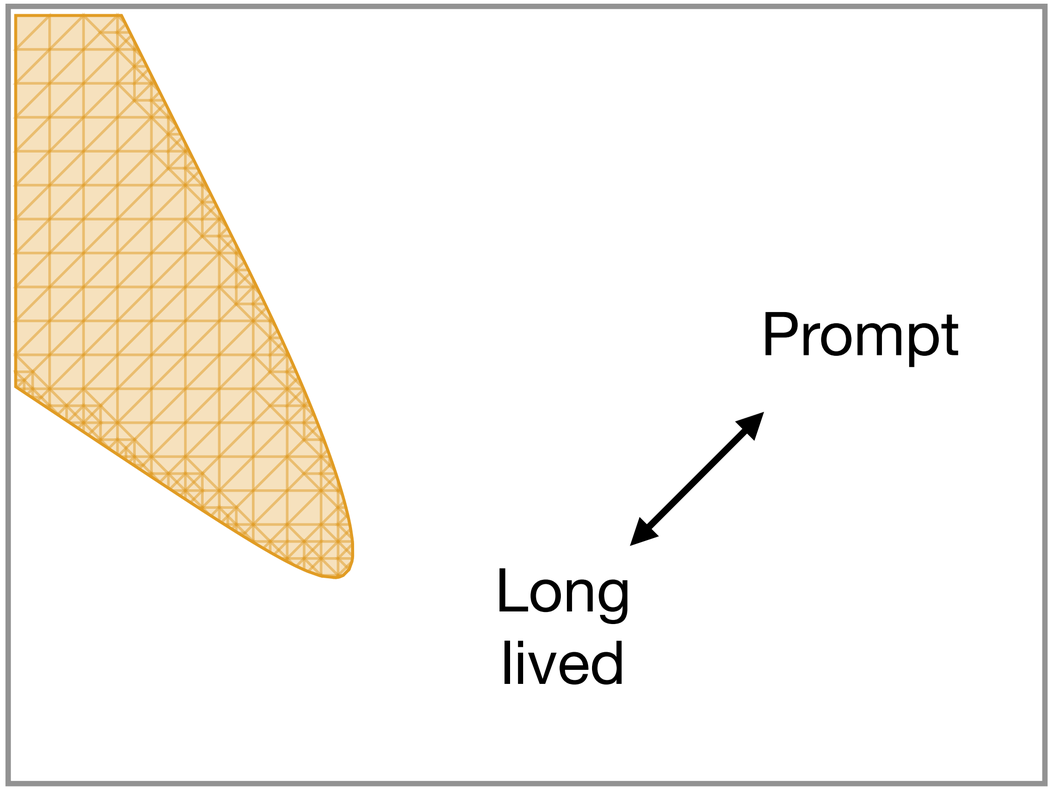
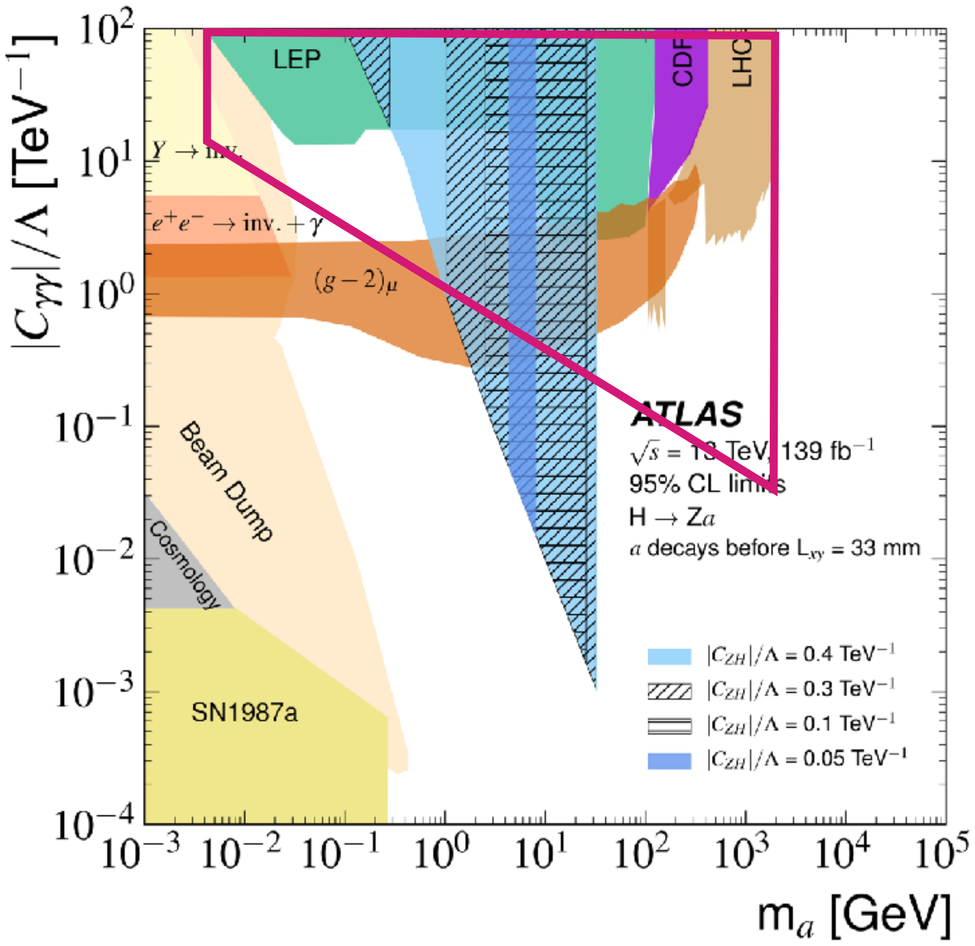


Decay length L_a m_a

$$\exp\left(-\frac{L_a}{L_{\text{det}}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\text{det}}}\right)$$

ALPs at colliders



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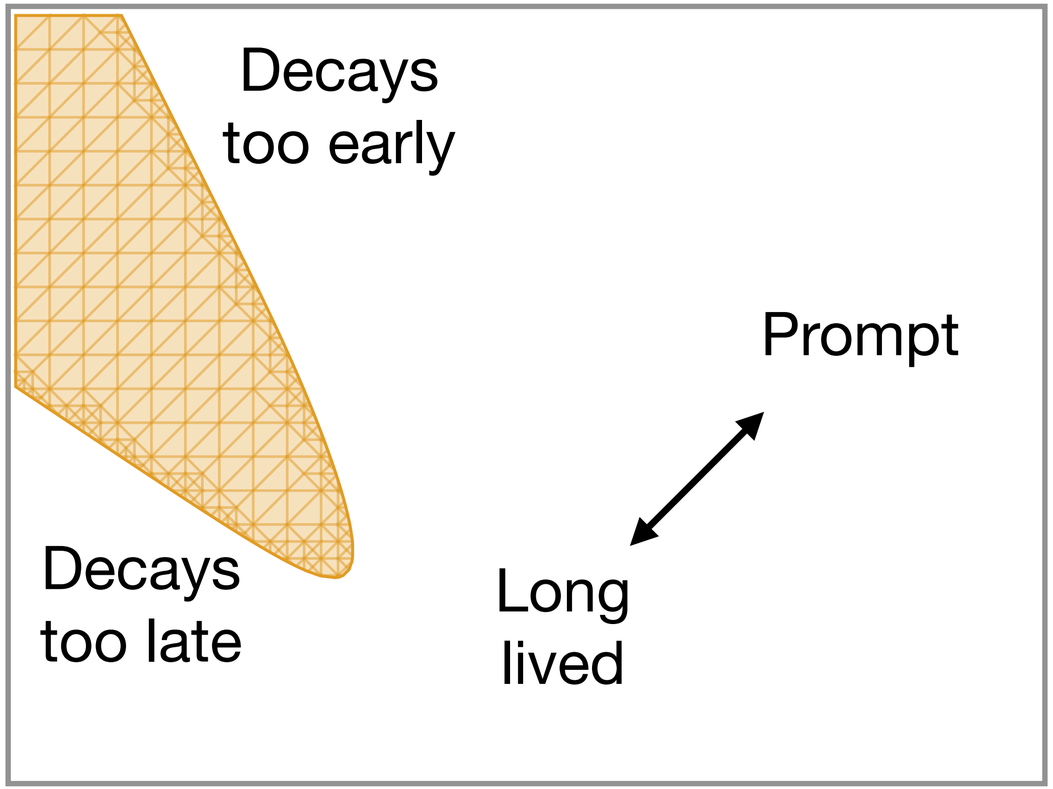

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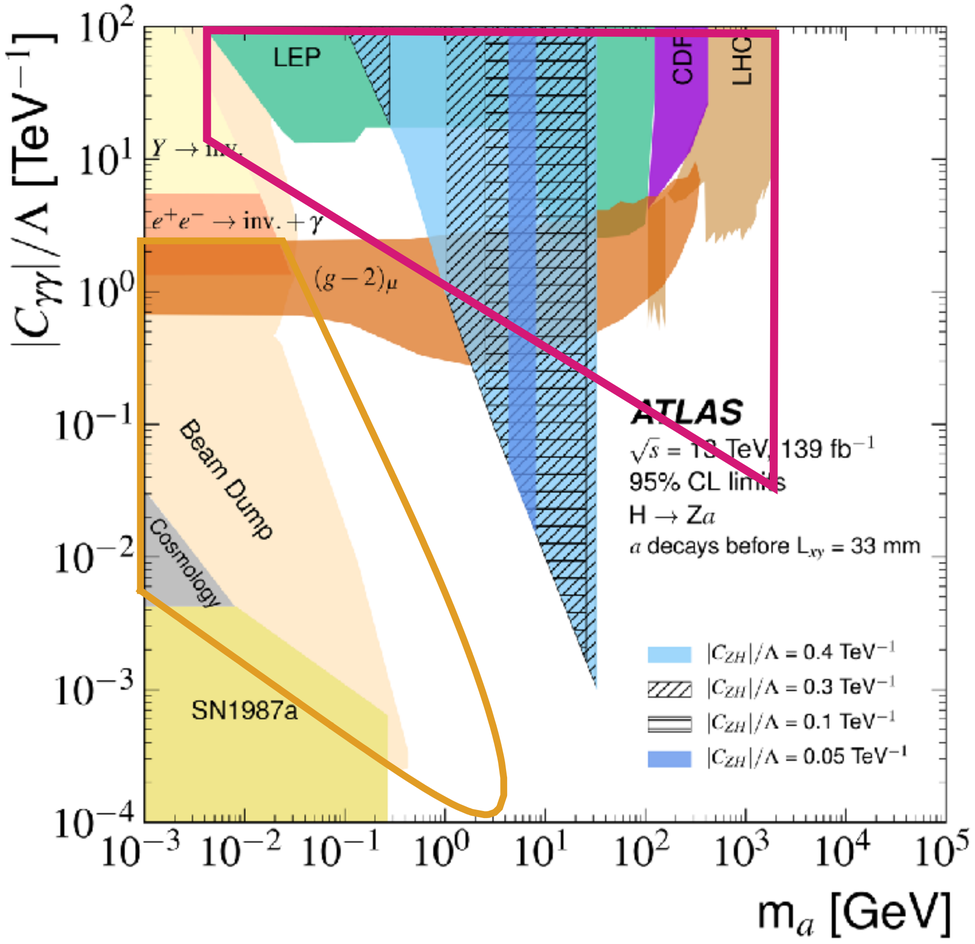

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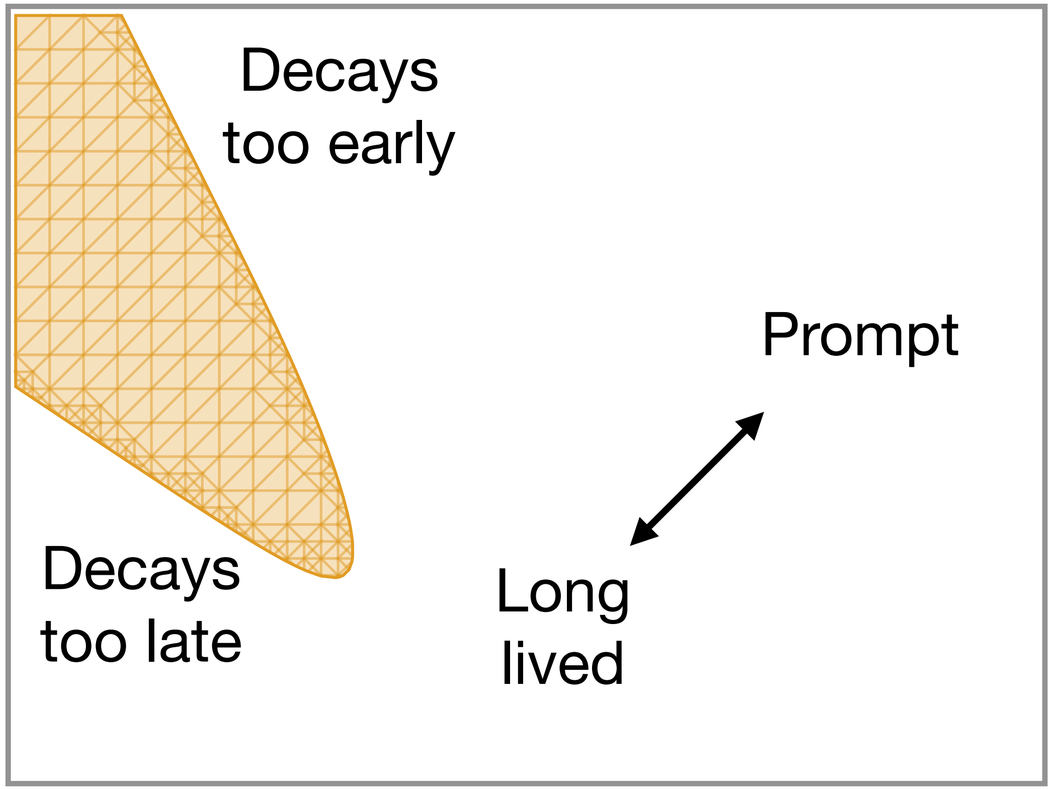

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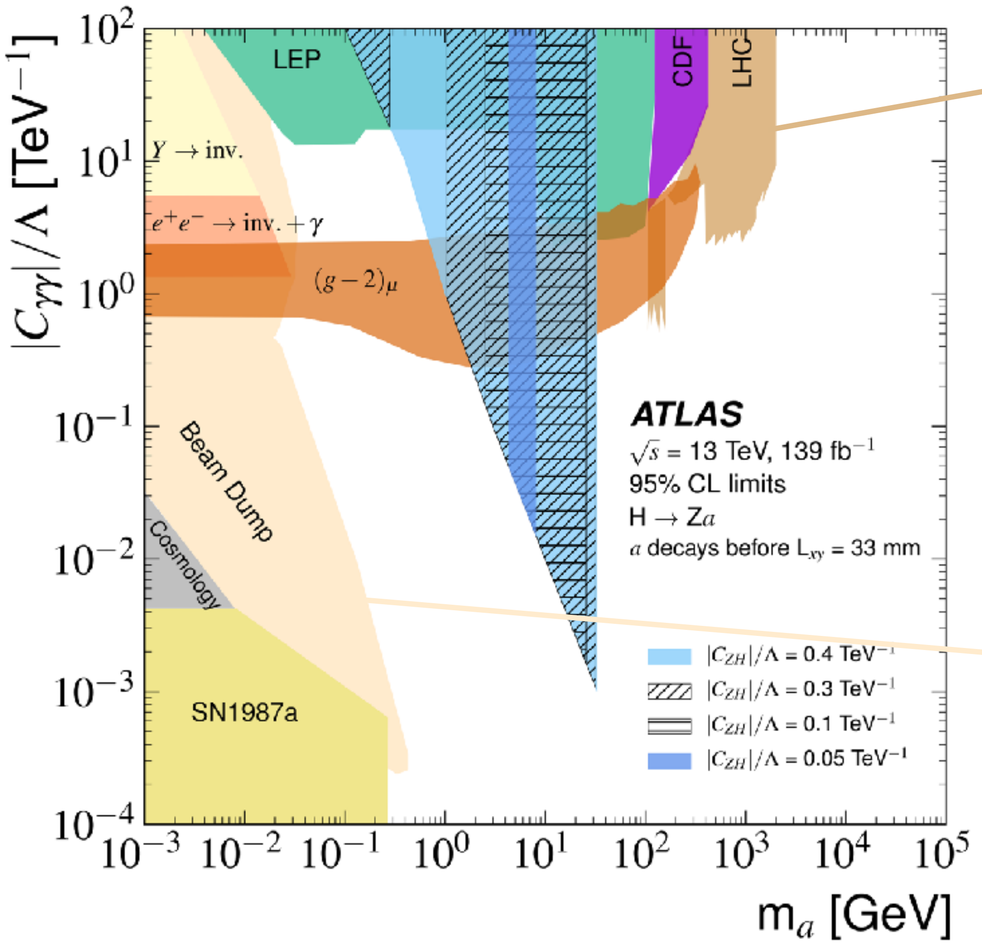
2D ALP bounds



[ATLAS (2312.01942)]

LHC limits

$pp \to a \to \gamma\gamma$

Mass-dependent (resonance search)

Assuming $\mathrm{BR}(a \to \gamma\gamma) = 100\,\%$

$\mathrm{BR}(a \to ZZ)$?

$\mathrm{BR}(a \to Z\gamma)$?

Beam dump limits

Can be changed (or invalidated) if $a \to e^+e^-$ decay possible

ALPs and top quarks

ALP Lagrangian

derivative basis

$$\mathcal{L}^{D\leq 5}_{\rm SM+ALP} = c_{GG}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + c_{WW}\frac{a}{f}W^A_{\mu\nu}\tilde{W}^{A,\mu\nu} + c_{BB}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\mathbf{c}_F\,\gamma_\mu\psi_F$$

$$\psi_F \to \psi_F + i\,\frac{a}{f}\,\mathbf{c}_F\,\psi_F$$

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pseudoscalar basis

$$\mathcal{L}^{D\leq 5}_{\rm SM+ALP} = C_{GG}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\tilde{Y}_u\,u_R + \bar{Q}\,H\,\tilde{Y}_d\,d_R + \bar{L}\,H\,\tilde{Y}_e\,e_R + \text{h.c.}\right)$$

$$\tilde{Y}_u = i(Y_u\,c_u - c_Q\,Y_u), \quad \tilde{Y}_d = i(Y_d\,c_d - c_Q\,Y_d), \quad \tilde{Y}_e = i(Y_e\,c_e - c_L\,Y_e)$$

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$\tilde{c}_X = c_X \mathbb{1}_3$ Flavor universal

$$\tilde{Y}_u = i(c_u - c_Q)Y_u = -iC_uY_u, \quad \tilde{Y}_d = i(c_d - c_Q)Y_d = -iC_dY_d, \quad \tilde{Y}_e = i(c_e - c_L)Y_e = -iC_eY_e$$

ALP couplings to top quarks

$$\mathcal{L}_{\rm ferm} = -\frac{a}{f}\left(C_u\, i\bar{Q}\tilde{H}\, Y_u\, u_R + C_d\, i\bar{Q}H\, Y_d\, d_R + C_e\, i\bar{L}H\, Y_e\, e_R + \text{h.c.}\right)$$

- ALP-top quark couplings naturally dominant
- Consistent with minimal flavor violation (MFV)
- Promising candidate at colliders
- Recent activities:

[Esser, Madigan, Sanz, Ubiali (2303.17634)]

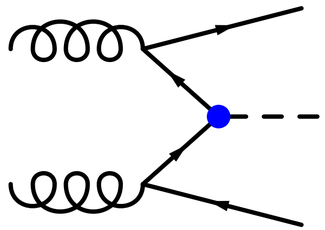
[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]

[Phan, Westhoff (2312.00872)]

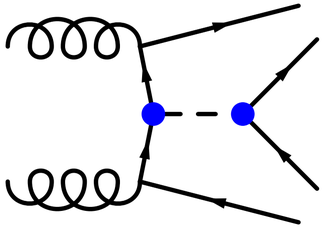
[Cheung, Lu, Ouseph, Sarmah (2404.14833)]

[Anuar, AB, Biekötter, Grohsjean, Heinemeyer, Jeppe, Schwanenberger, Weiglein (2404.19014)]

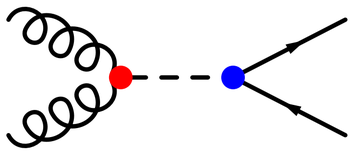
ALPs and tops @ colliders



$t\bar{t}a$

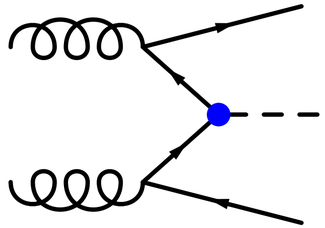


$t\bar{t}t\bar{t}$



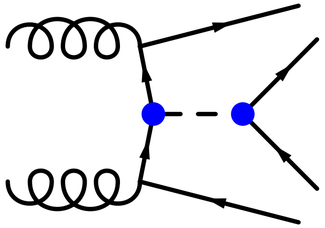
$t\bar{t}$

ALPs and tops @ colliders

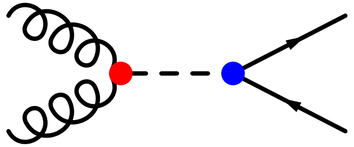


$t\bar{t}a \to t\bar{t}(f\bar{f})$

$\to t\bar{t} + \mathrm{MET}$

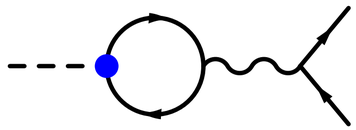


$t\bar{t}t\bar{t}$

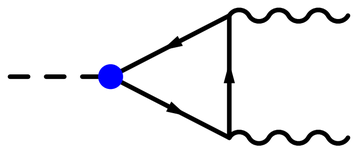


$t\bar{t}$

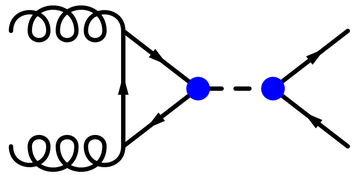
Loop effects

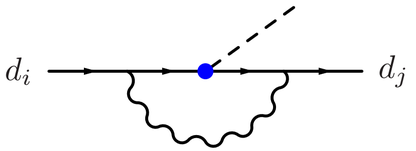


$a \to f\bar{f}$



$a \to VV$

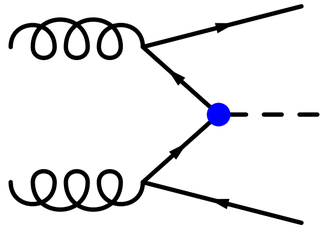




$B \to Ka$

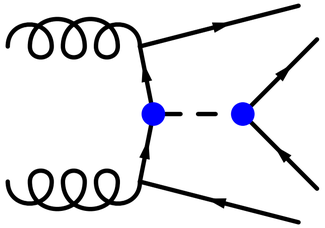
$K \to \pi a$

ALPs and tops @ colliders

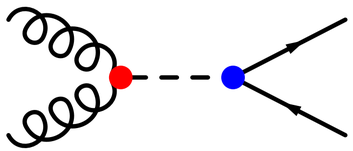


$t\bar{t}a \to t\bar{t}(f\bar{f})$

$\to t\bar{t} + \mathrm{MET}$

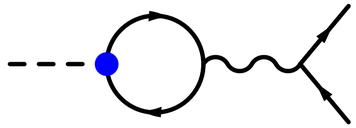


$t\bar{t}t\bar{t}$

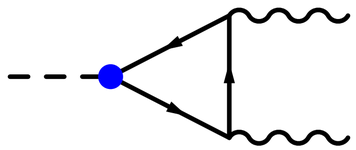


$t\bar{t}$

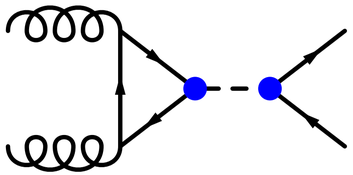
Loop effects $c_f(m_t) \sim \dfrac{y_t^2}{16\pi^2} \log \dfrac{\Lambda}{m_t}$

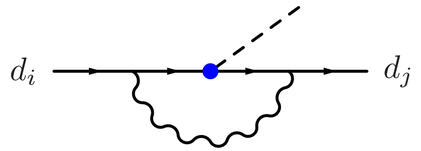


$a \to f\bar{f}$



$a \to VV$





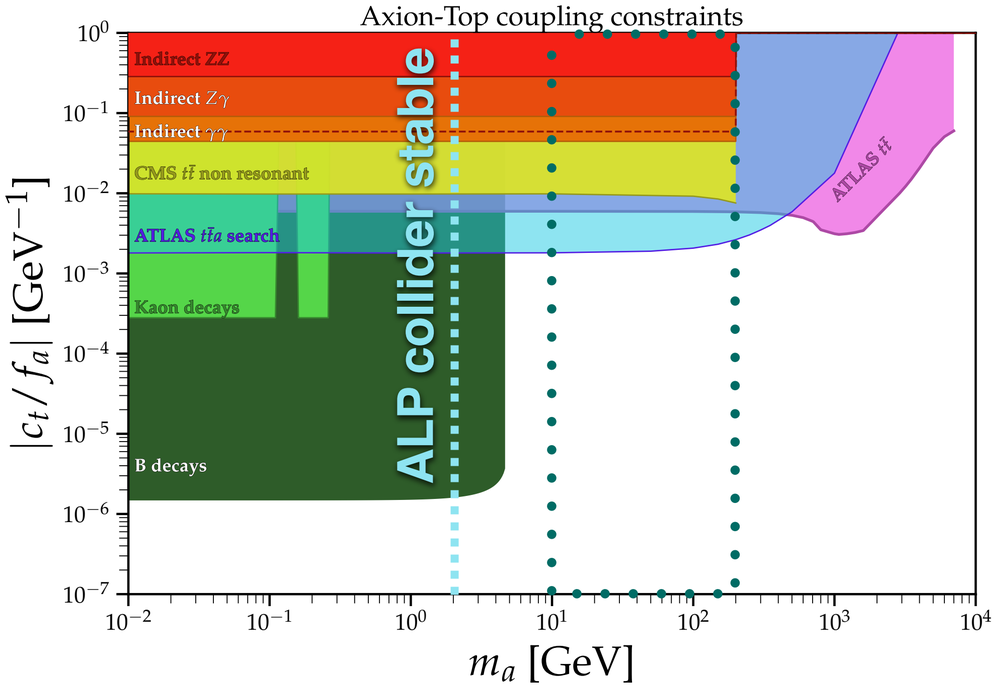
$B \to K a$

$K \to \pi a$

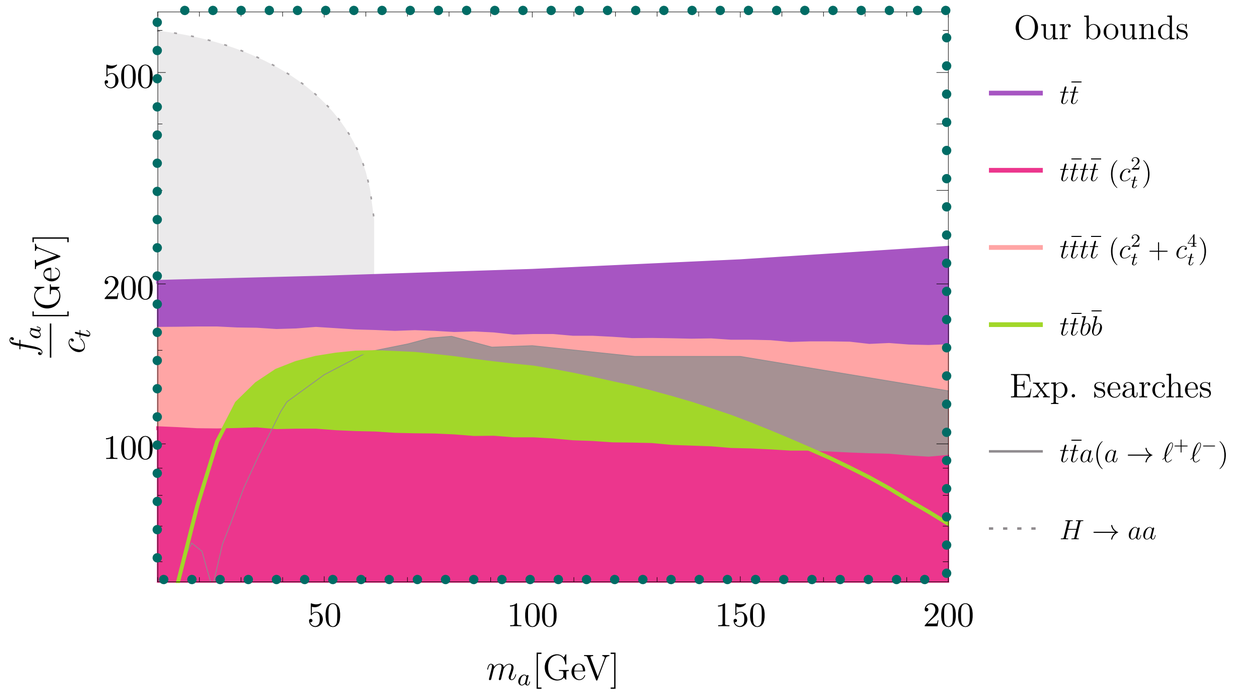
ALPs and tops @ colliders

see also [Phan, Westhoff (2312.00872)]

[Esser, Madigan, Sanz, Ubiali (2303.17634)]



[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]

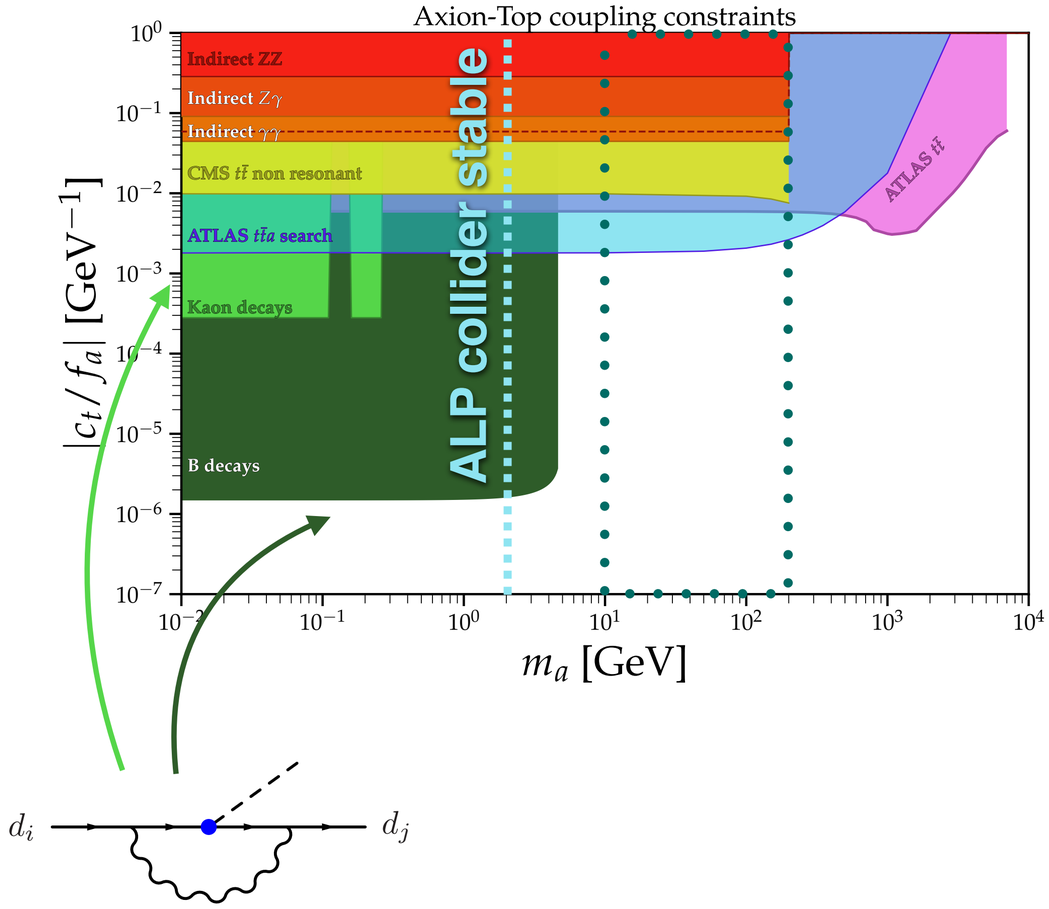


c_t in derivative basis

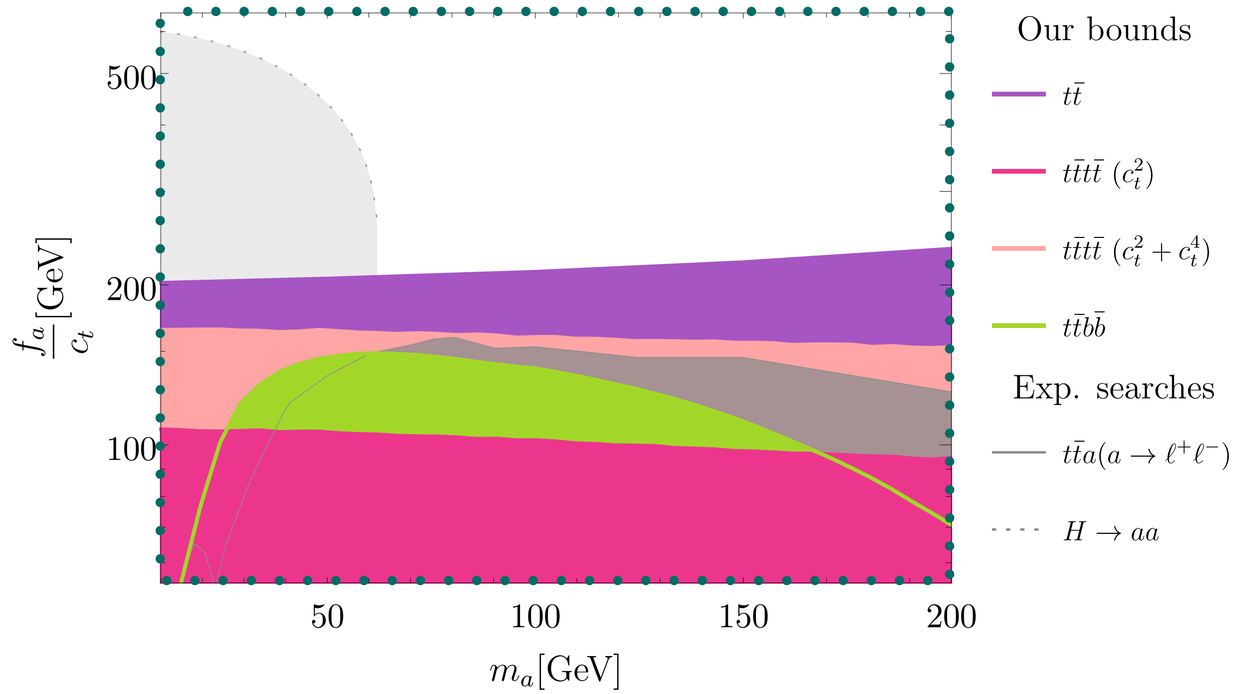
ALPs and tops @ colliders

see also [Phan, Westhoff (2312.00872)]

[Esser, Madigan, Sanz, Ubiali (2303.17634)]



[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]



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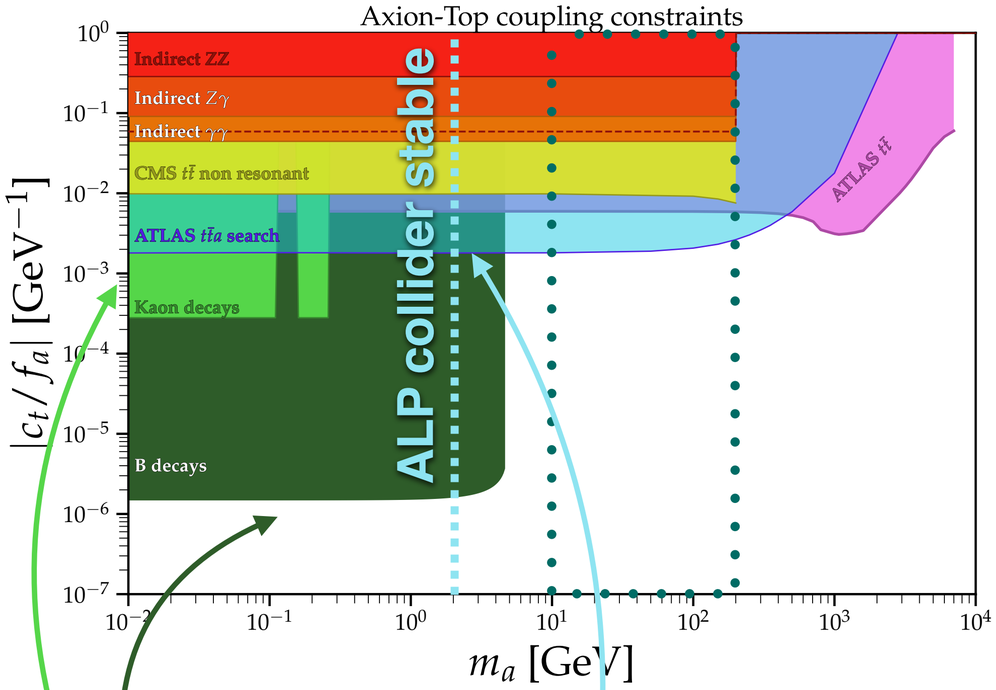
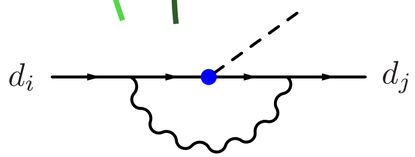
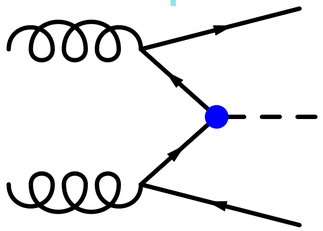
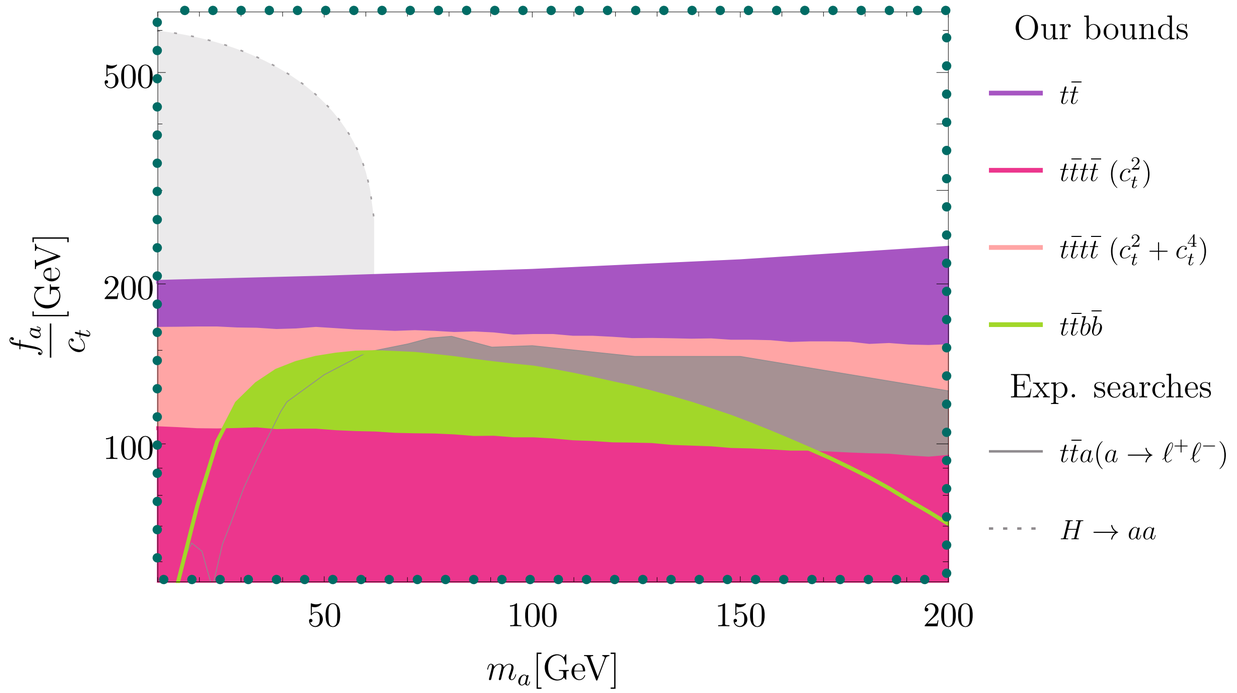






$t\bar{t}a(\text{inv})$

[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]



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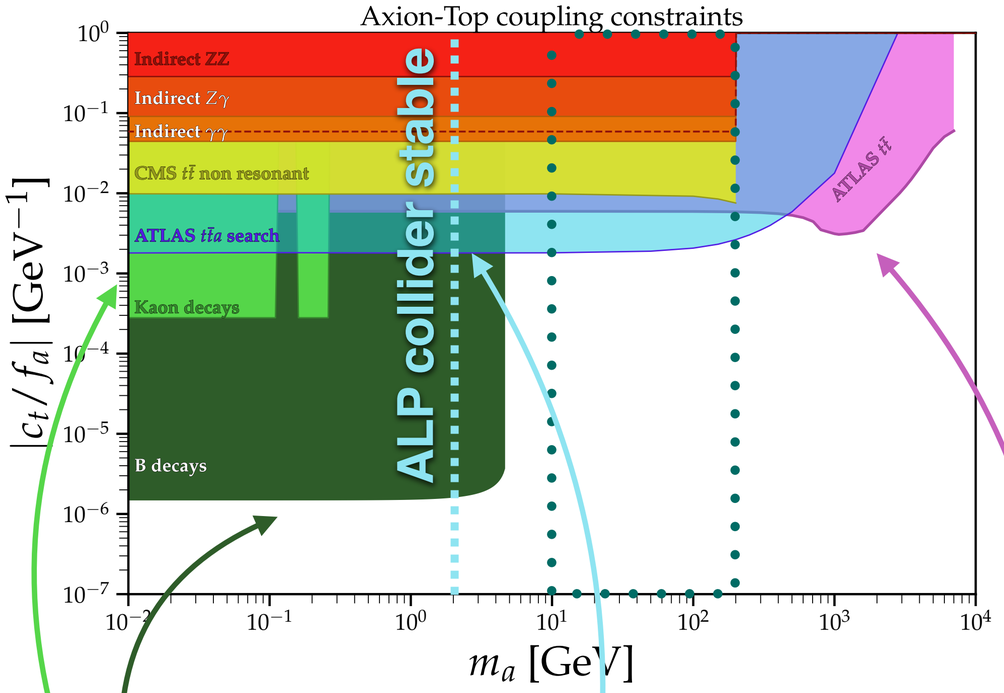
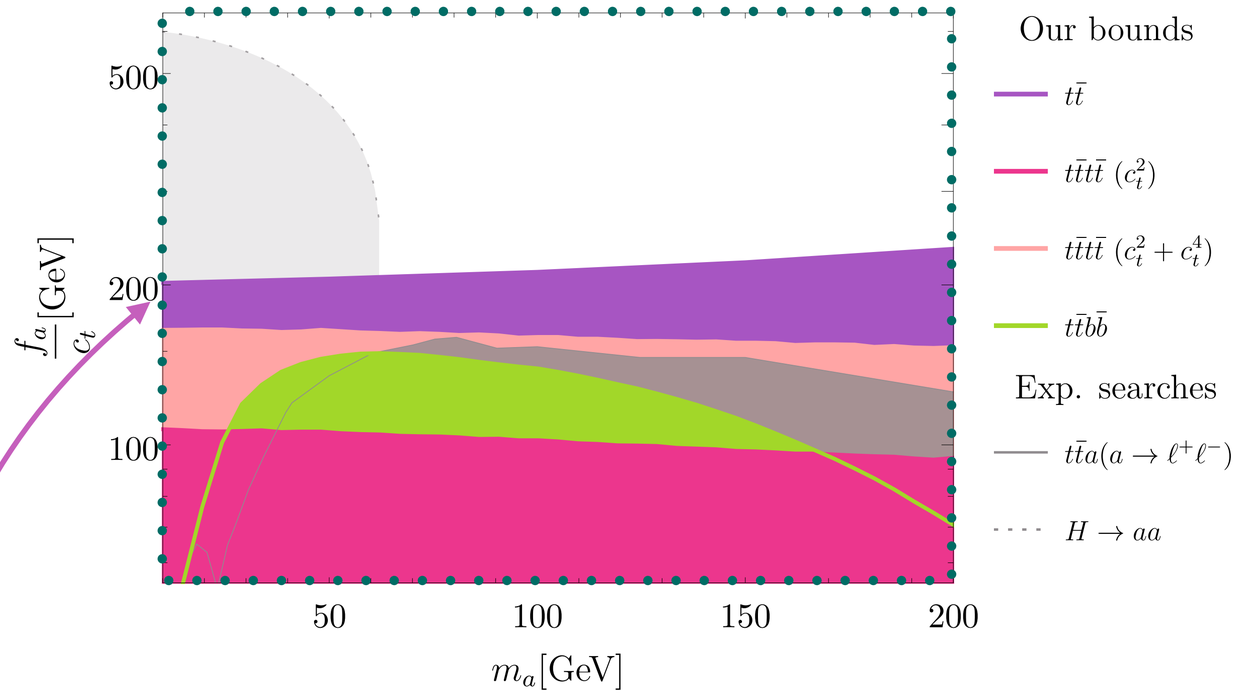
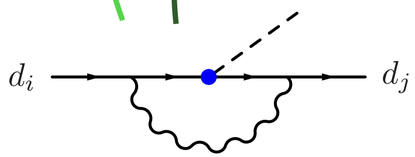
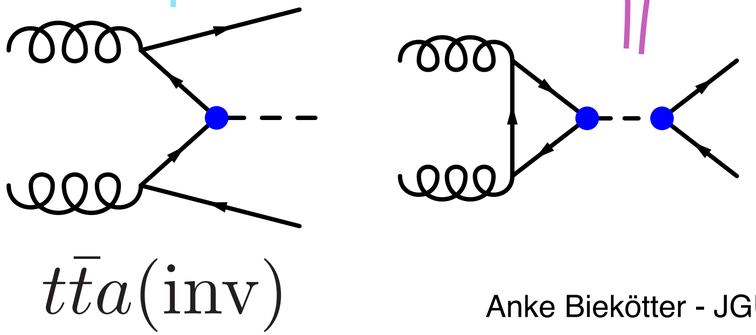


[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]





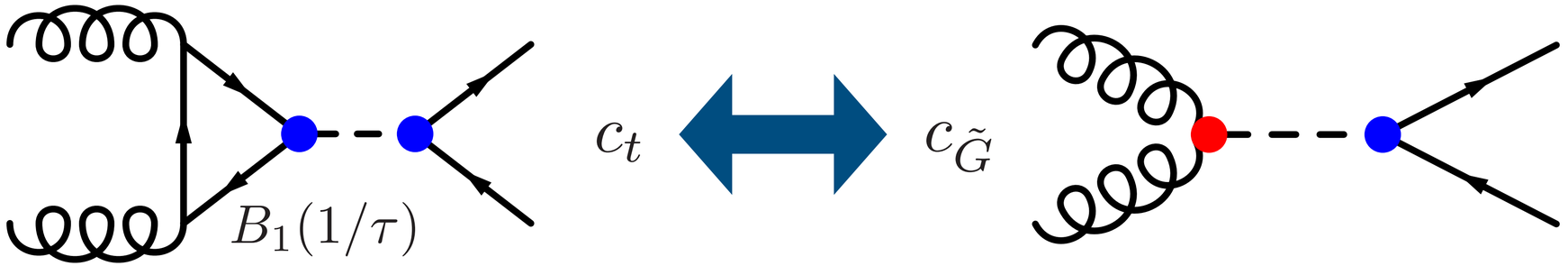


$t\bar{t}a(\text{inv})$

$t\bar{t}$ most relevant at high ALP masses

c_t in derivative basis

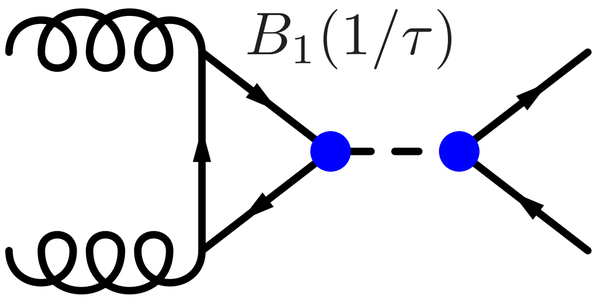
ALP contribution to $t\bar{t}$ production

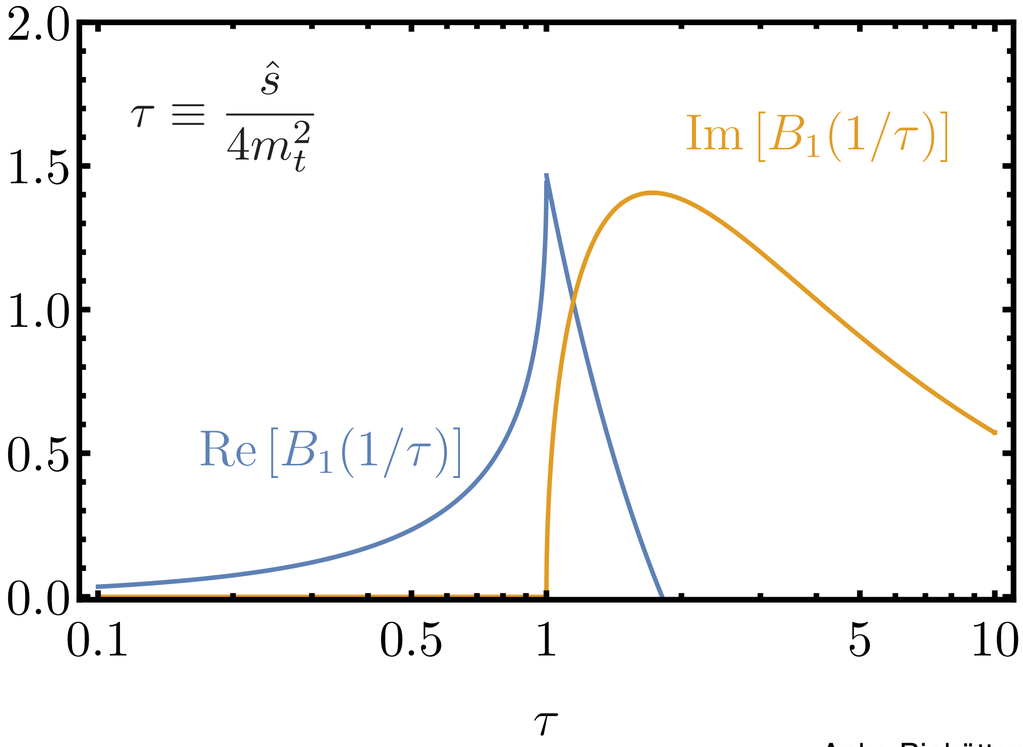


$$\tau \equiv \frac{\hat{s}}{4m_t^2} \qquad \frac{1}{\hat{s} - m_a^2 + i m_a \Gamma_a}$$

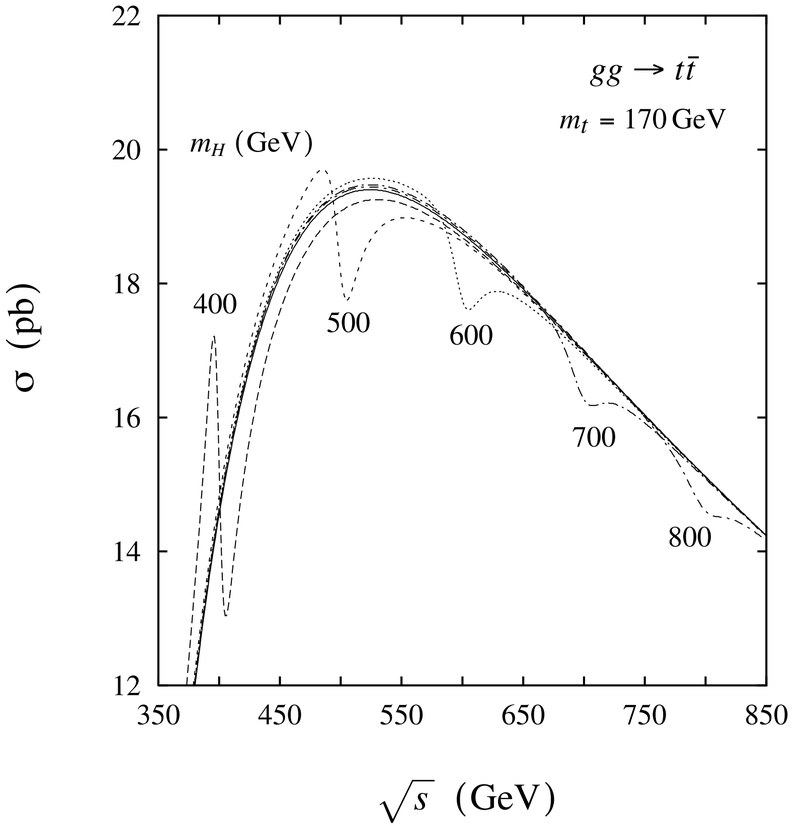
- Loop function develops imaginary part above the $t\bar{t}$ threshold
- Interference contribution $\sim \mathrm{Im}\left[B_1(1/\tau)\right] m_a \Gamma_a$
- Peak-dip (or dip-peak) structure in $m_{t\bar{t}}$

ALP peaks and dips in $t\bar{t}$ production





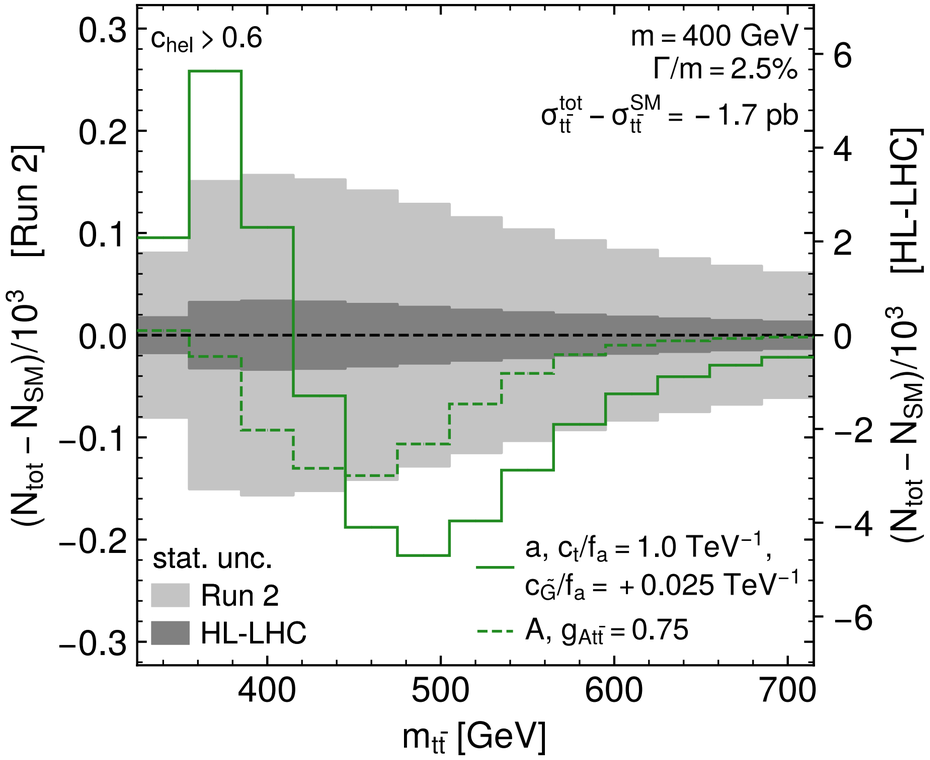
[Dicus, Stange, Willenbrock (hep-ph/9404359)]

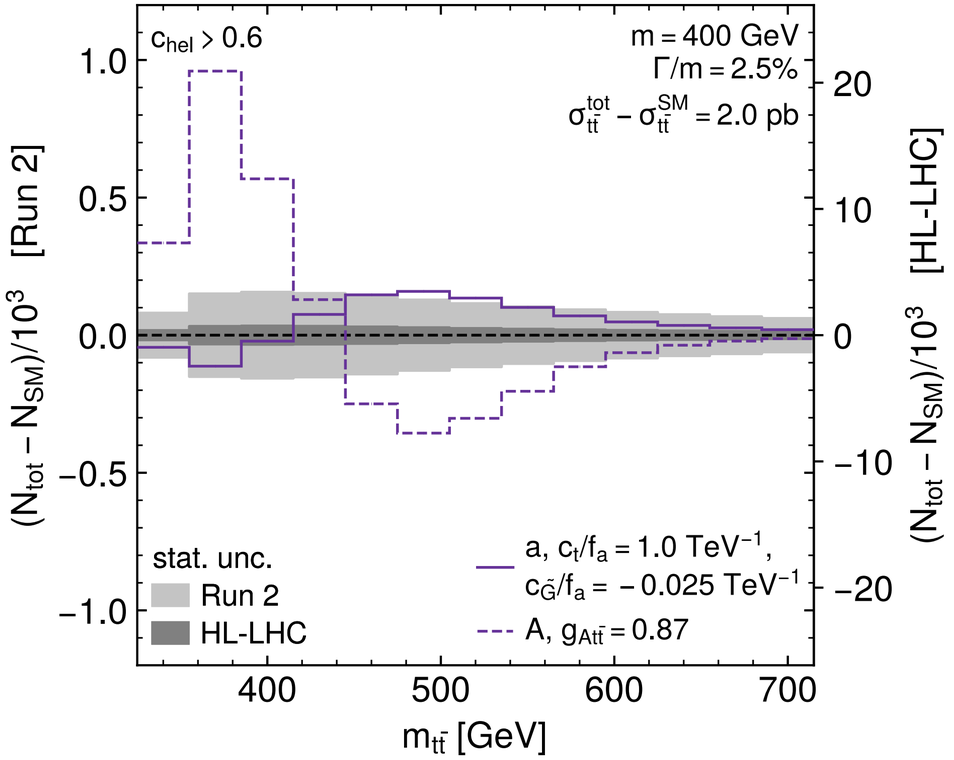


ALP-top vs ALP-gluon coupling

c_t in pseudoscalar basis

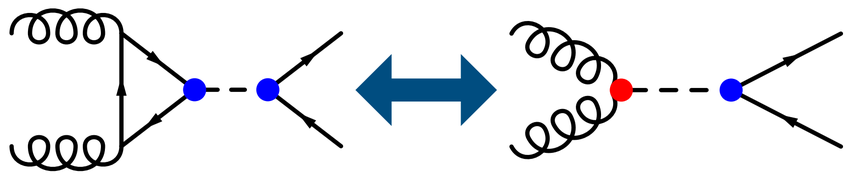
[Anuar, AB, Biekötter, Grohsjean, Heinemeyer, Jeppe, Schwanenberger, Weiglein (2404.19014)]





Solid: c_t, $c_{\tilde{G}}$

Dashed: c_t only (same total cross section)



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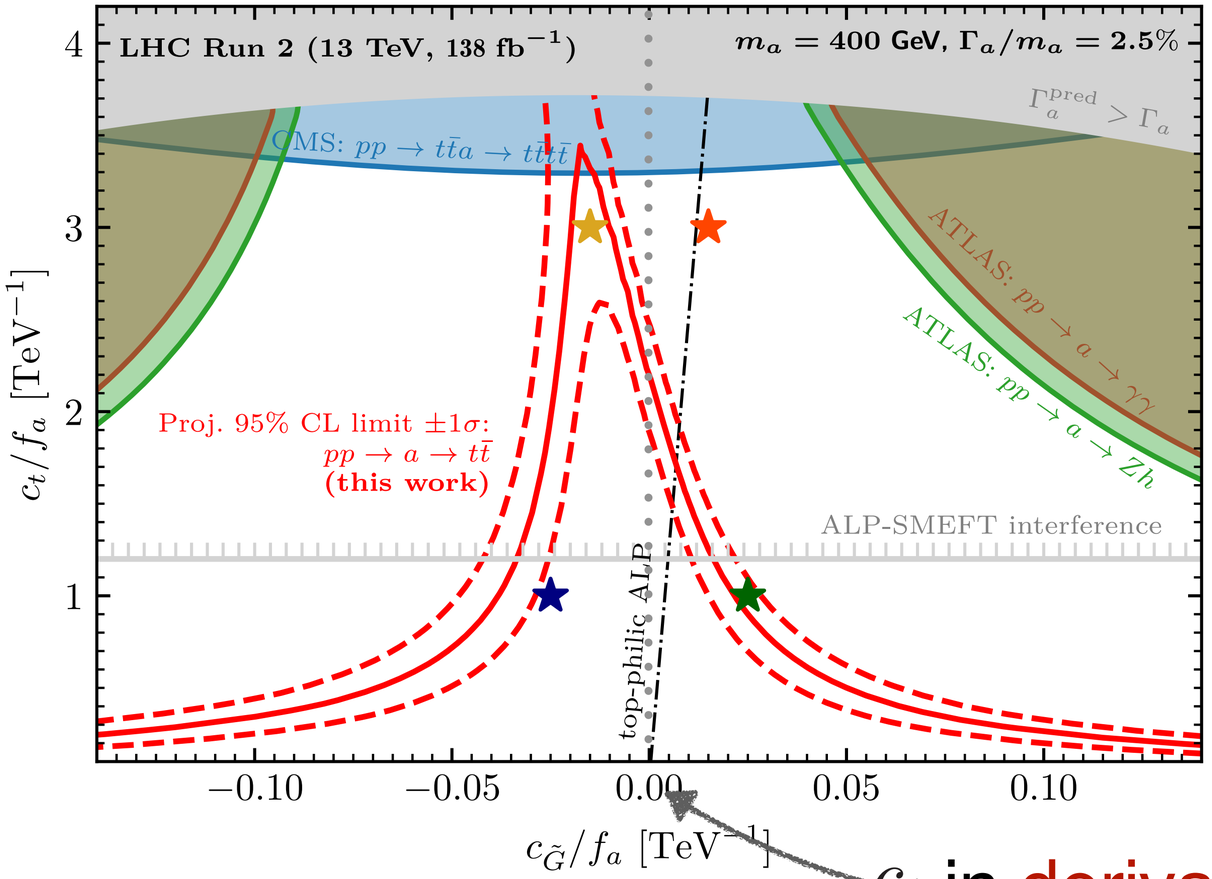


Complementary limits from

- $t\bar{t}t\bar{t}$
- $a \to \gamma\gamma$
- $a \to Zh$

c_t in derivative basis

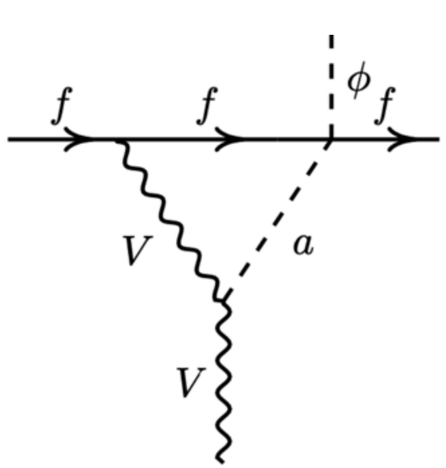
Indirect limits on ALPs
-
ALP-SMEFT interference

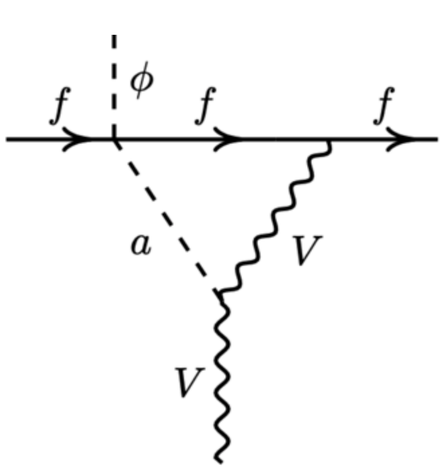
Indirect ALP effects

[Marciano, Masiero, Paradisi, Passera (1607.01022)]

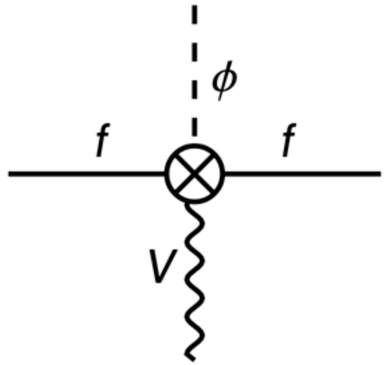
[Bauer, Neubert, Thamm (1704.08207)]

- Virtual ALP exchange induces UV-divergent one-loop graphs
- Dimension-6 operators required as counterterms





$\sim 1/\epsilon$



Requires D6 operator as counterterm

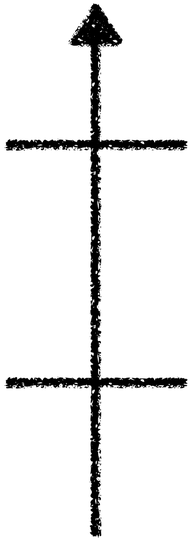
SMEFT!

ALP as a solution for g - 2 discrepancy

ALP-SMEFT interference

[Galda, Neubert, Renner (2105.01078)]

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \frac{S_i}{(4\pi f)^2}$$



$$C^{\mathrm{ALP}}(\Lambda) \neq 0,$$
$$C^{\mathrm{SMEFT}}(\Lambda) = 0$$

$$C^{\mathrm{ALP}}(\mu) \neq 0$$
$$C^{\mathrm{SMEFT}}(\mu) \neq 0$$

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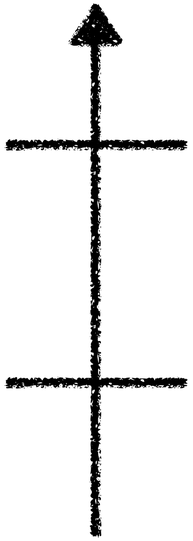

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ALP running induces non-zero SMEFT coefficients!

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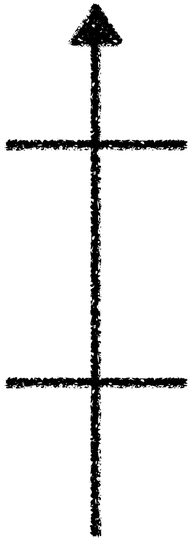

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ALP running induces non-zero SMEFT coefficients!

ALP source terms for D6 SMEFT Wilson coefficients are **ALP mass independent**

$$S_{HG} = 0\,, \qquad S_{H\tilde{G}} = 0\,,$$
$$S_{HW} = -2g_2^2\, C_{WW}^2\,, \qquad S_{H\widetilde{W}} = 0\,,$$
$$S_{HB} = -2g_1^2\, C_{BB}^2\,, \qquad S_{H\widetilde{B}} = 0\,,$$
$$S_{HWB} = -4g_1 g_2\, C_{WW} C_{BB}\,, \qquad S_{H\widetilde{W}B} = 0\,.$$

ALP-SMEFT interference

[Galda, Neubert, Renner (2105.01078)]

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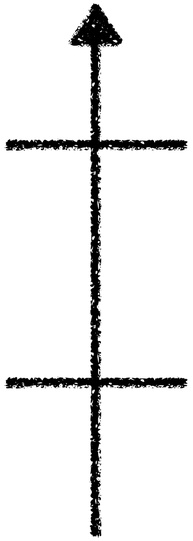

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ALP running induces non-zero SMEFT coefficients!

ALP source terms for D6 SMEFT Wilson coefficients are **ALP mass independent**

Can we use SMEFT constraints to obtain mass-independent constraints on the ALP Wilson coefficients?

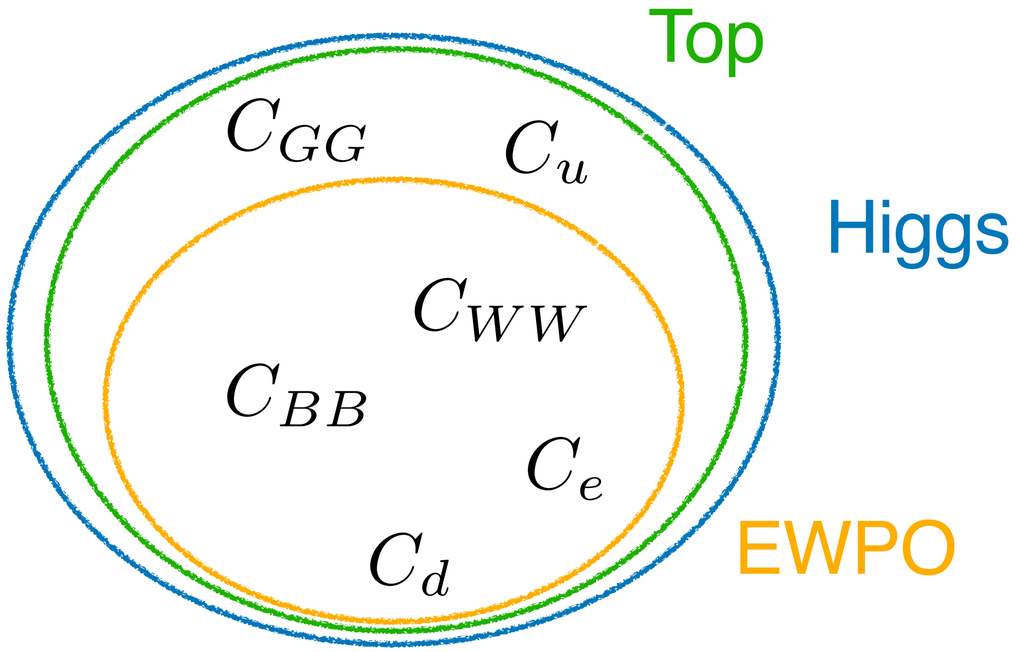
Exploiting the ALP-SMEFT interference

Observables used

- Low energy:
  - Electroweak precision observables (EWPO)
  - Parity violation experiments
  - Lepton scattering
- Higgs [Falkowski et al. (1706.03783)]
- Top [Ellis et al. (2012.02779)]

Six free parameters

$C_{GG}, C_{WW}, C_{BB}, C_u, C_d, C_e$



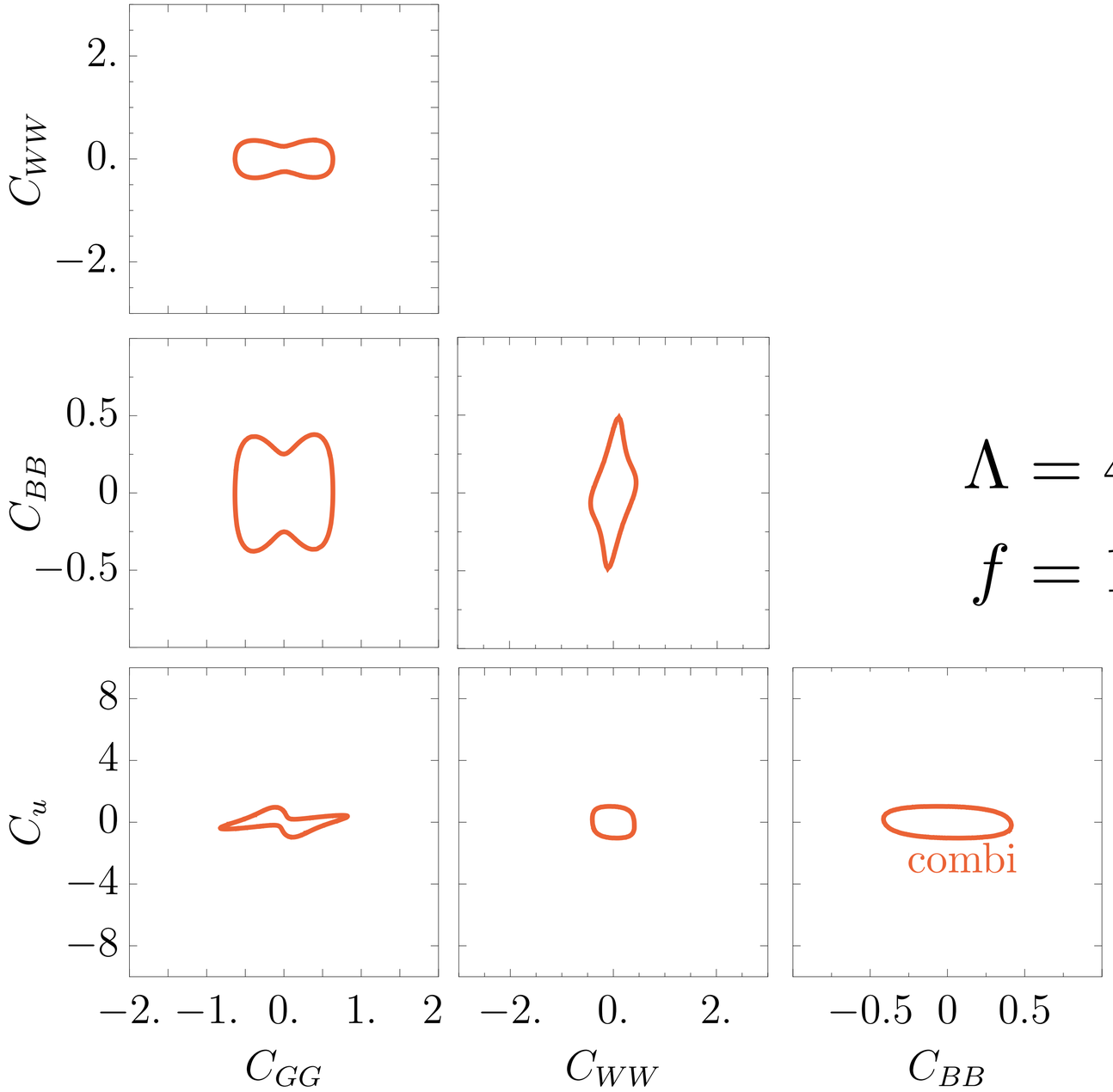
2D limits

Dominant constraints

- C_{GG} : Higgs + Top
- C_{WW} : LE + Higgs
- C_{BB} : low energy
- C_u : low energy

- C_d : low energy
- C_e : low energy

ALP-top



$$\Lambda = 4\pi f$$

$$f = 1 \text{ TeV}$$

 [AB, Fuentes Martín, Galda, Neubert (2307.10372)]

2D limits

Dominant constraints

- C_{GG} : Higgs + Top
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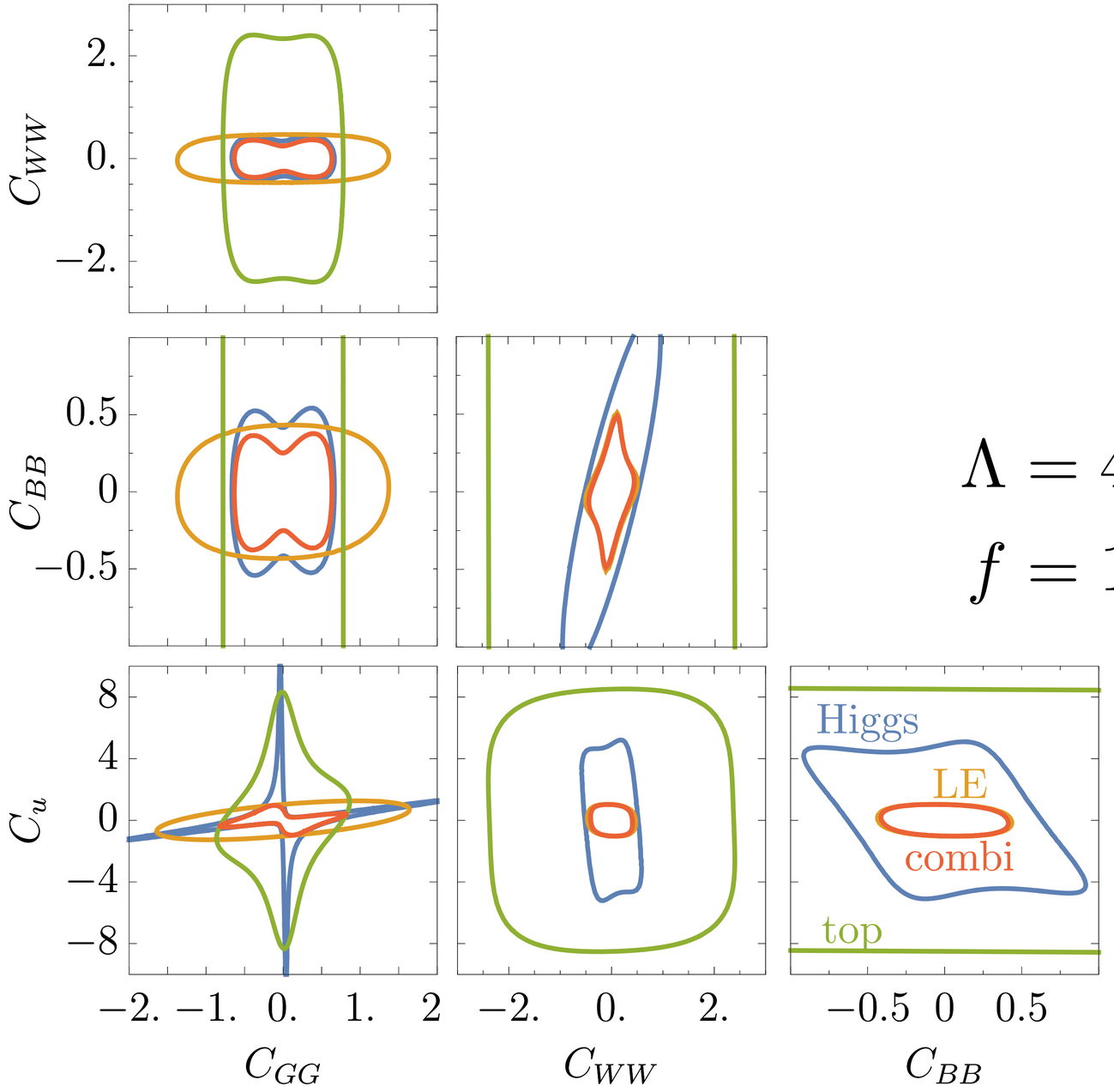
ALP-top



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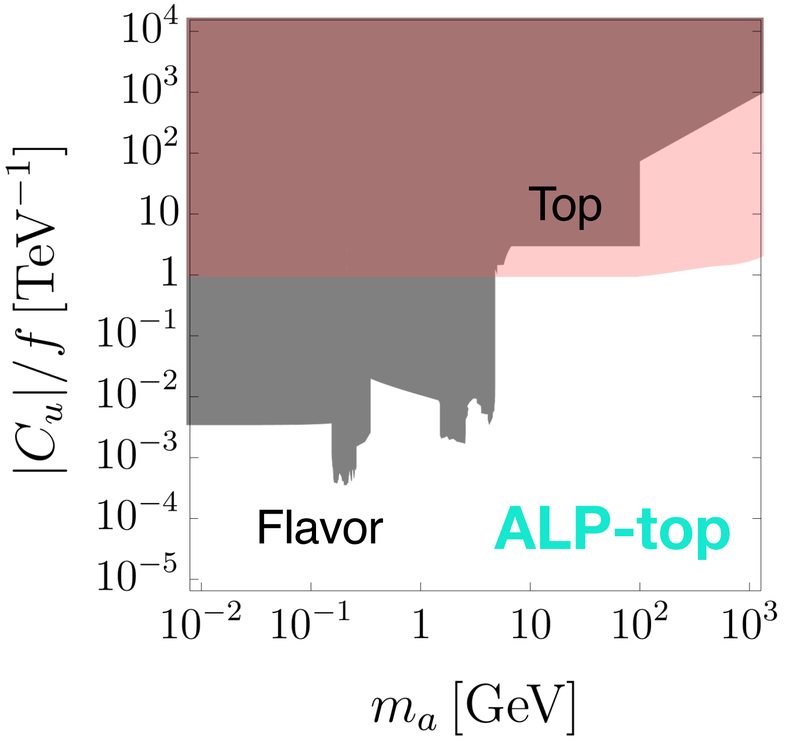
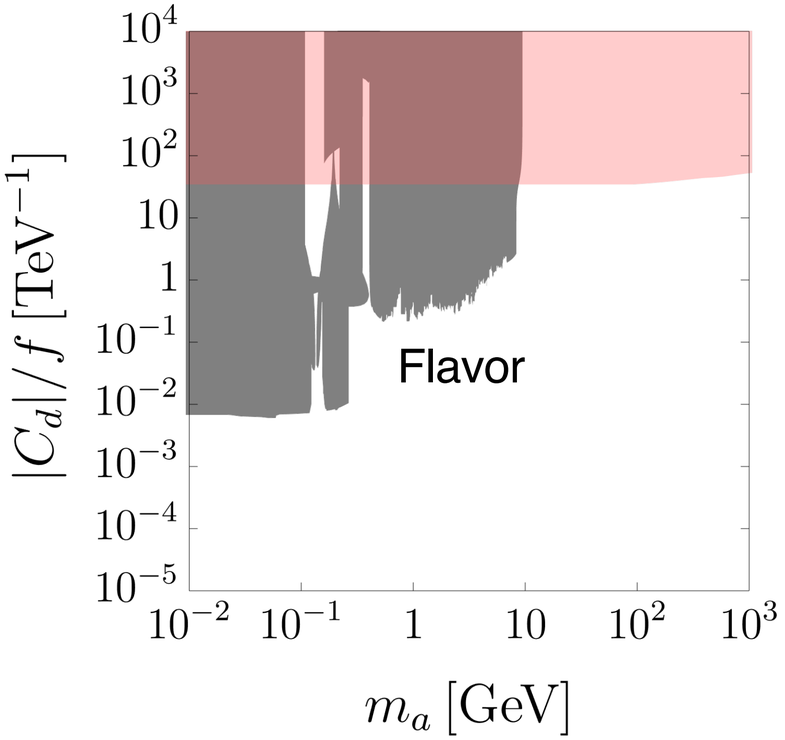
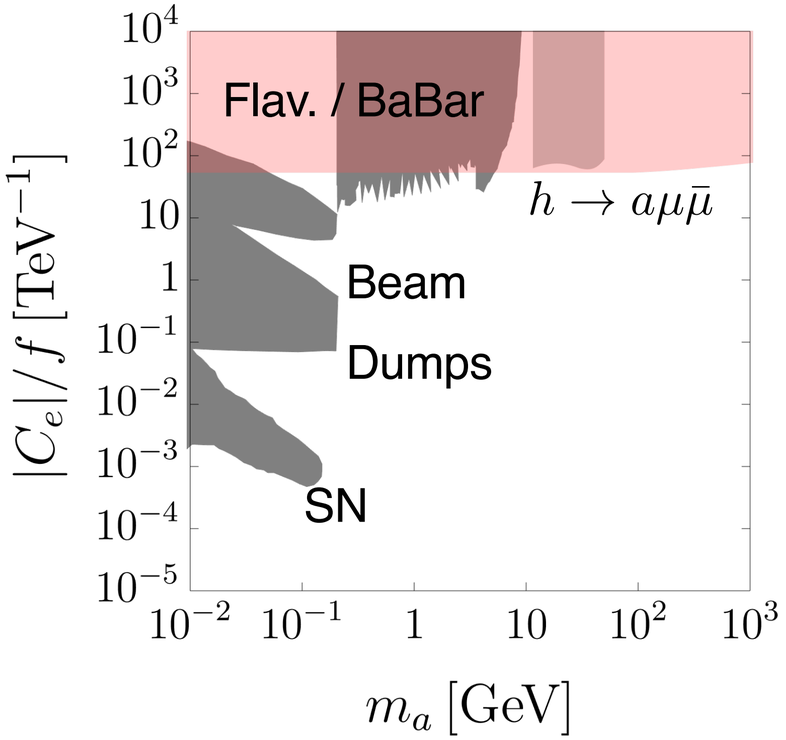
 [AB, Fuentes Martín, Galda, Neubert (2307.10372)]

Comparison with direct bounds - fermions

[AB, Fuentes Martín, Galda, Neubert (2307.10372)]







[Esser, Madigan, Sanz, Ubiali (2303.17634)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

[BaBar (1406.2980)]

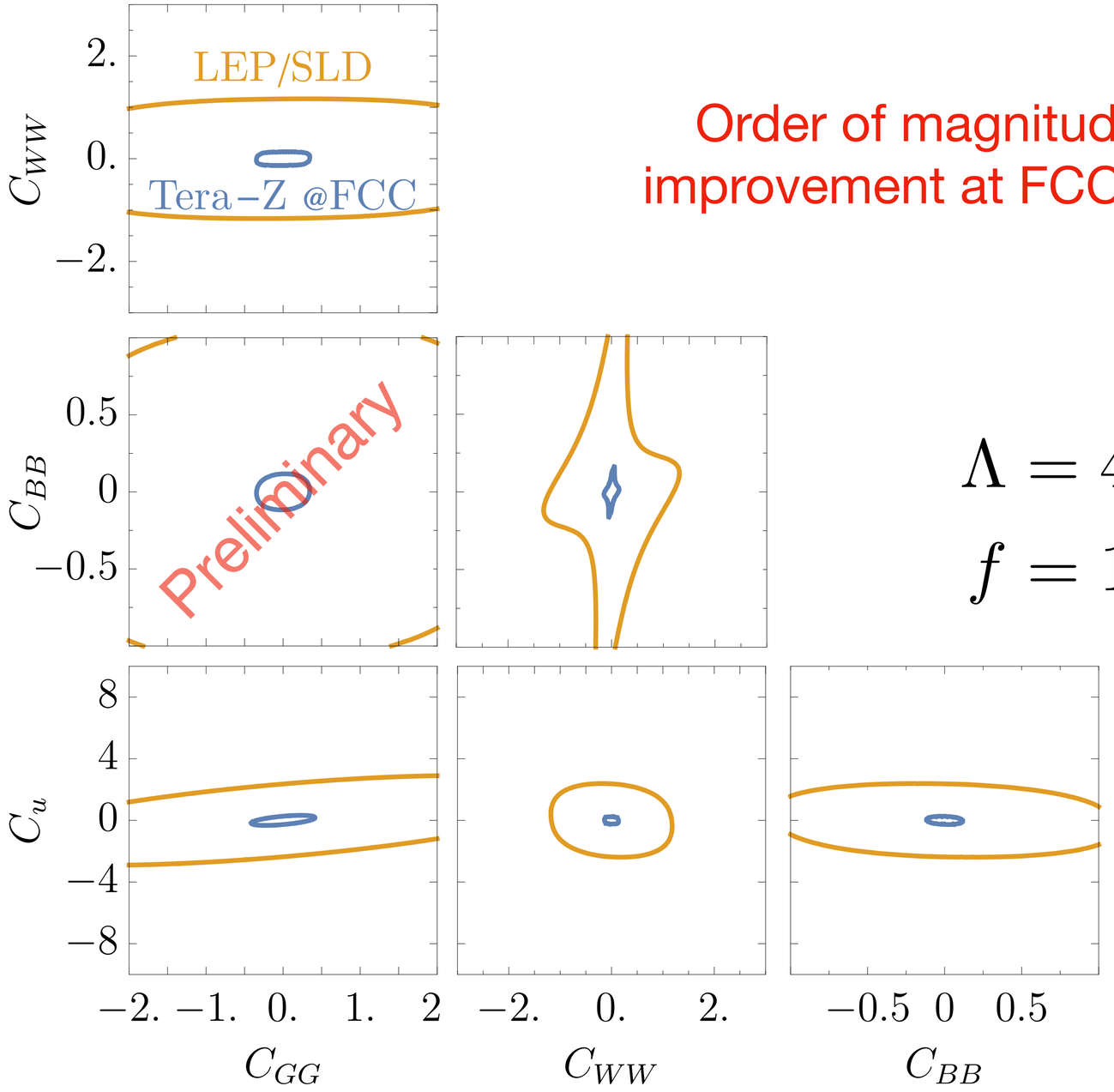
[AB, Chala, Spannowski (2203.14984)]

[Lucente, Carenza (2107.12393)]

[Essig, Harnik, Kaplan, Toro (1008.0636)]

FCC-ee Tera-Z

FCC-ee sensitivity estimates from FCC midterm report



Order of magnitude improvement at FCC-ee

$$\Lambda = 4\pi f$$

$$f = 1 \text{ TeV}$$

see also:

[de Blas, Durieux, Grojean, Gu, Paul (1907.04311)]

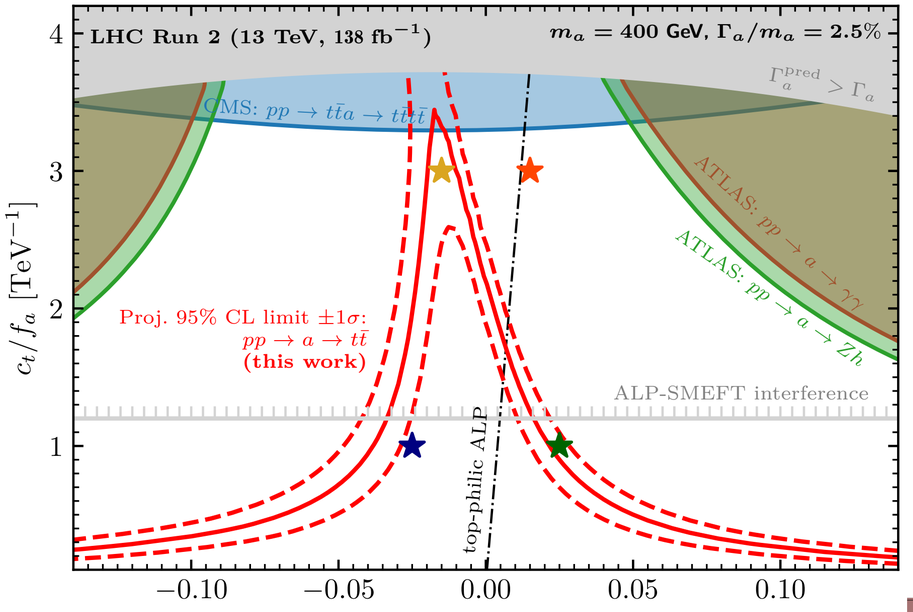
[FCC Snowmass (2203.06520)]

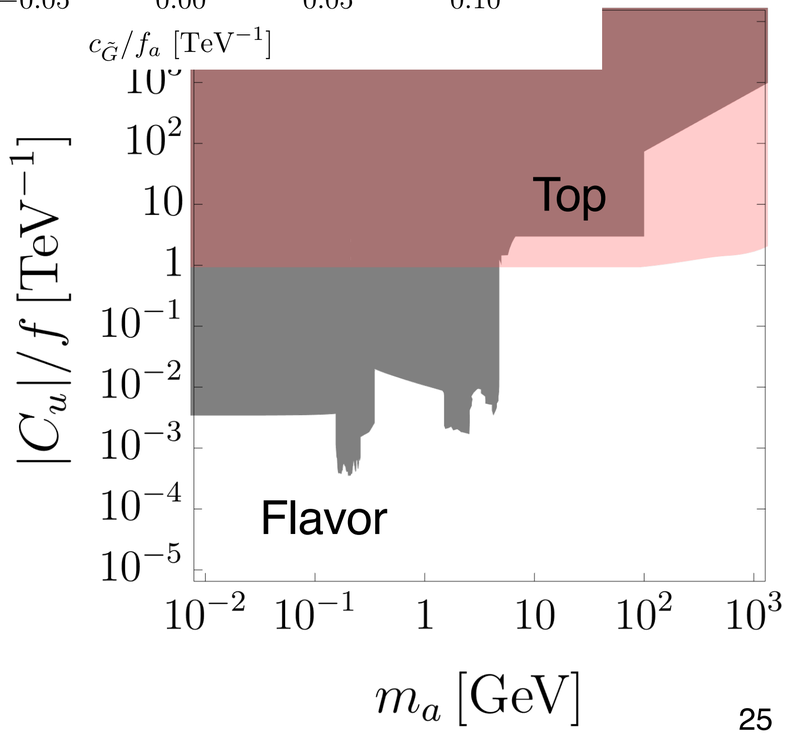
[Dubovyk, Freitas, Gluza, Grzanka, Jadach, Riemann, Usovitsch (1809.01830)]

Conclusions

- Very rich ALP phenomenology

- ALP-top coupling
  - Complementarity of flavor, $t\bar{t}a$, $t\bar{t}$ production
- Complementary of direct and indirect bounds





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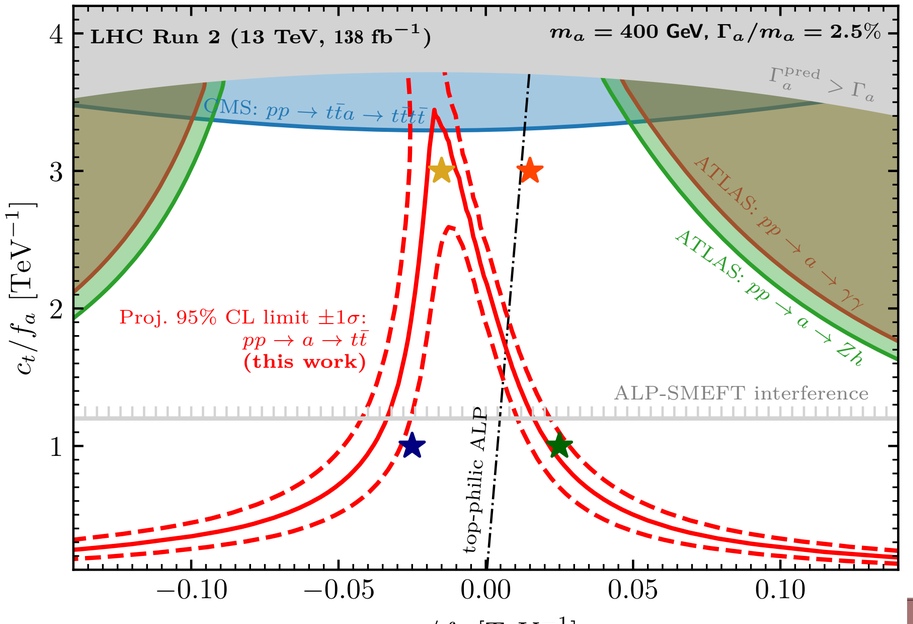

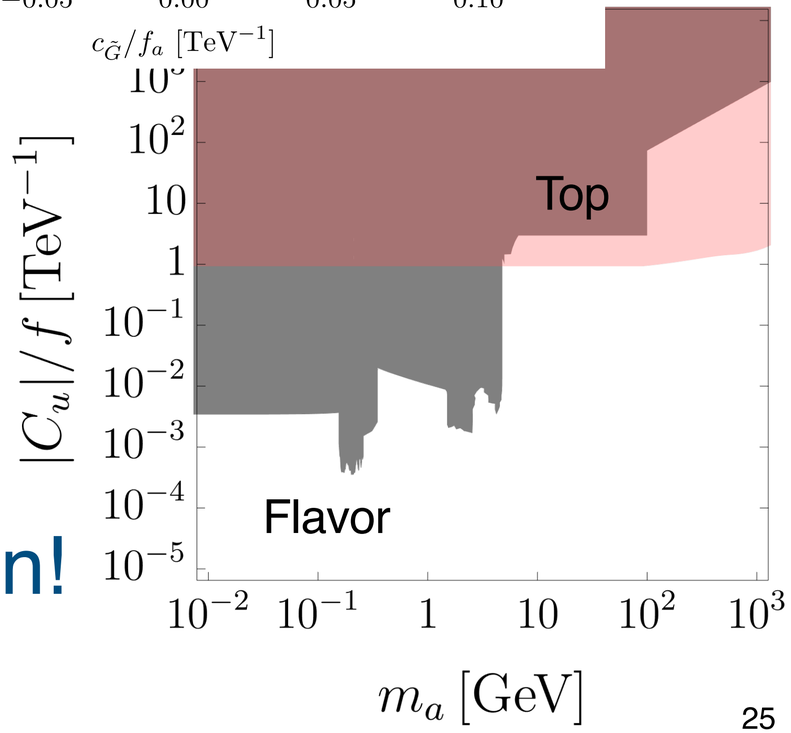

Thank you for your attention!