What the Higgs can tell us about axion-like particles

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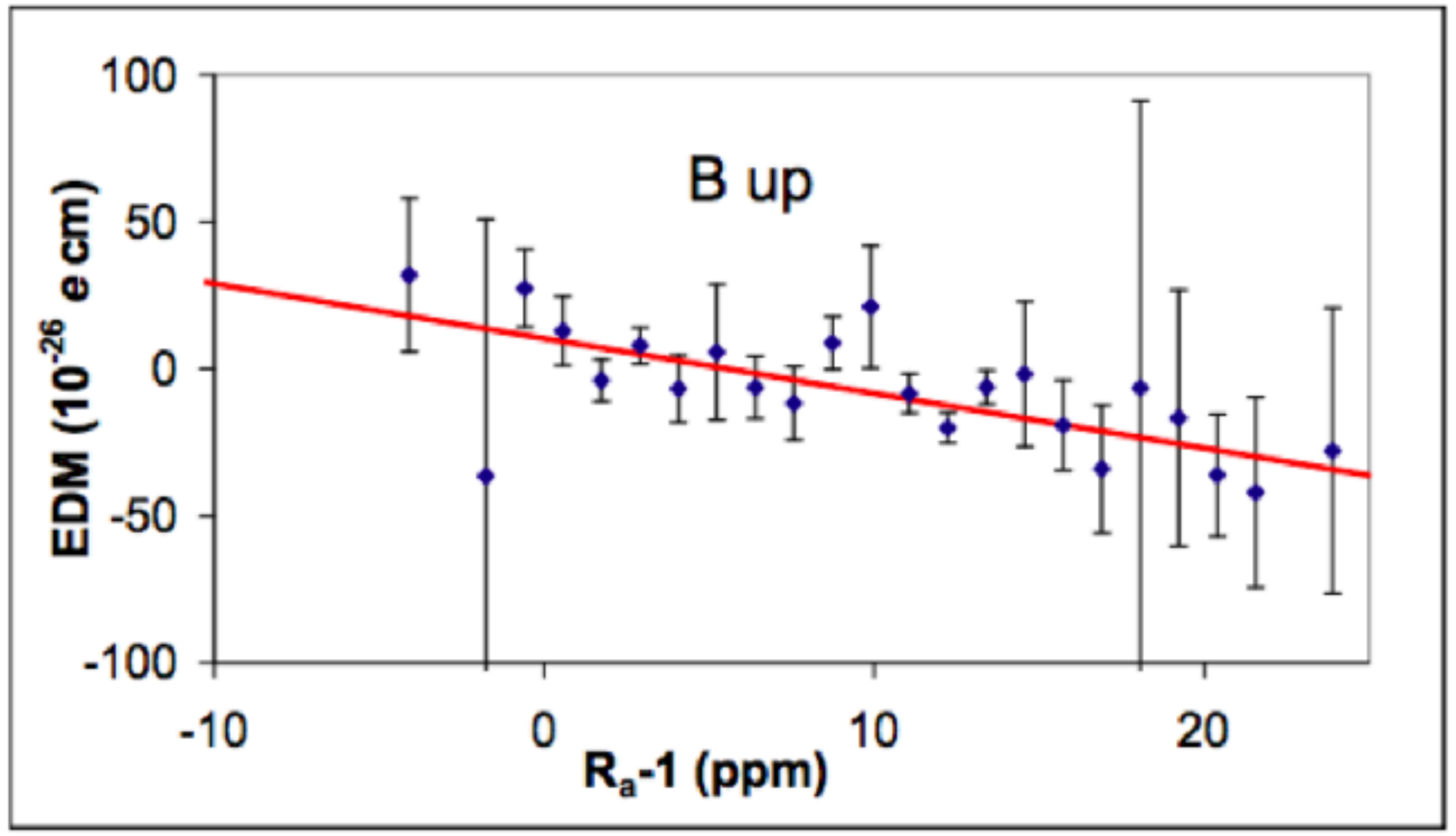
Axions

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

Why is the theta term so small?

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



Electric dipole moment of the neutron

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

Dynamical solution to the strong CP problem

[Peccei, Quinn (ref1, ref2)]

[Weinberg] [Wilczek]

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

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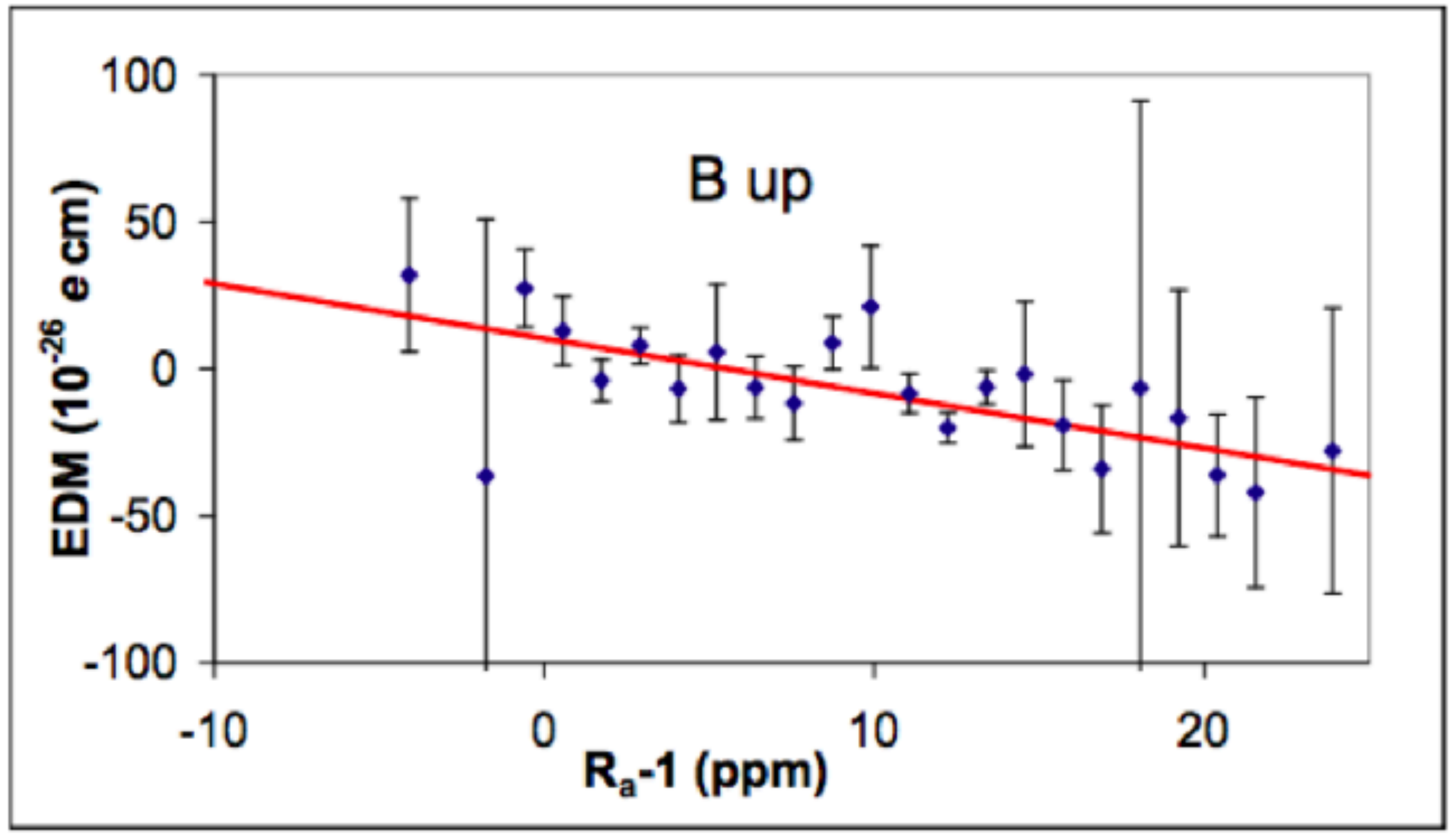

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Dynamical solution to the strong CP problem

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

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

Does not hold for axion-like particles (ALPs)

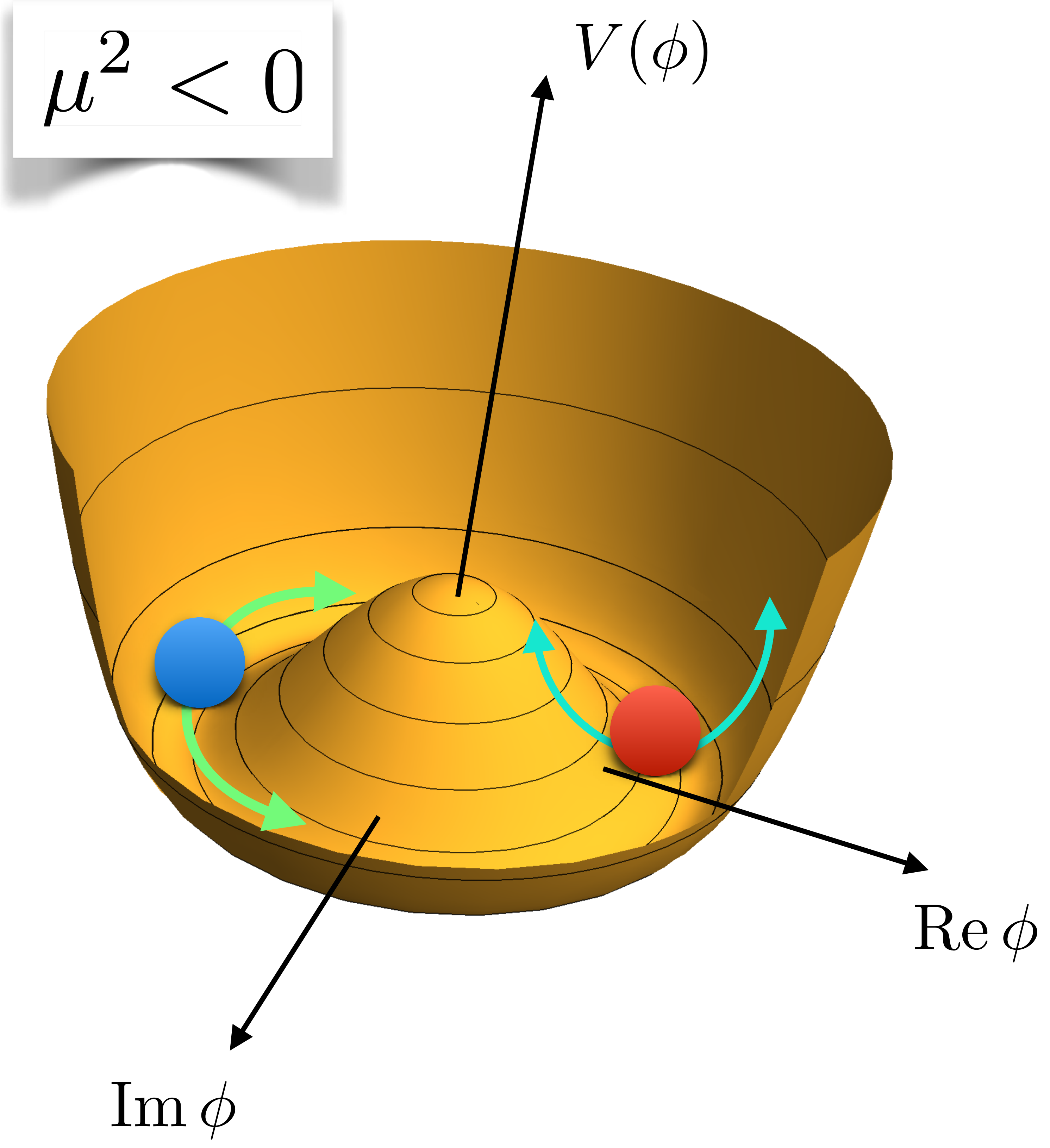
Axion-like particles - motivation

A spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$
$$\phi = (f+s)e^{ia/f}$$

Shift symmetry
$$a \to a + a_0$$

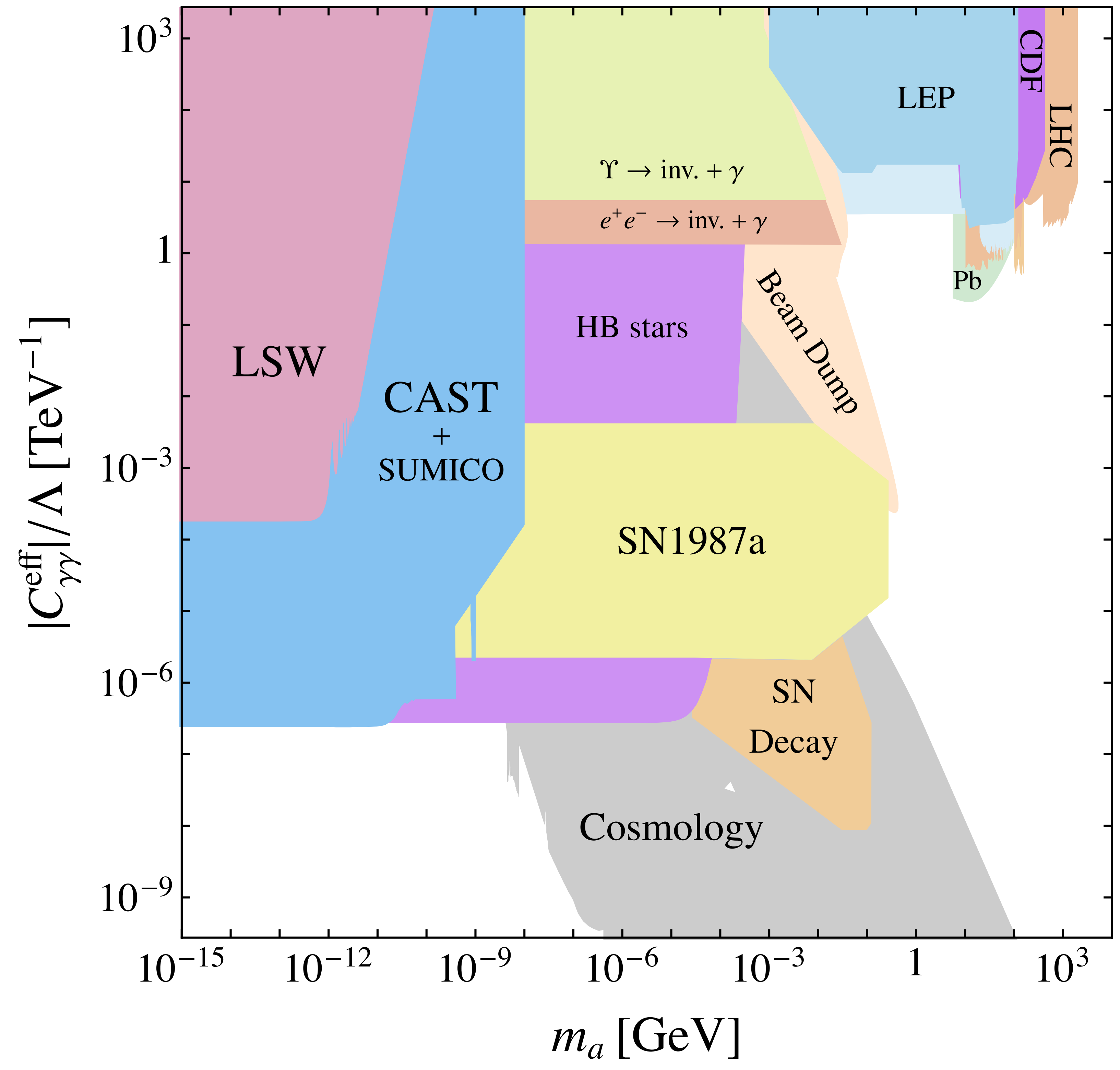
$$m_s^2 = 4\lambda f^2 = |\mu|^2$$
$$m_a^2 = 0$$



[Bauer (PADUA23)]

Light BSM particles at the LHC

Example: axion-like-particles



Andrea Thamm

18

[Thamm (LHCP24)]

ALP mass range covered by the **LHC** interesting in the context of

- Heavy axions
- Pseudo Nambu Goldstone bosons from SUSY, composite Higgs
- g-2

Interplay of experiments/ observations crucial

Light BSM particles at the LHC

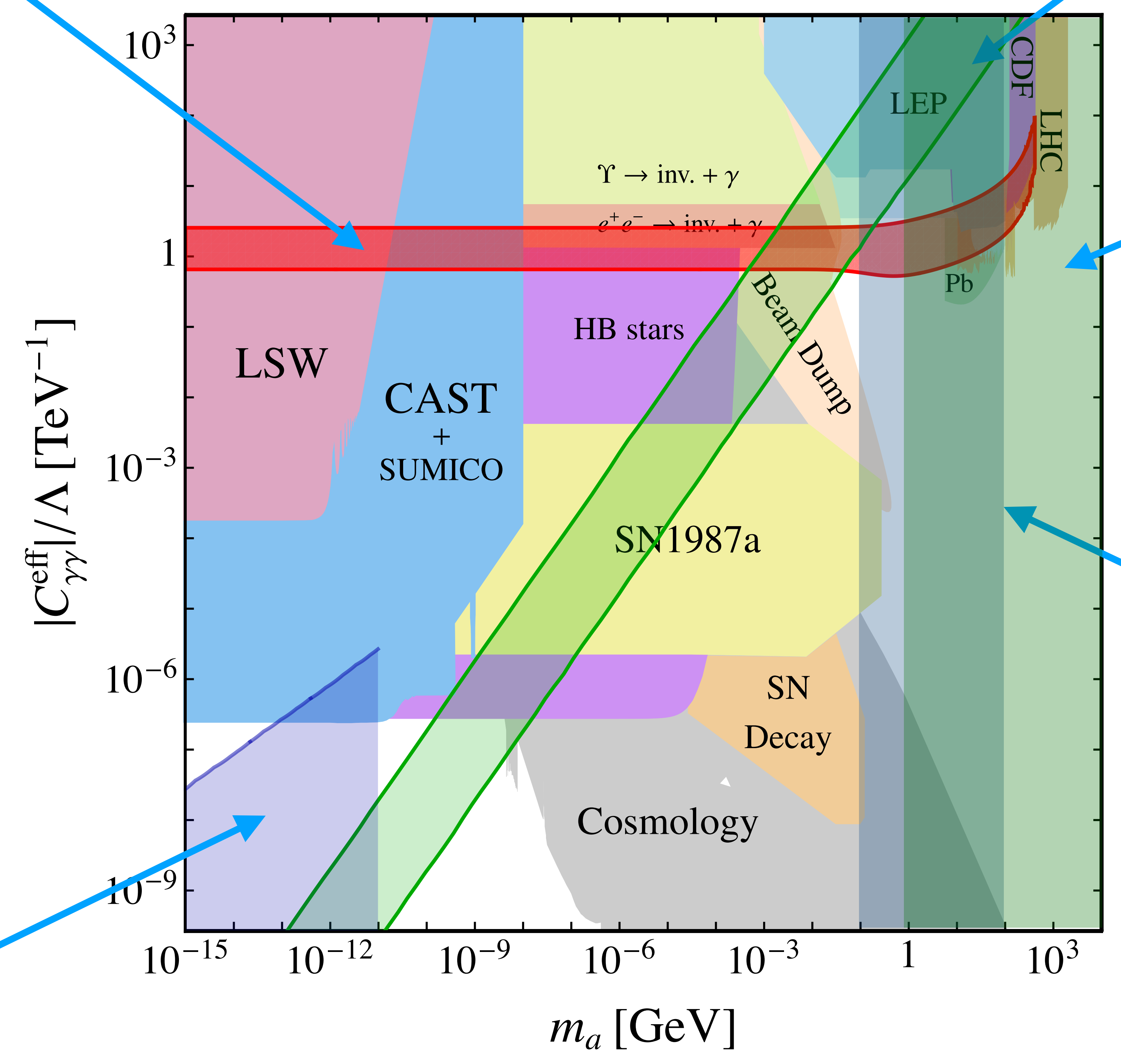
[Thamm (LHCP24)]

Example: axion-like-particles

Solves $(g-2)_\mu$ anomaly
1708.00443, 1908.00008

QCD axion
9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Heavy axion



pNGB in supersymmetric or composite models
0902.1483, 1312.5330, 1702.02152, 2104.11064

DM candidate

Andrea Thamm

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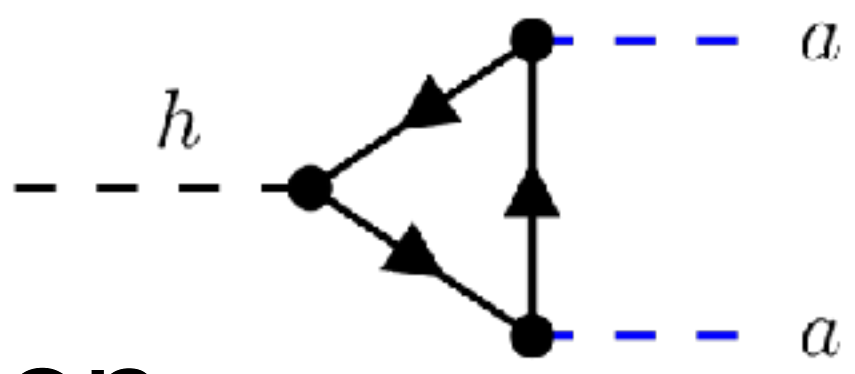
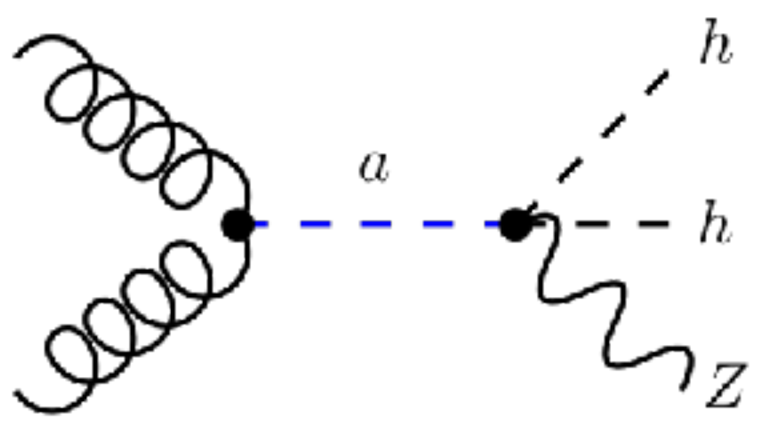
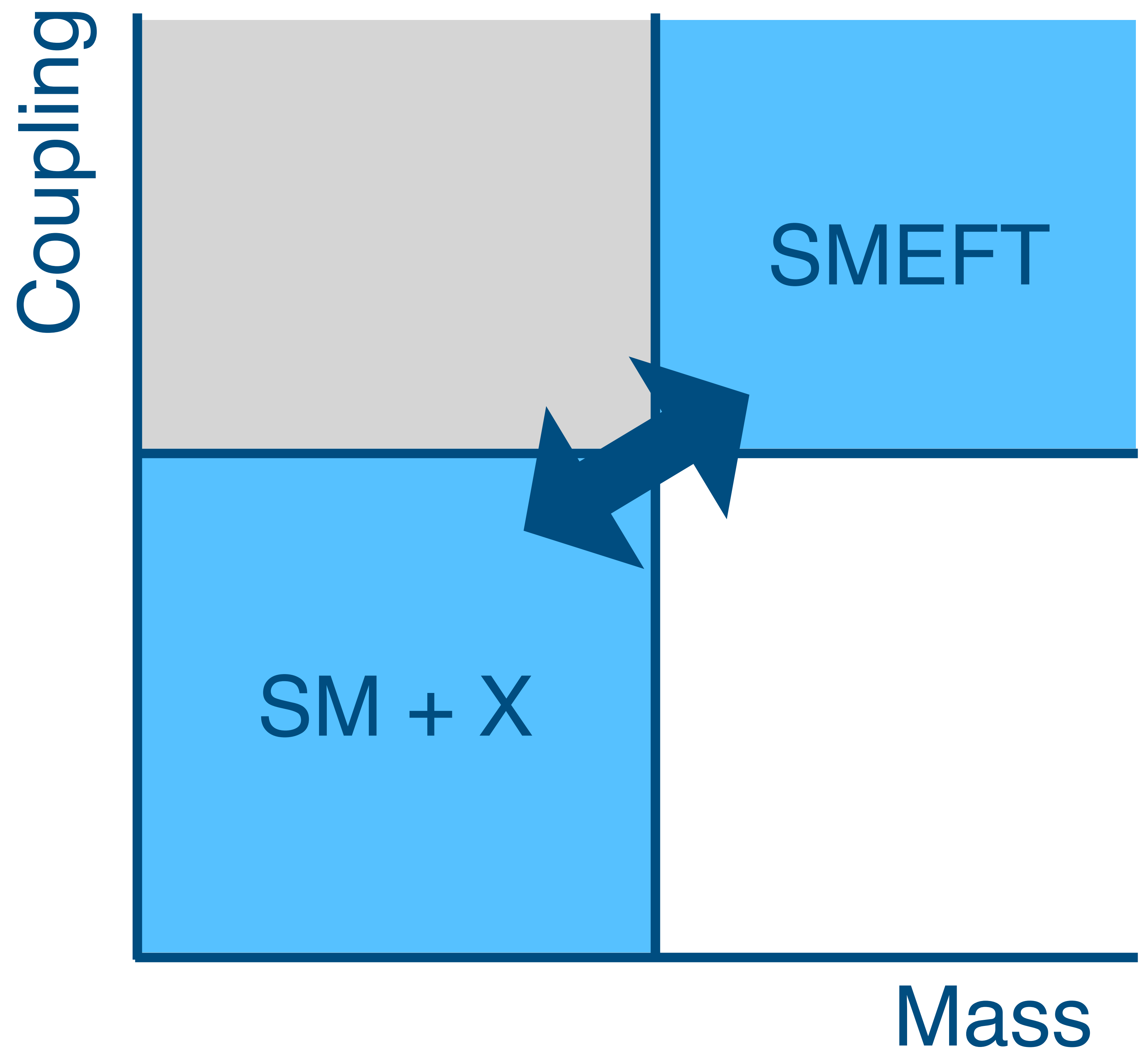
Interplay of experiments/ observations crucial

Outline

- Axion-like particle (ALP) EFT
  - Issues with 2D ALP limits
- Higgs decays to ALPs and di-Higgs production
- **Indirect** effect of ALPs on Higgs physics
  - ALP-SMEFT interference
  - Global analysis







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, …
- Consider a generic ALP with effective Lagrangian
- Shift symmetry $a \to a + a_0$, Lagrangian terms: $\frac{\partial_\mu a}{f_a} (\mathrm{SM})^\mu$

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

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

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

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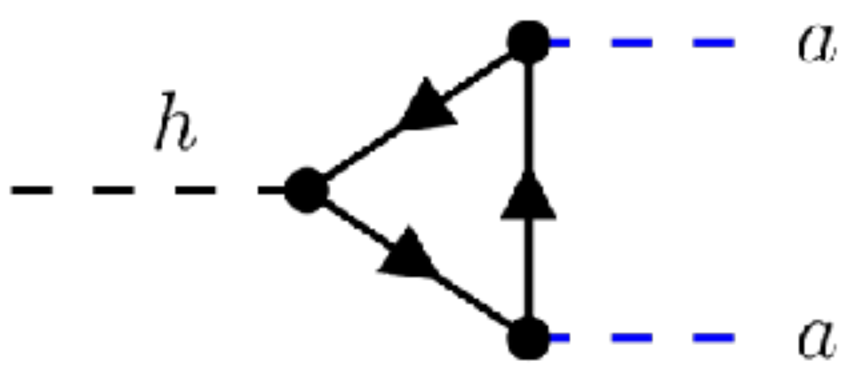
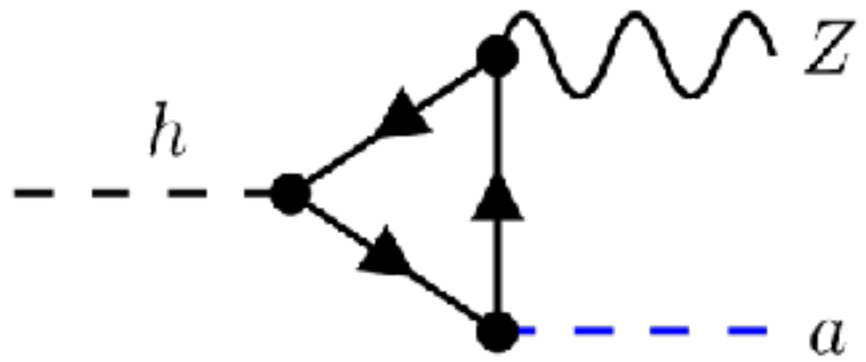
Redundant

ALPs and the Higgs

Exotic Higgs decays could be an interesting signature of ALPs at the LHC

- Higgs-ALP interactions generated at one loop





- and at dimensions $\geq$ six

$h \to aa$ $\qquad$ $h \to Za$

$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{f^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C'_{ah}}{f^2} m_{a,0}^2\, a^2\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{f^3}(\partial^\mu a)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

Breaks ALP shift symmetry

(suppressed by $m_{a,0}^2$)

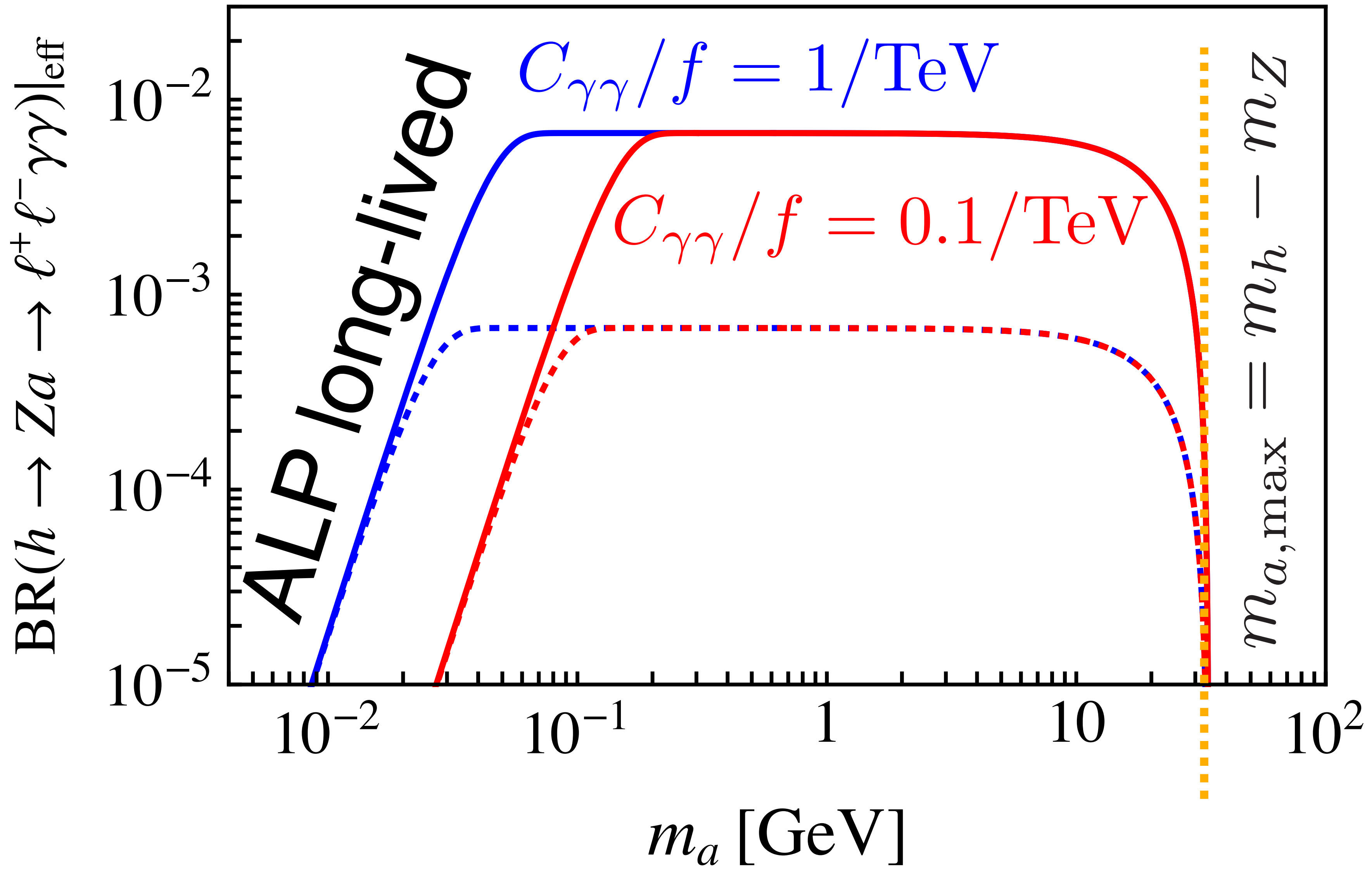
ALPs in exotic Higgs decays

[BSM Higgs physics 1 (Tue)]
[Priscilla Pani]

$$\Gamma(h \to \mathrm{BSM})$$

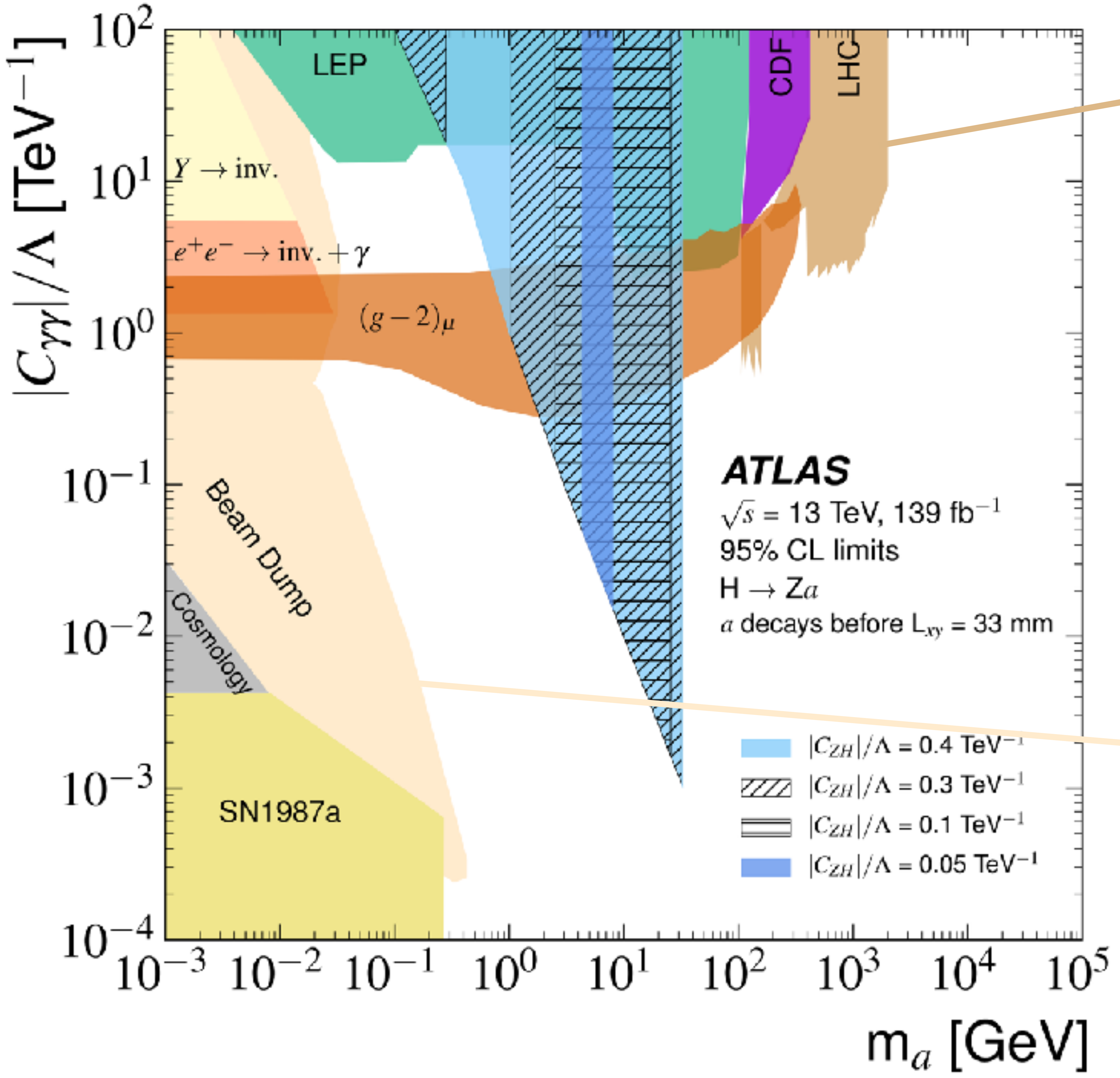
$$\begin{aligned} h &\to Za \\ &\to (\ell^+\ell^-)(\gamma\gamma),\ (\ell\ell)(\gamma) \\ &\to (\ell^+\ell^-)(\ell'^+\ell'^-) \\ &\to (\ell^+\ell^-)(E_T^{\text{miss}}) \end{aligned}$$

[Bauer, Neubert, Thamm (1708.00443)]



$$\begin{aligned} h &\to aa \\ &\to (\gamma\gamma)(\gamma\gamma),\ (\gamma\gamma)(\gamma) \\ &\to (\ell^+\ell^-)(\gamma\gamma),\ (\ell\ell)(\gamma) \\ &\to (\ell^+\ell^-)(\ell'^+\ell'^-) \\ &\to (\ell^+\ell^-)(b\bar{b}) \\ &\to \ldots \end{aligned}$$

2D ALP bounds



[ATLAS (2312.01942)]

LHC limits

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

Mass-dependent (resonance search)

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

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

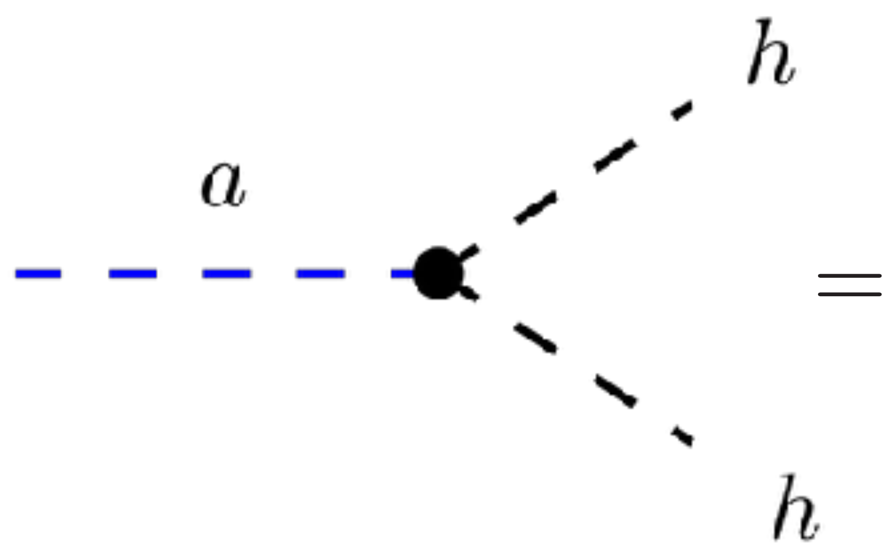
$\mathrm{BR}(a \to Z\gamma)$?

Beam dump limits

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

ALPs in di-Higgs production

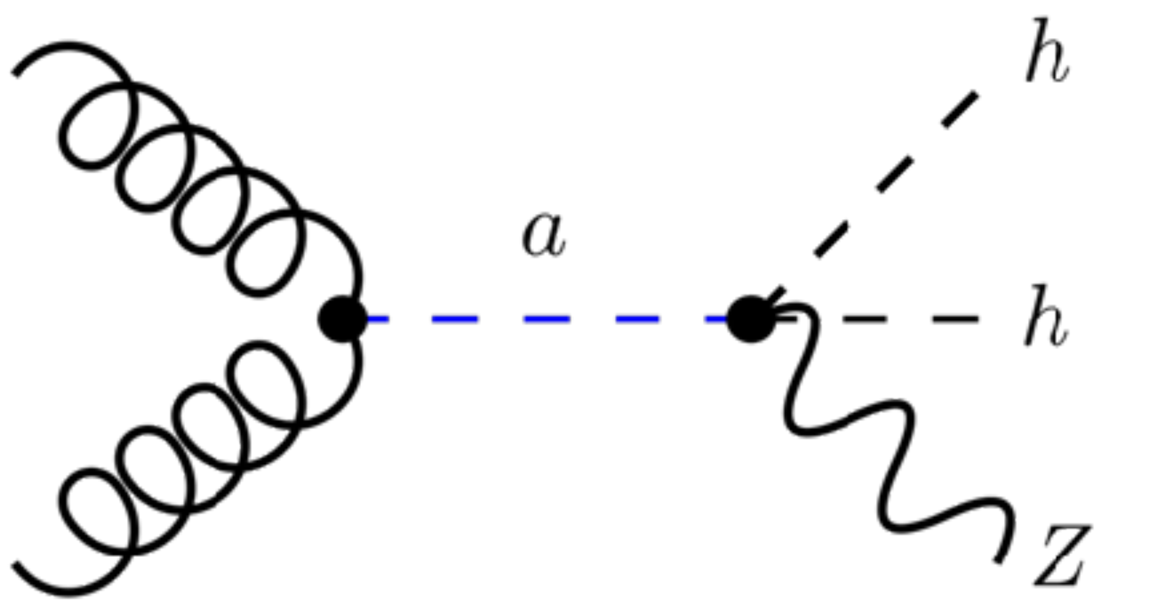
[Esser, Madigan, Salas-Bernárdez, Sanz, Ubiali (2404.08062)]



$= 0$

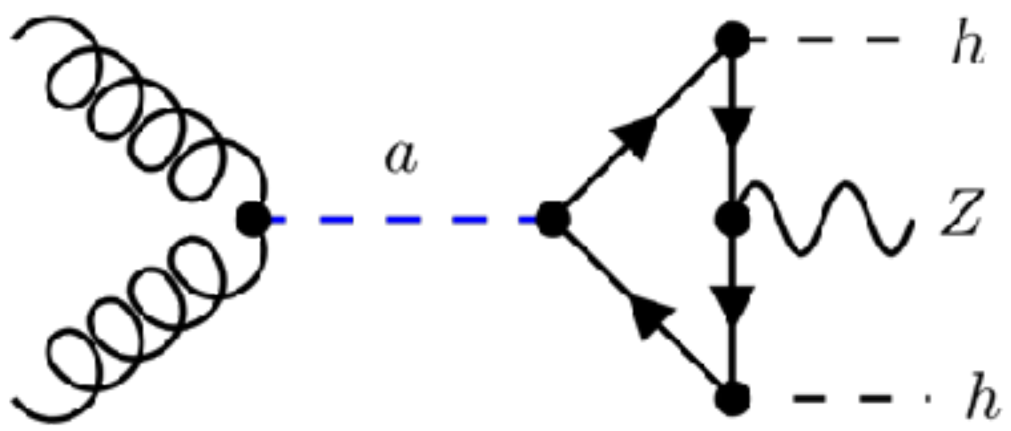
Forbidden

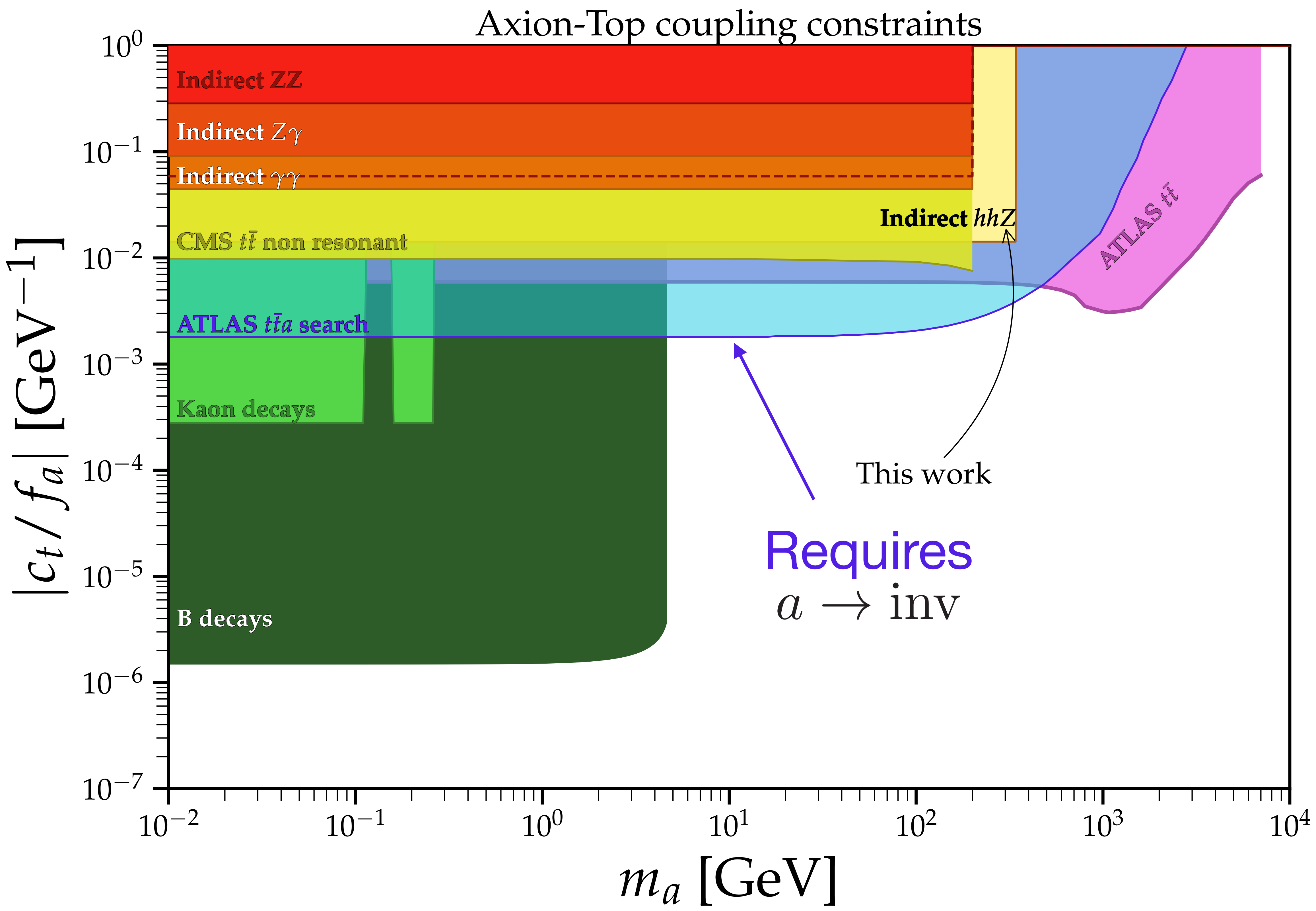
$0^- \nrightarrow 0^+$



di-Higgs + Z allowed

No experimental search for this yet



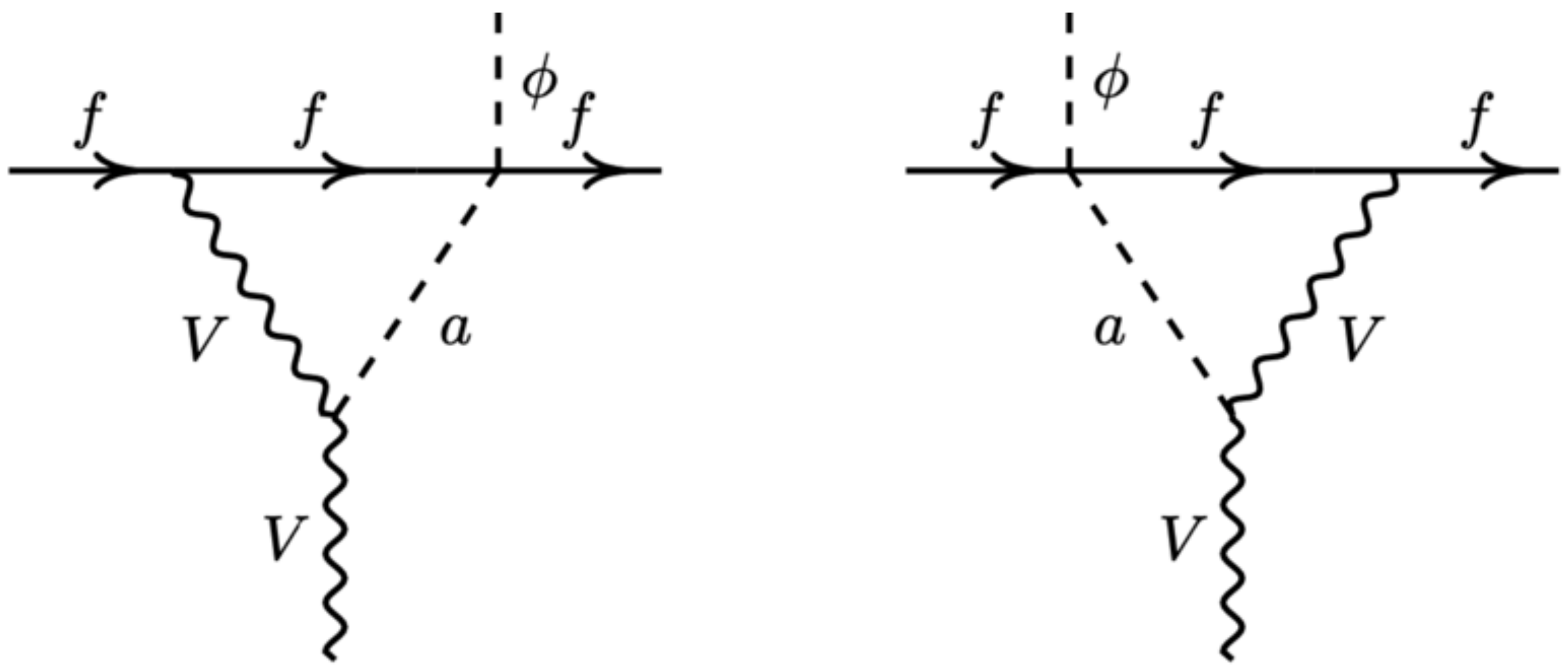


Indirect effects of ALPs

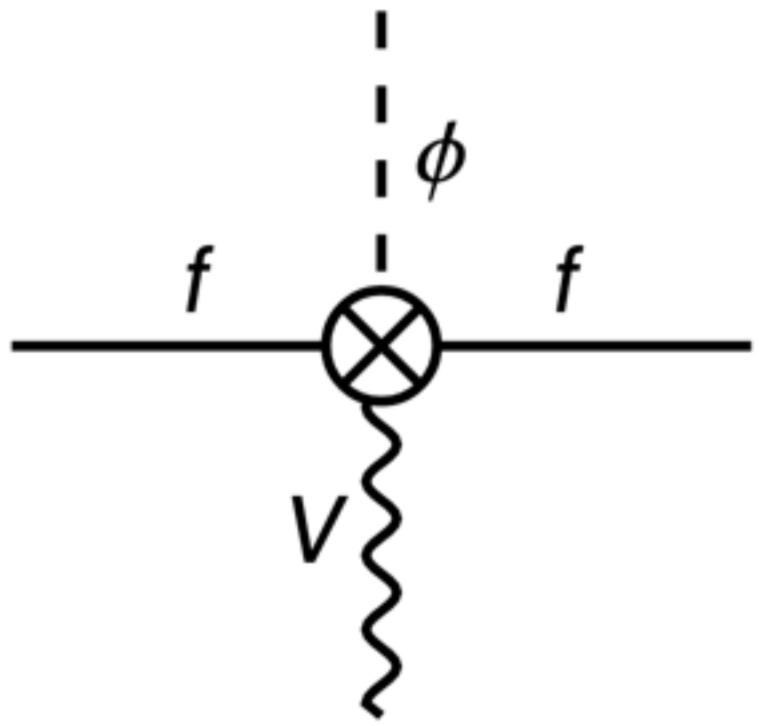
Indirect ALP effects

[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



$\sim 1/\epsilon$



ALP as a solution for g - 2 discrepancy

Requires D6 operator as counterterm

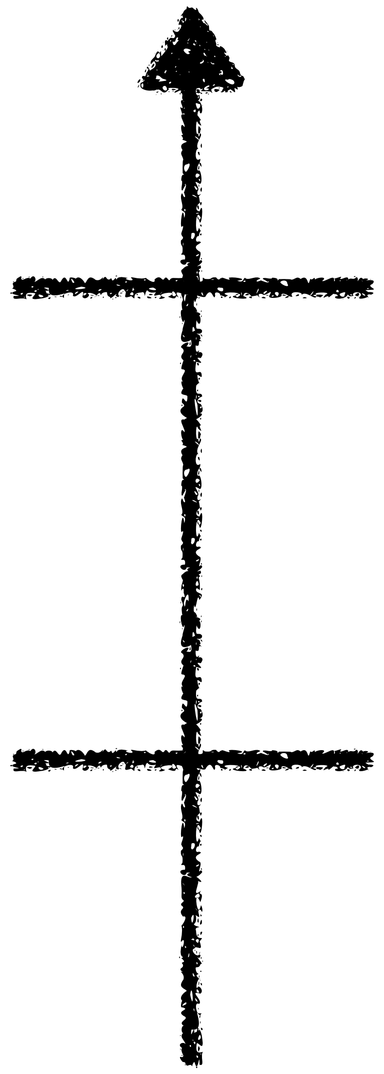
SMEFT!

ALP-SMEFT interference

[Galda, Neubert, Renner (2105.01078)]

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

$$S_i \propto \left(C^{\mathrm{ALP}}\right)^2$$



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

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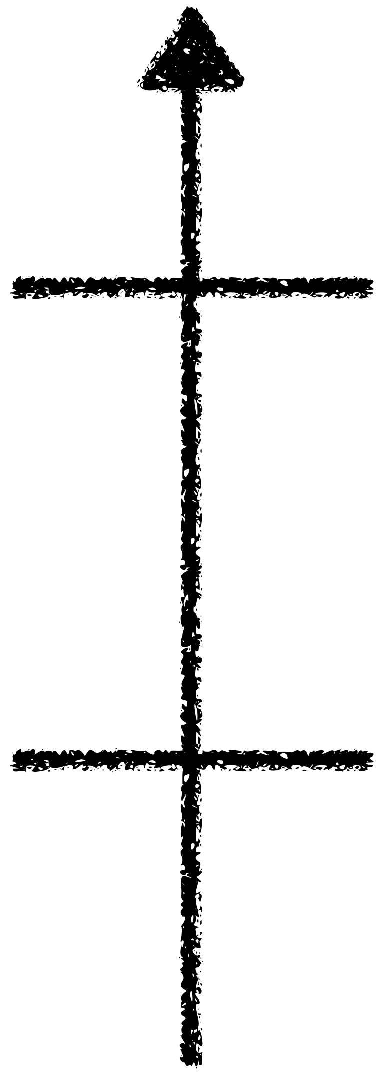

$$C^{\mathrm{ALP}}(\Lambda) \neq 0,$$
$$C^{\mathrm{SMEFT}}(\Lambda) = 0$$

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

ALP running induces non-zero SMEFT coefficients!

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

Aside: different ALP bases

derivative
basis

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

⬇

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

Aside: different ALP bases

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pseudoscalar basis

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

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

Aside: different ALP bases

derivative basis

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

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

Aside: different ALP bases

derivative basis

$\ldots_{\nu}\tilde{B}^{\mu\nu}$

Six free parameters in the flavor-universal case

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

pseudoscalar basis

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Exploiting the ALP-SMEFT interference

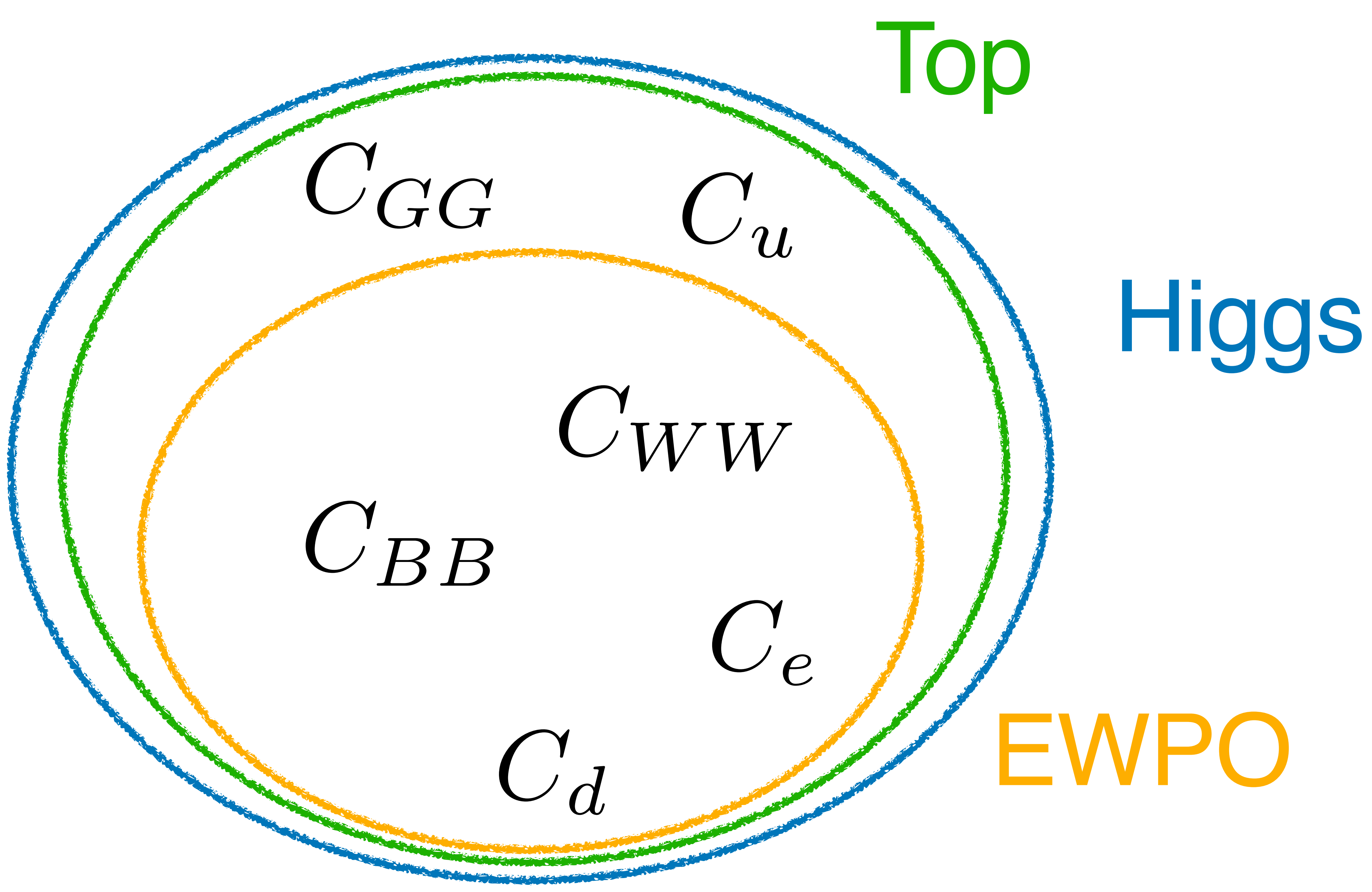
Observables used

- Low energy:
  - Electroweak precision observables (EWPO)
  - Parity violation experiments
  - Lepton scattering

  [Falkowski et al. (1706.03783)]
- **Higgs**
- Top [Ellis et al. (2012.02779)]

Six free parameters

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



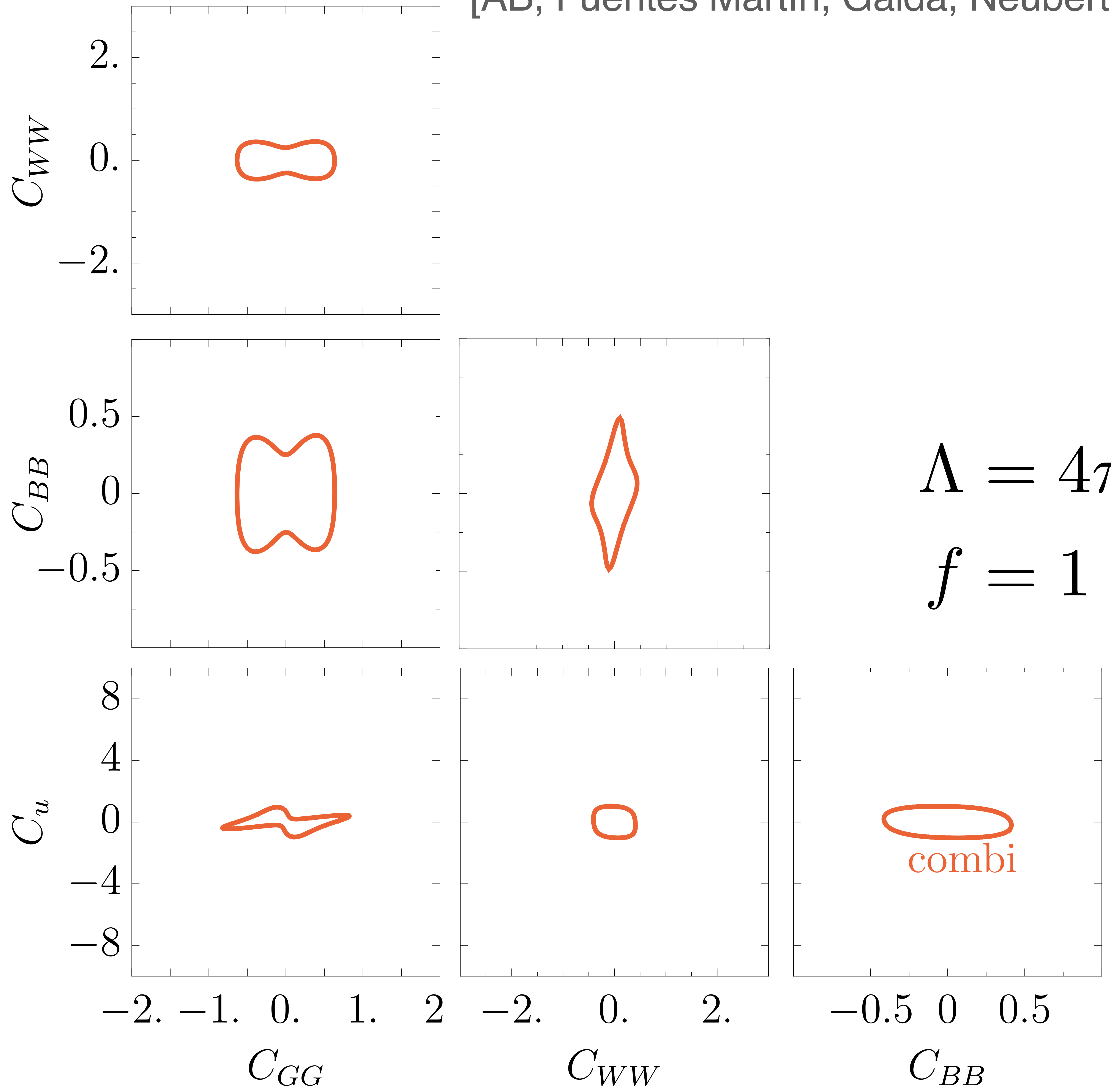
[AB, Fuentes Martín, Galda, Neubert (2307.10372)]

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



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

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

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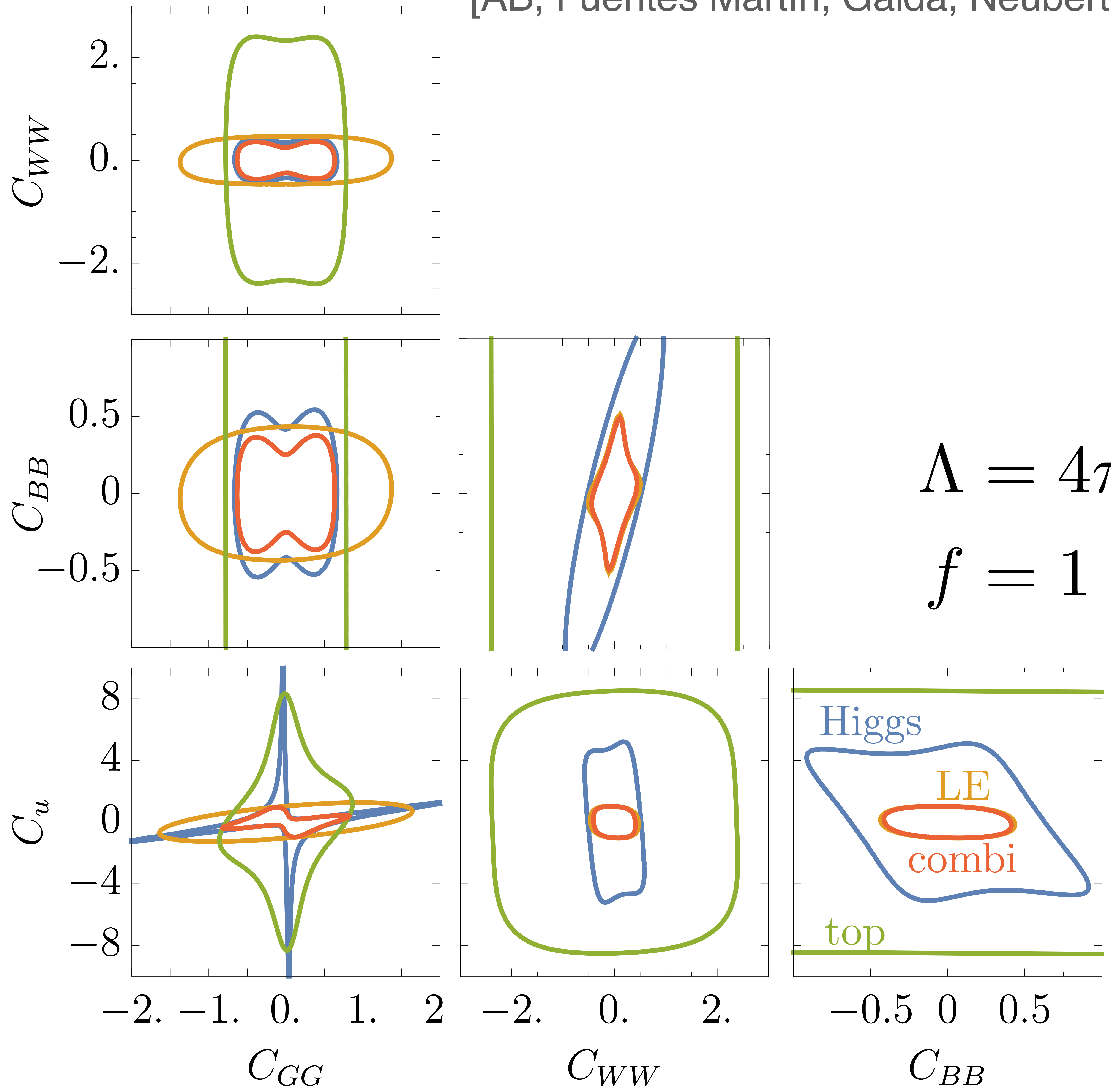

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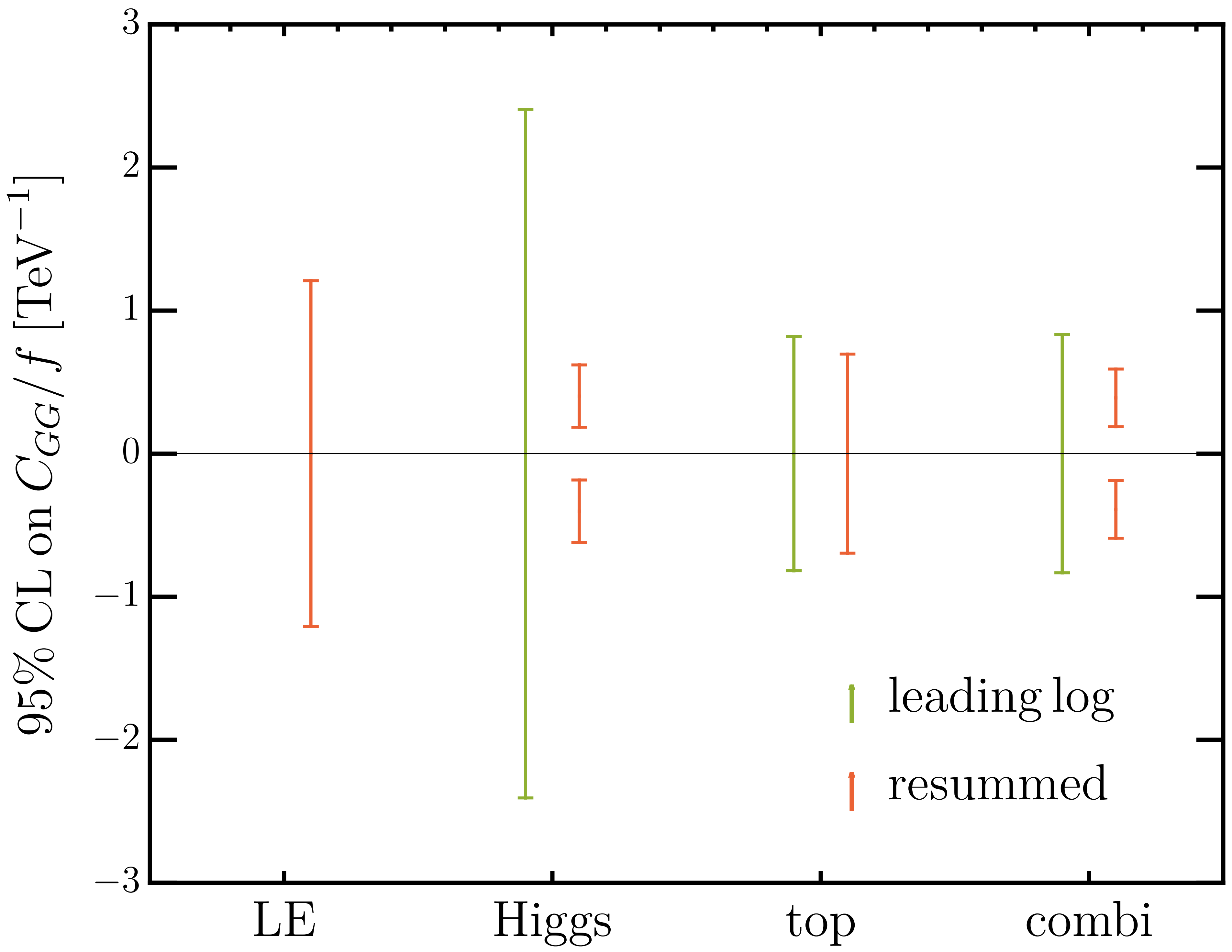
[AB, Fuentes Martín, Galda, Neubert (2307.10372)]

LL approximation - CGG

$$[C_{uG}]_{33}(\mu) \supset -\frac{25\, g_s\, y_t\, \alpha_s}{\pi}\, C_{GG}^2\, \ln^2 \frac{\mu}{\Lambda}$$

$$C_{HG}(\mu) \supset \frac{100\, \alpha_s^2\, \alpha_t}{3}\, C_{GG}^2\, \ln^3 \frac{\mu}{\Lambda}$$

CHG (Higgs-gluon coupling) and CuG (top-gluon coupling) strongly constrained through gluon-fusion Higgs production



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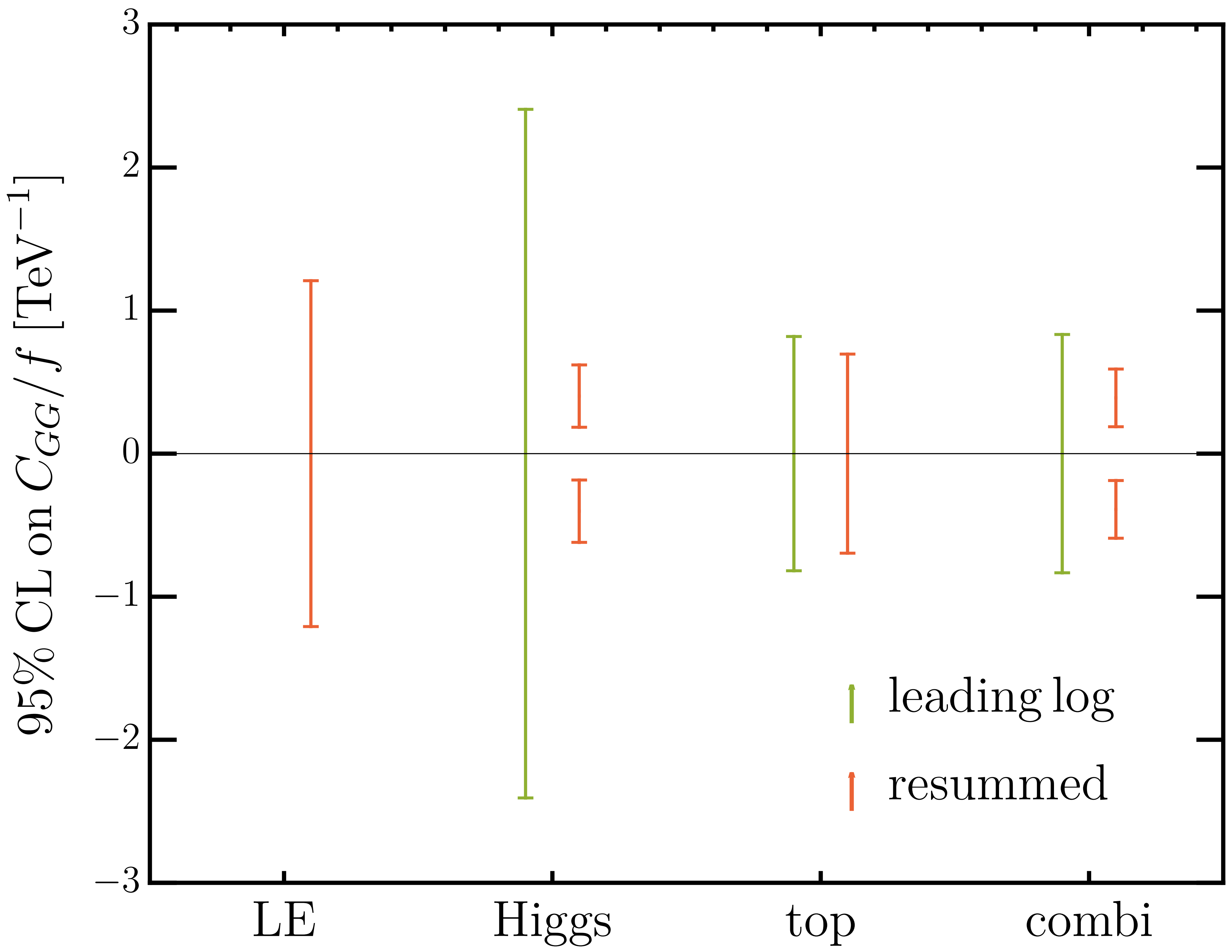
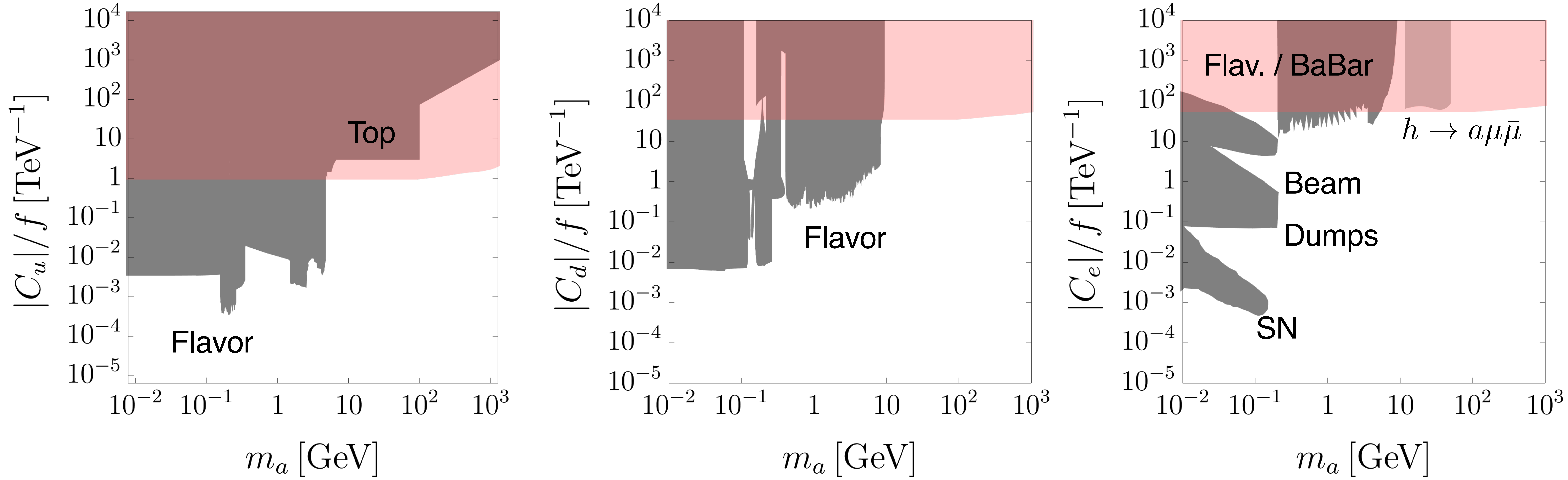
(Small) experimental anomaly in CMS Higgs STXS causes deviation at 95% CL



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

Comparison with direct bounds - fermions



[BaBar (1406.2980)]

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

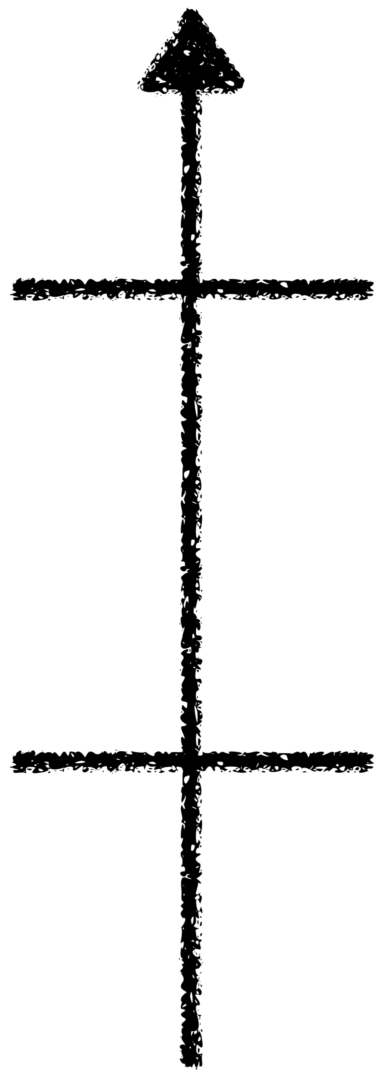
[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

[AB, Chala, Spannowski (2203.14984)]

[Lucente, Carenza (2107.12393)]

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

Caveats and future directions



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

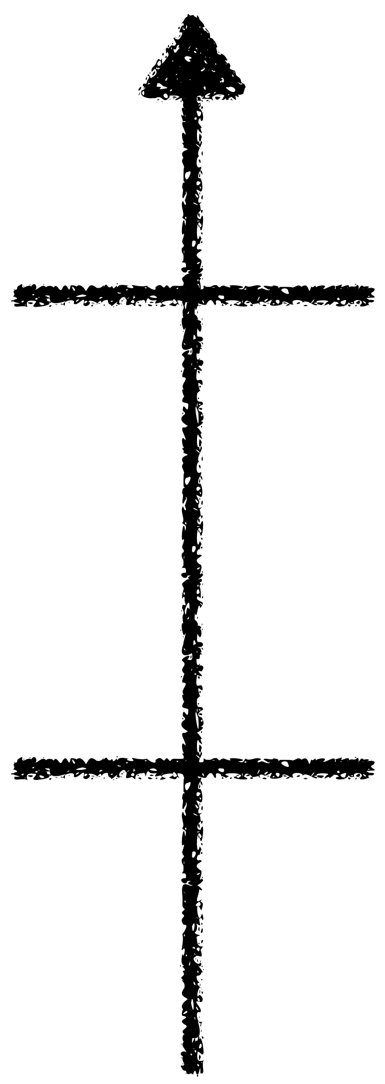
$$C^{\mathrm{ALP}}(\mu) \neq 0 \quad C^{\mathrm{SMEFT}}(\mu) \neq 0$$

What if C^{SMEFT} at the high scale are not zero?

Backup slides on UV model interpretations

Caveats and future directions

300 MeV ALP



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

$C^{\mathrm{SMEFT}}(\Lambda) = 0$?

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

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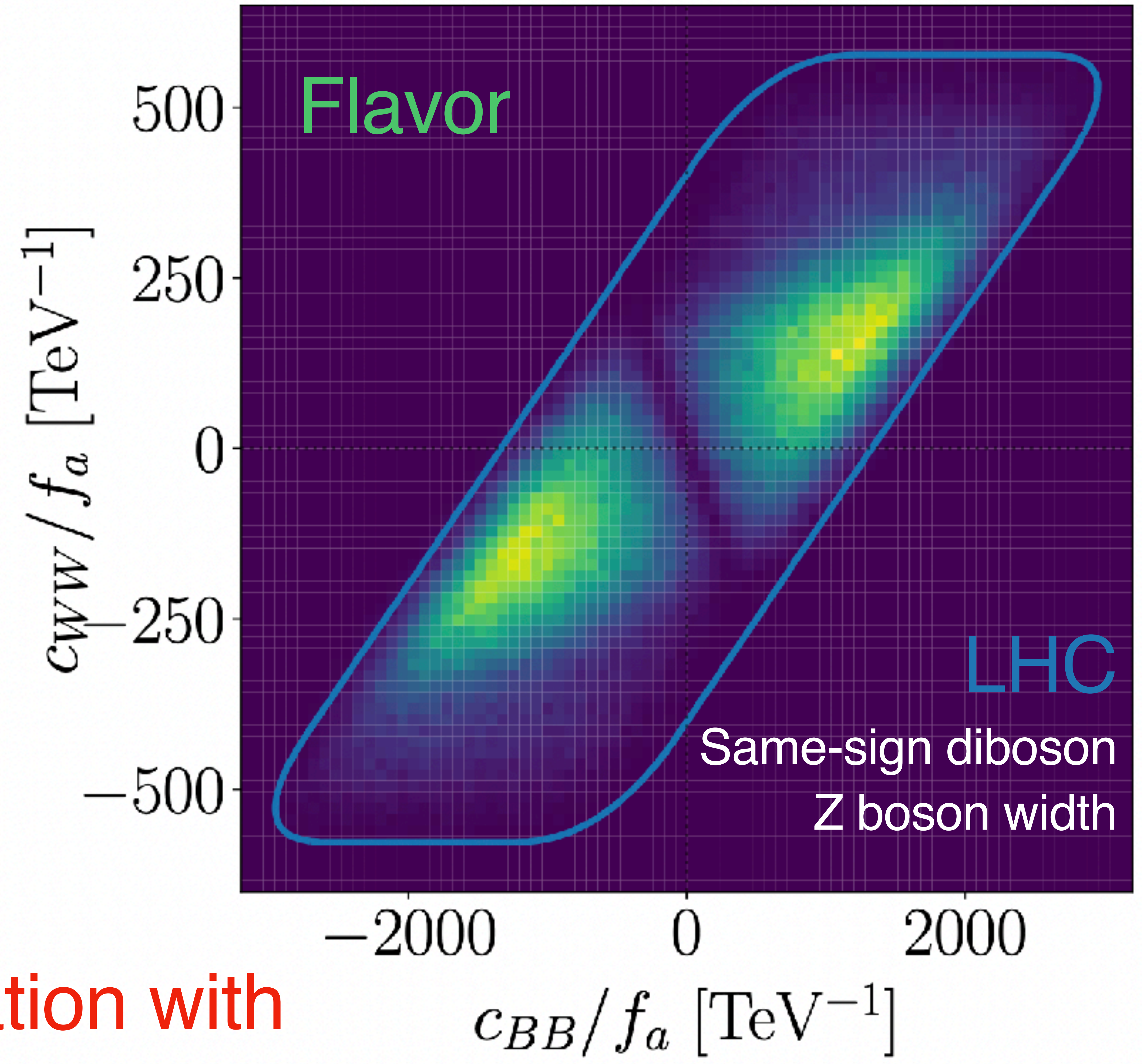
What if C^{SMEFT} at the high scale are not zero?

Backup slides on UV model interpretations

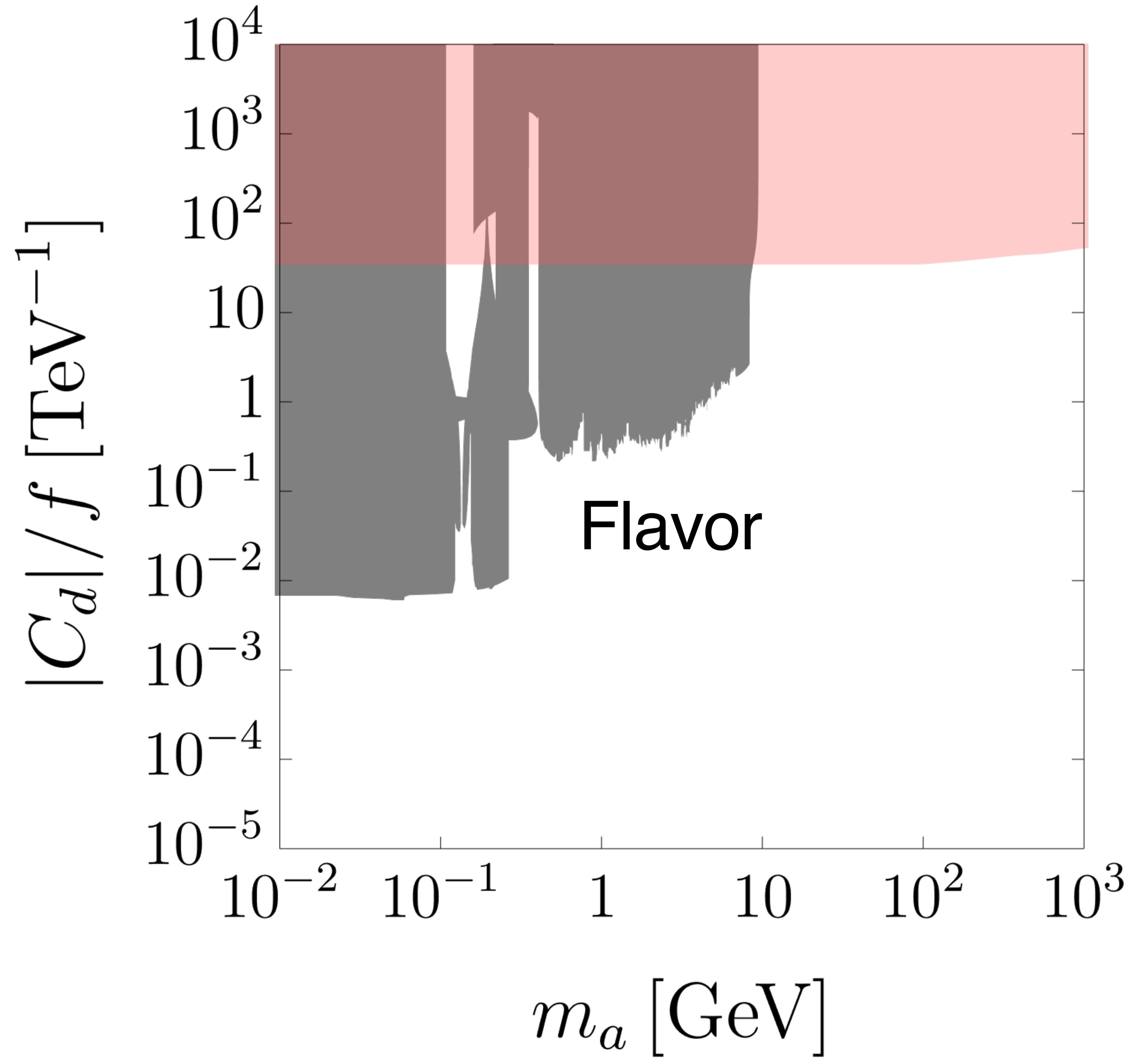
[Bruggisser, Grabitz, Westhoff (2308.11703)]



Combination with direct global fit efforts

Conclusions

- Higgs and ALPs closely related
- **Higgs decays** to ALPs
- ALP contribution to **di-Higgs production**
- **Indirect ALP limits from Higgs physics** and other EFT analyses
- Future: global analysis of direct and indirect ALP effects



Conclusions

- Higgs and ALPs closely related
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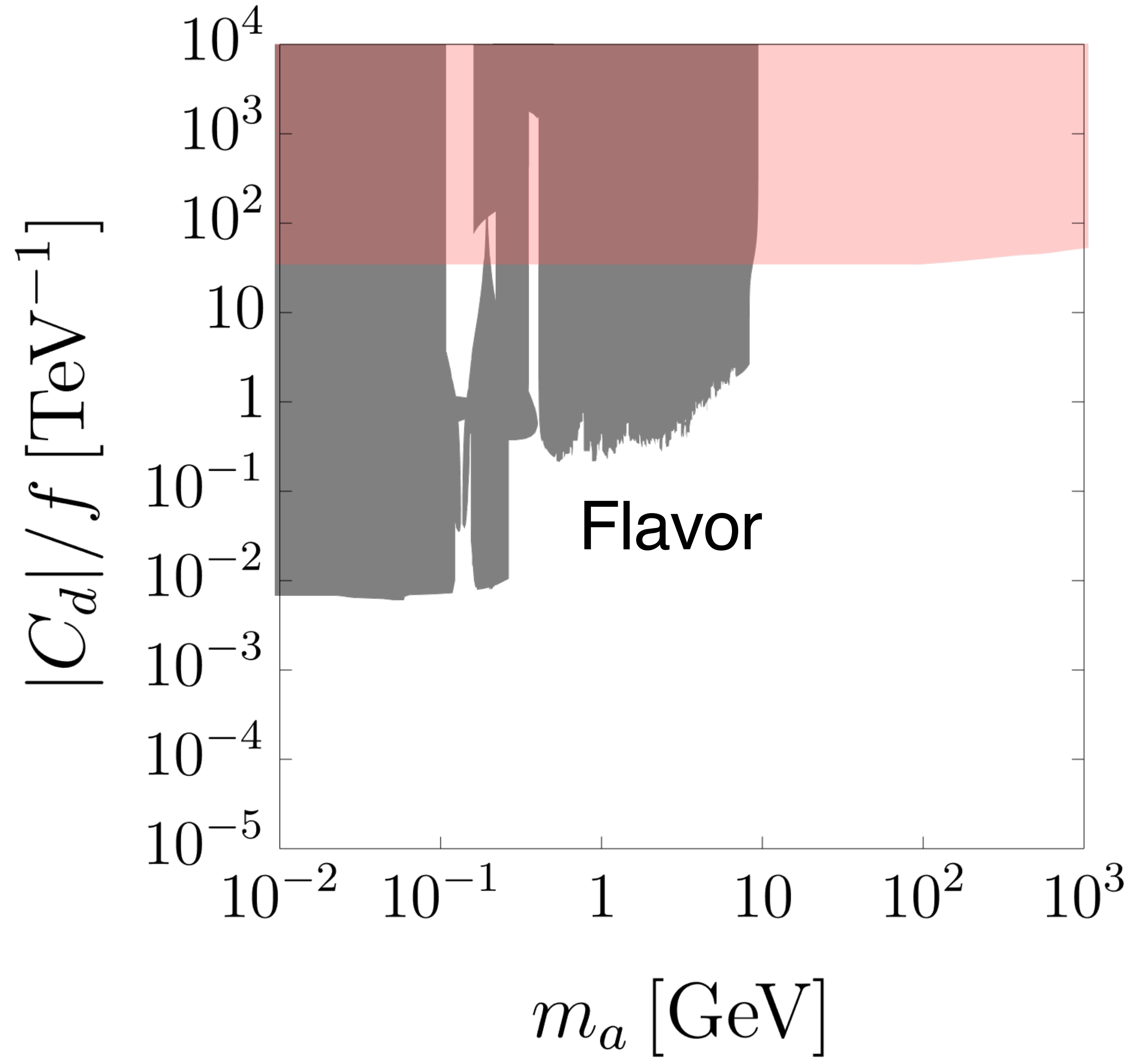
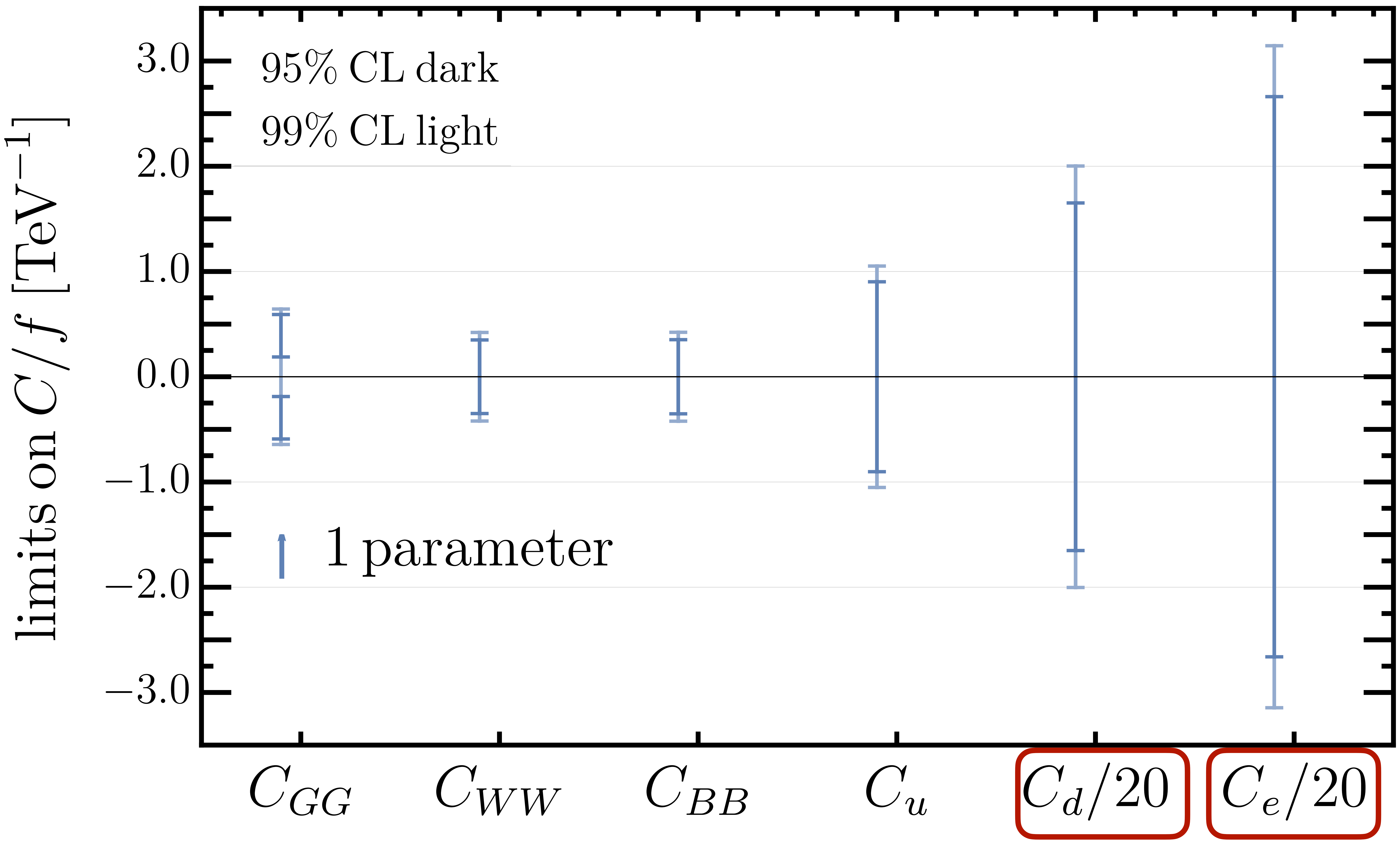


Thank you for your attention!

Backup

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

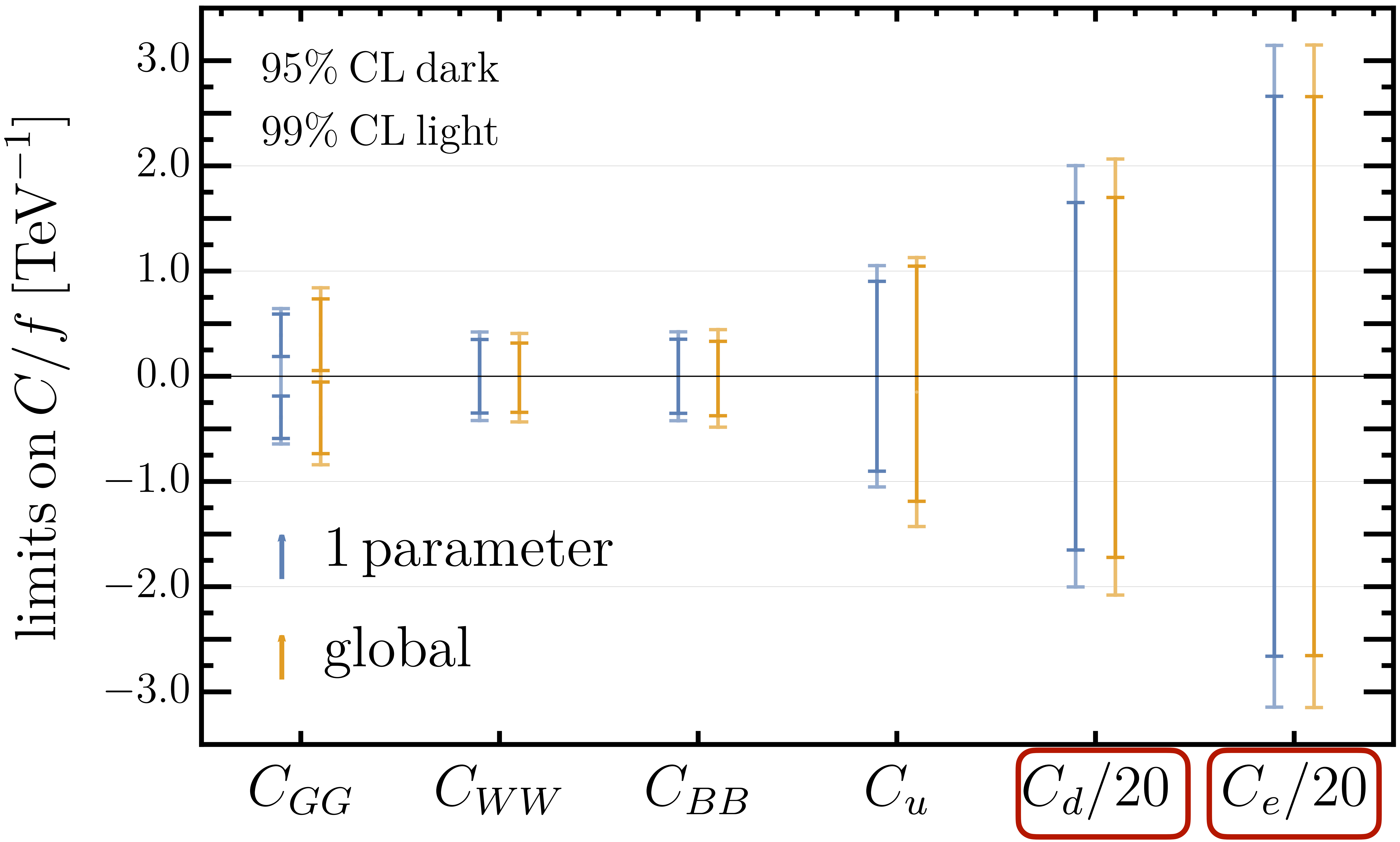
A global analysis



$$\Lambda = 4\pi f$$

$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

A global analysis



$\Lambda = 4\pi f$

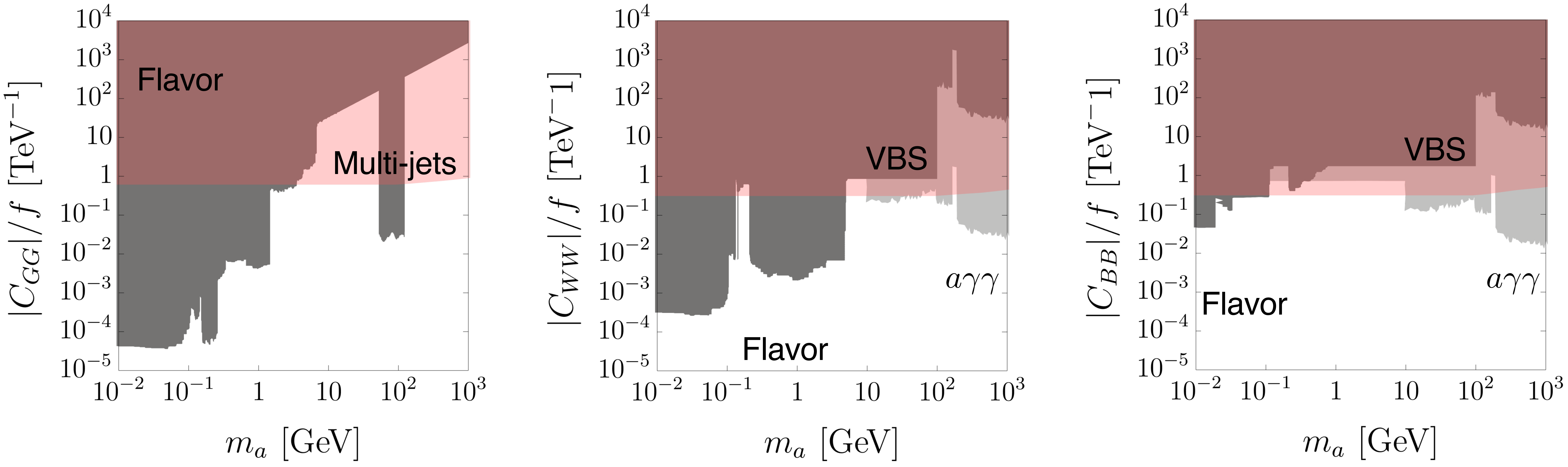
$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

Interplay between couplings is relatively small

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

Comparison with direct bounds

Light gray bounds with additional assumptions



[Mariotti, Redigolo, Sala, Tobiok (1710.01743)]

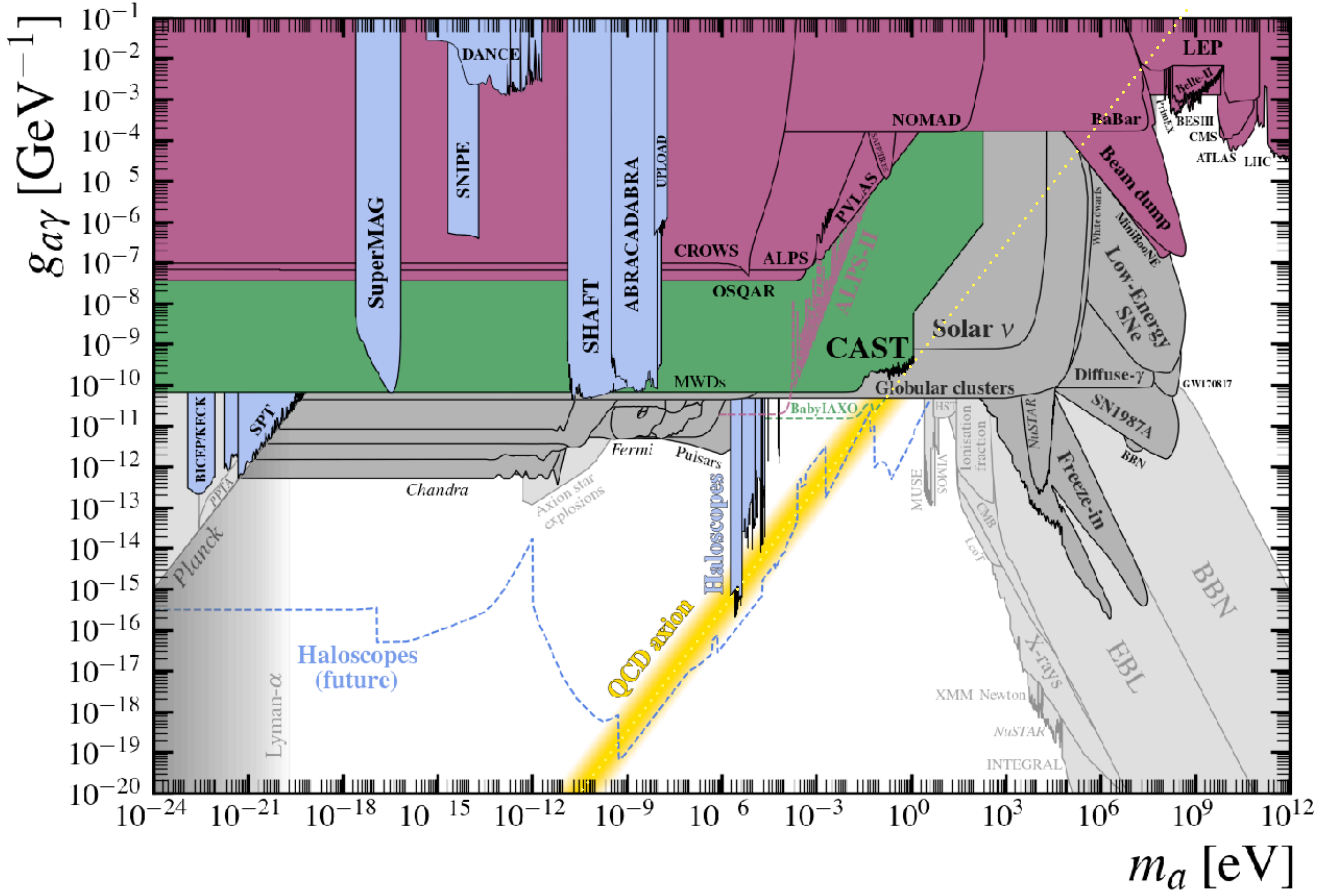
[Bonilla, Brivio, Machado-Rodríguez, de Trocóniz (2202.03450)]

[Bauer, Neubert, Thamm (1708.00443)]

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

ALP-SMEFT interference tests unconstrained parameter space

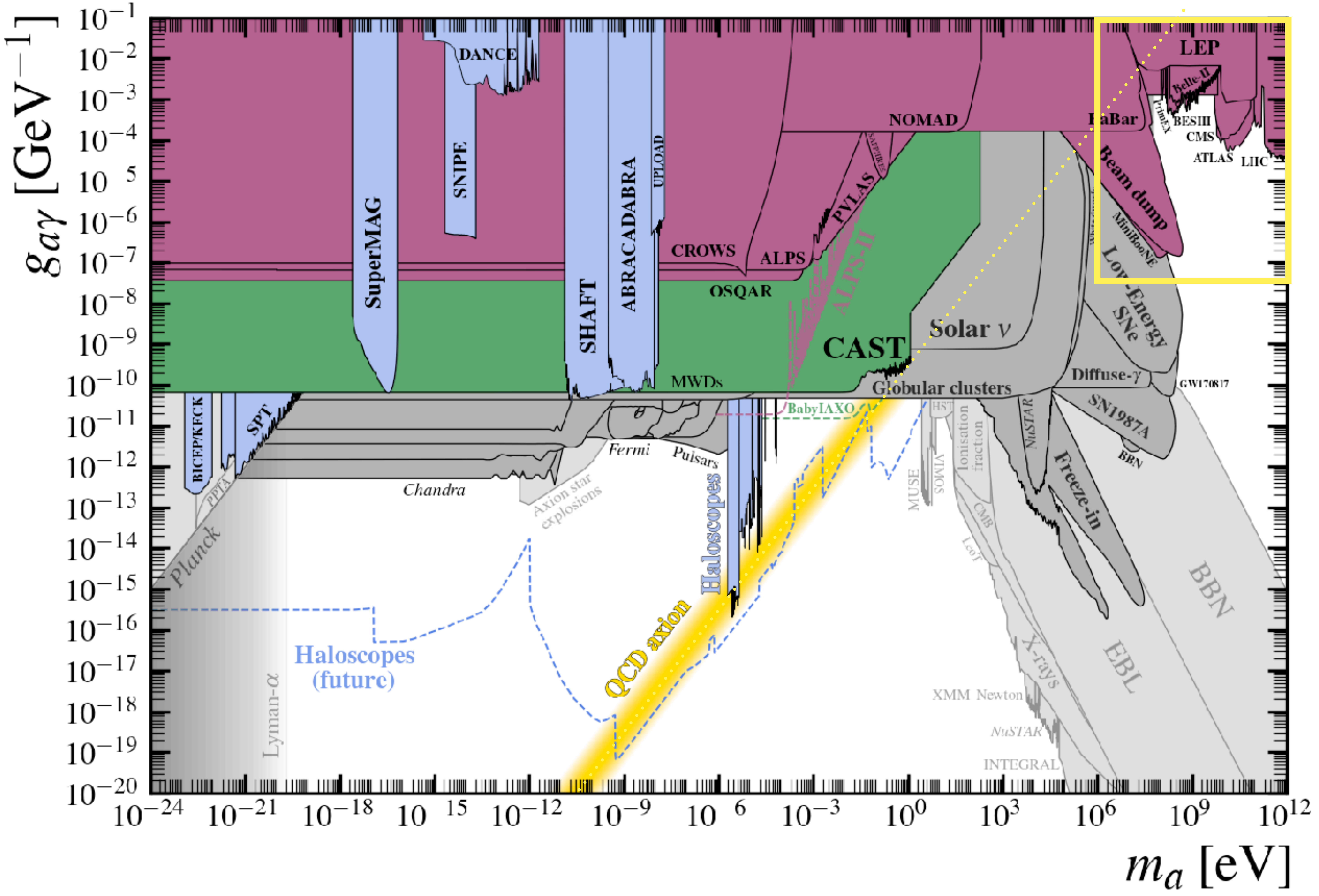
ALP phenomenology



Interplay of experiments/ observations crucial

[O'Hare (axion limits)]

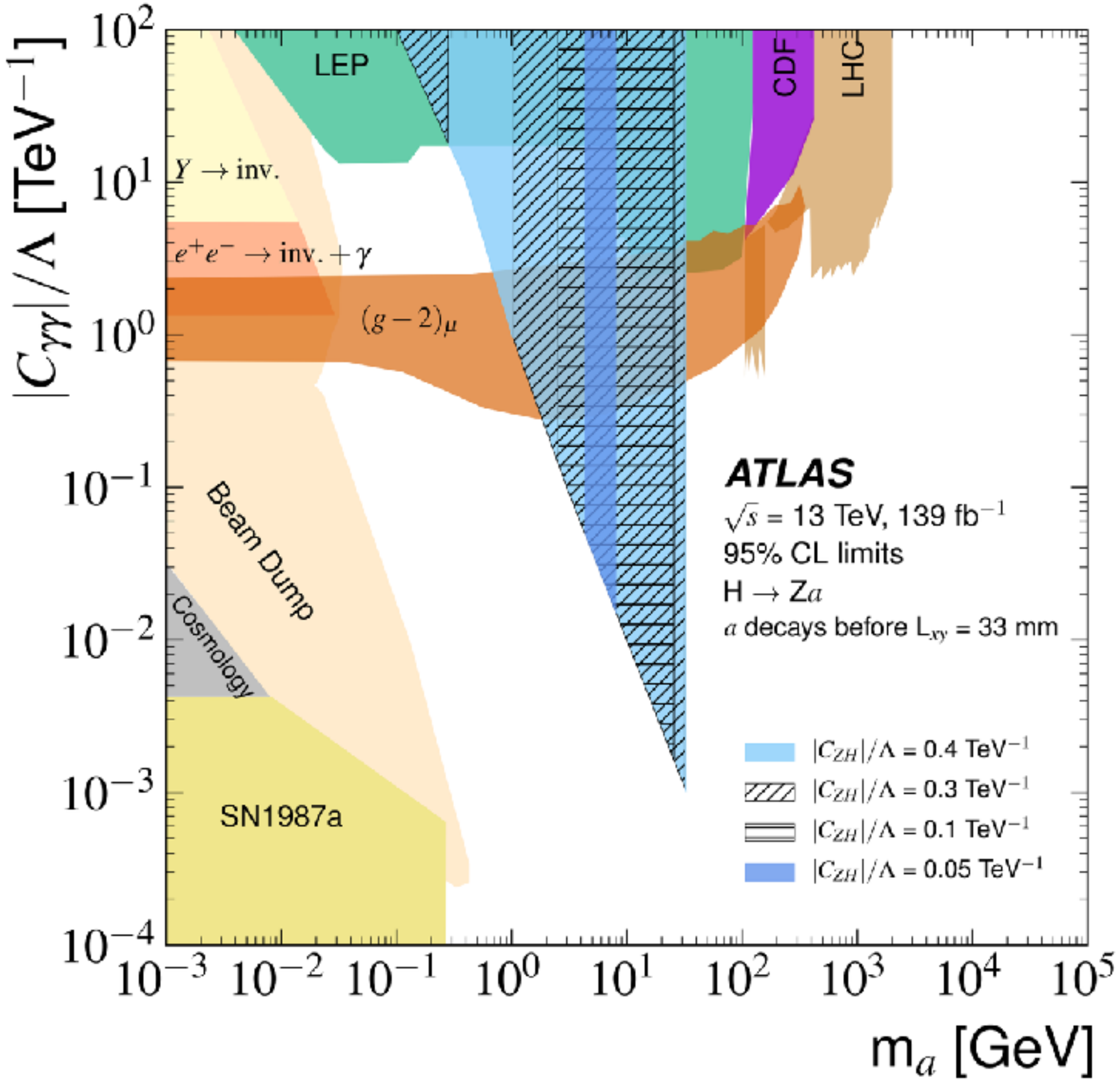
ALP phenomenology



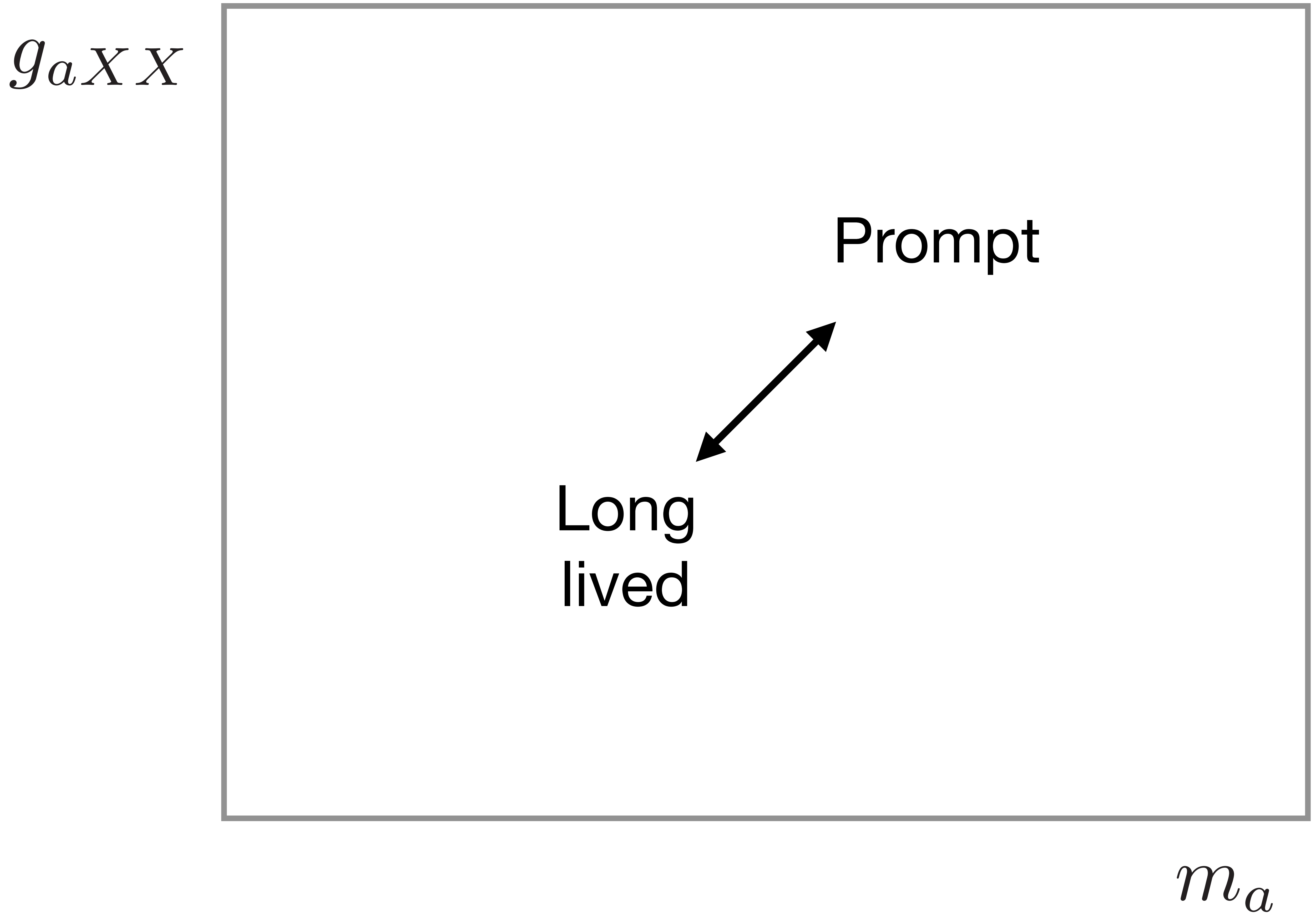
Interplay of experiments/ observations crucial

[O'Hare (axion limits)]

ALPs at colliders



[ATLAS (2312.01942)]



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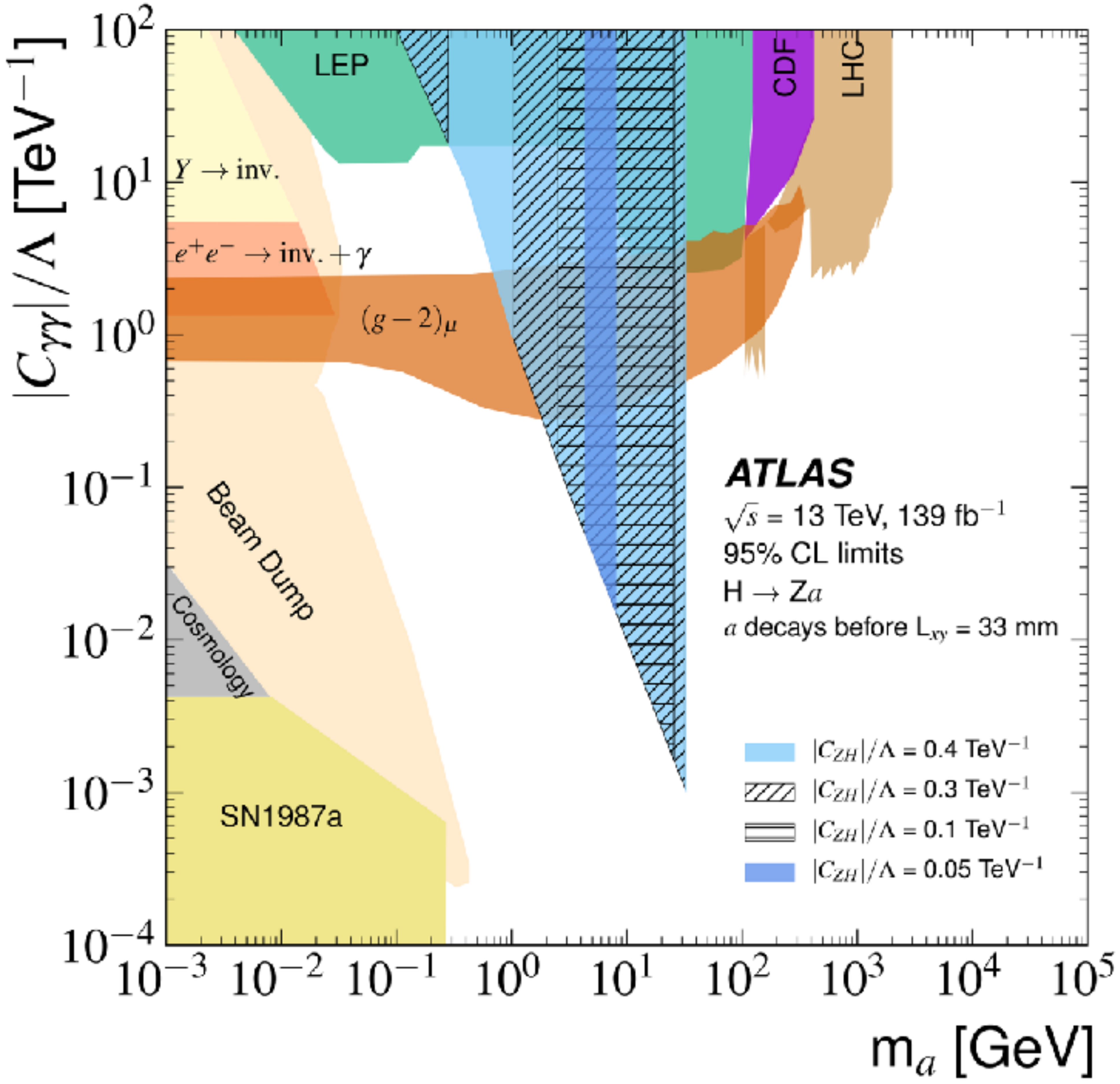

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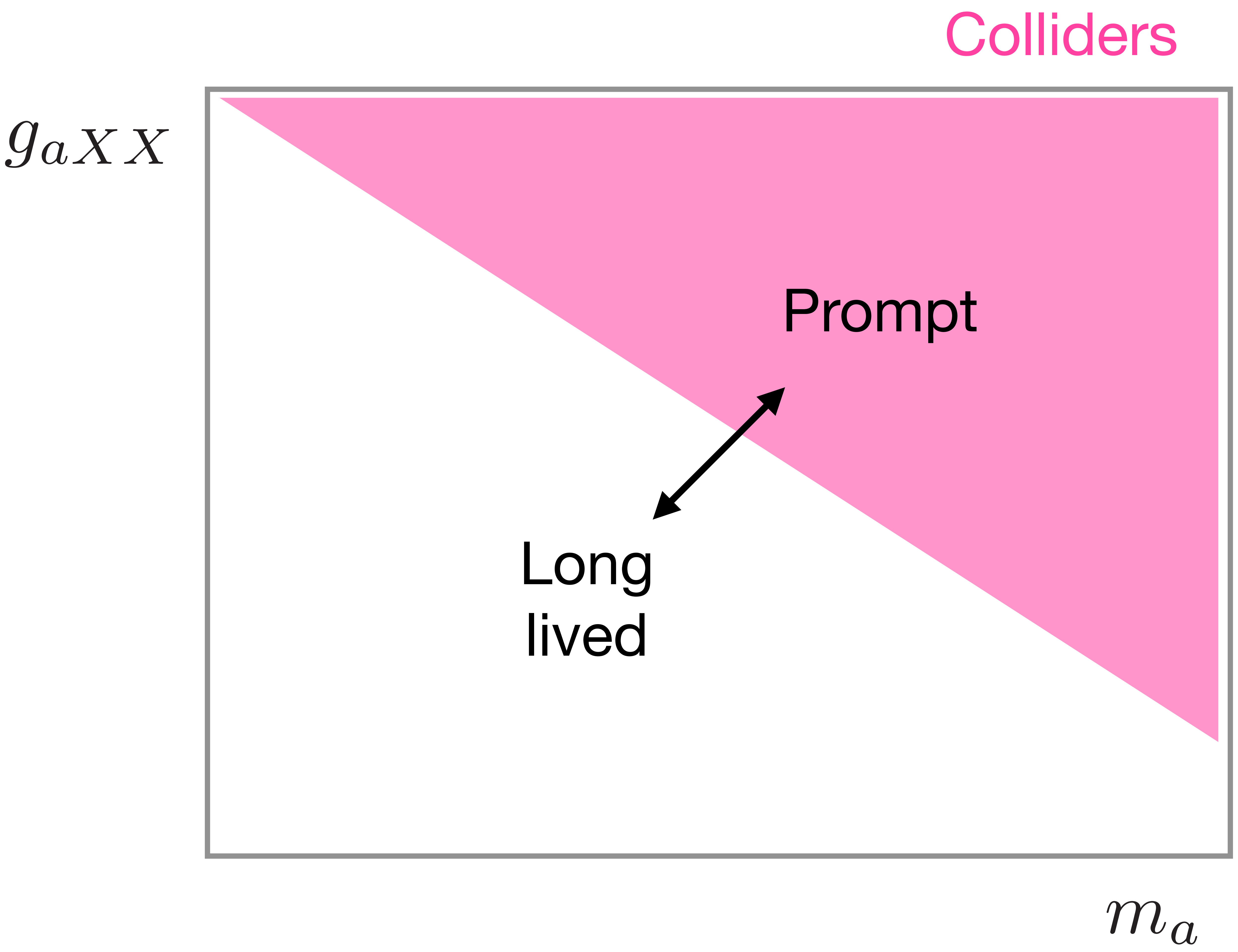

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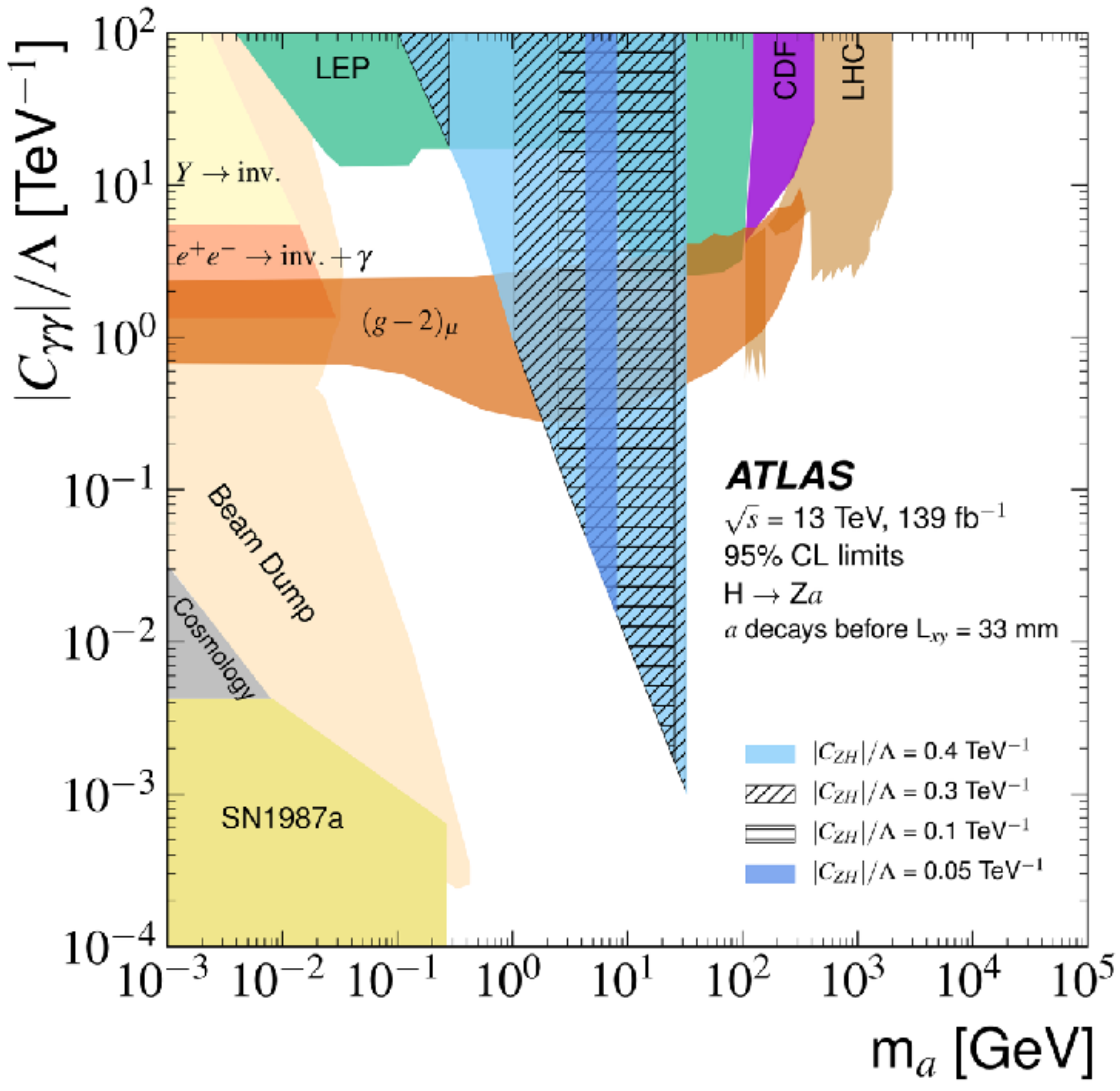

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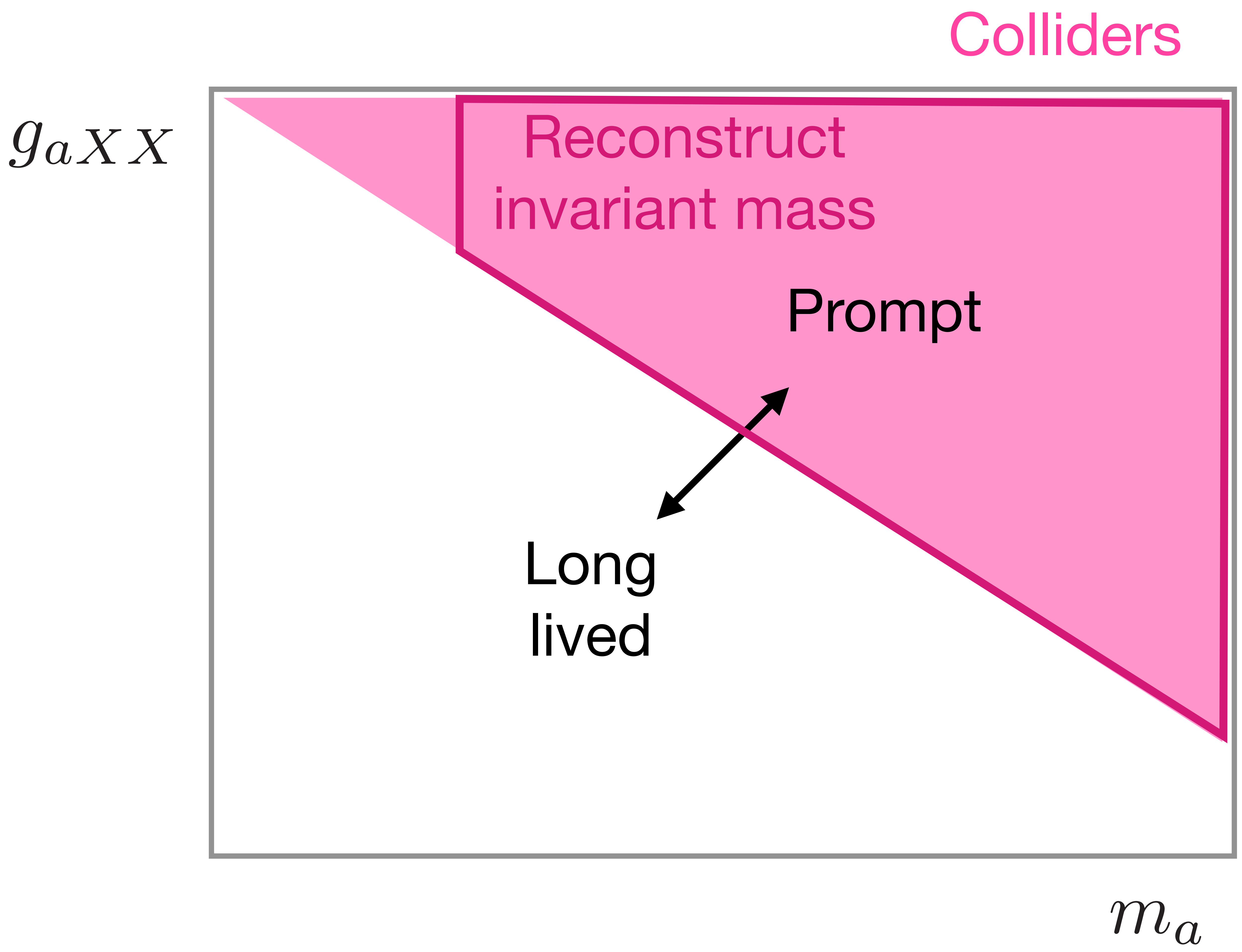
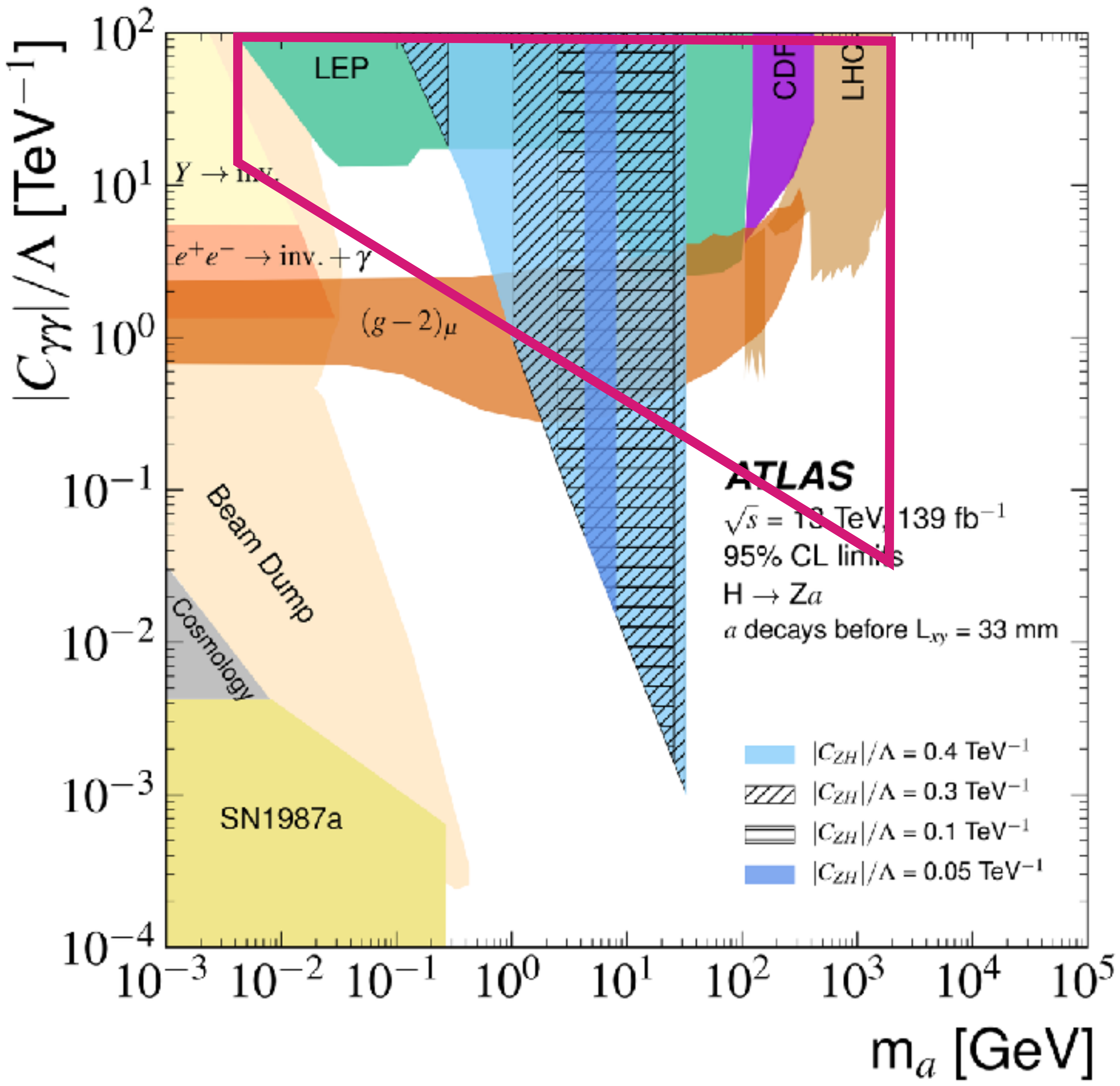
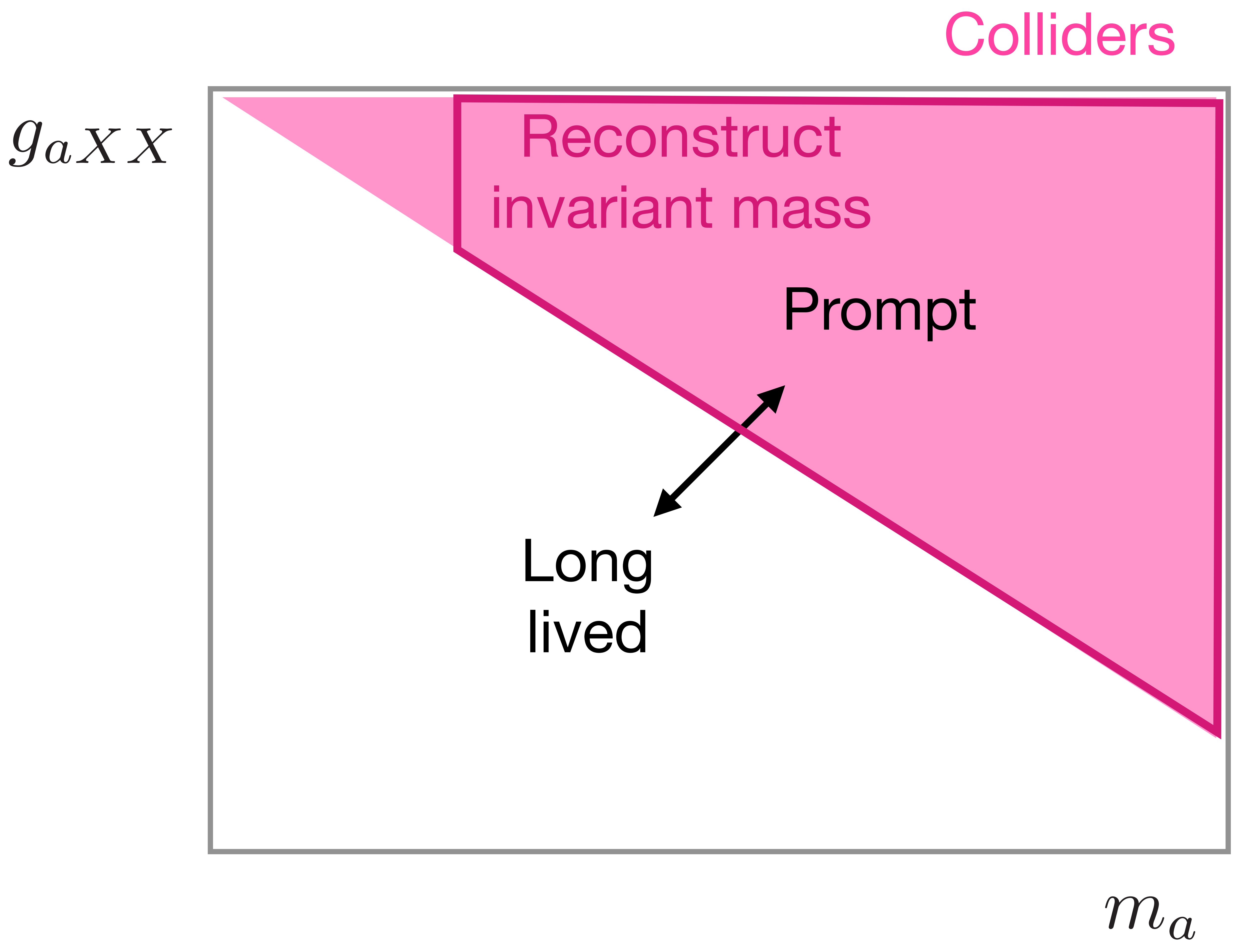


ALPs at colliders





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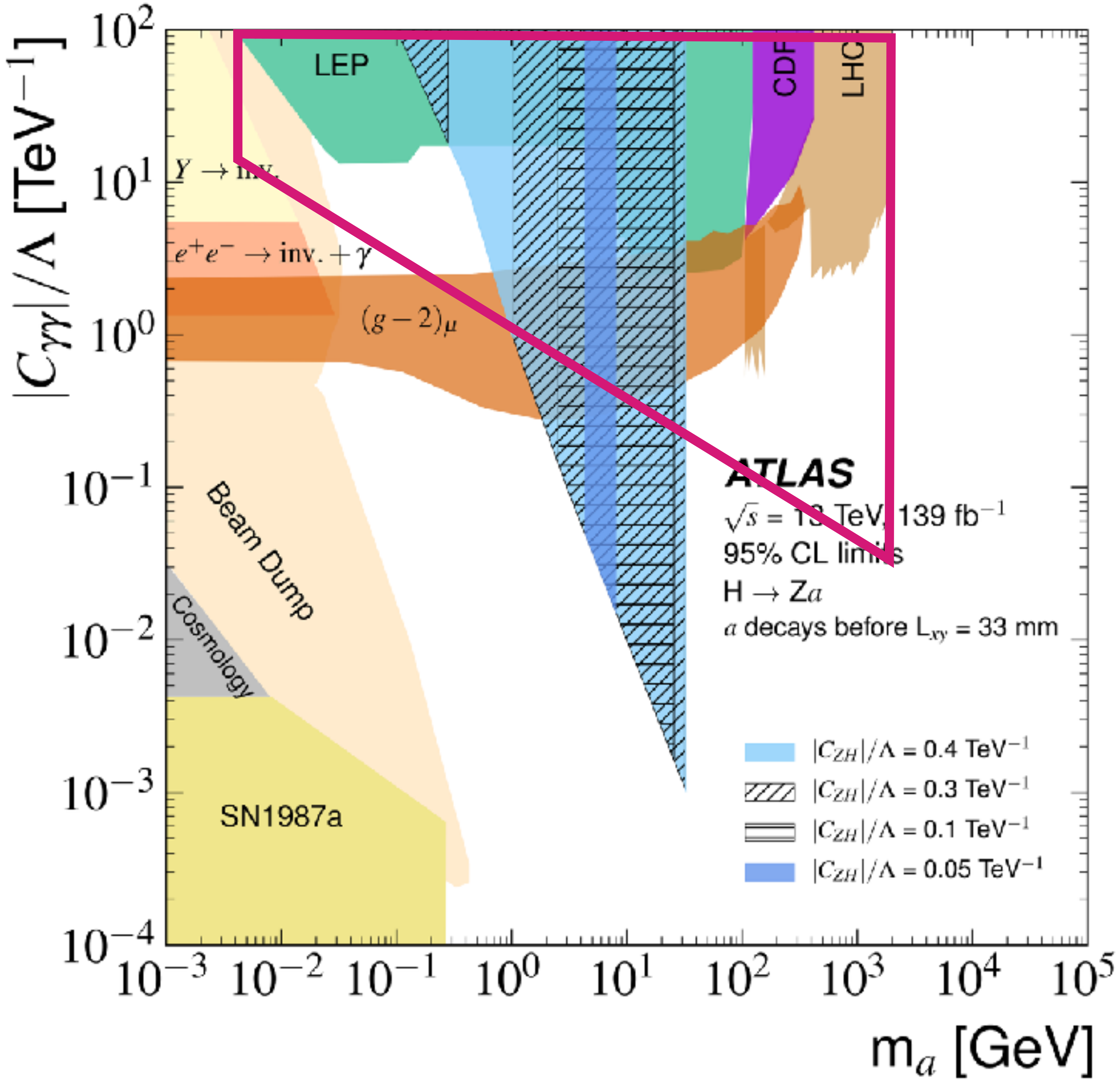
ALPs at colliders



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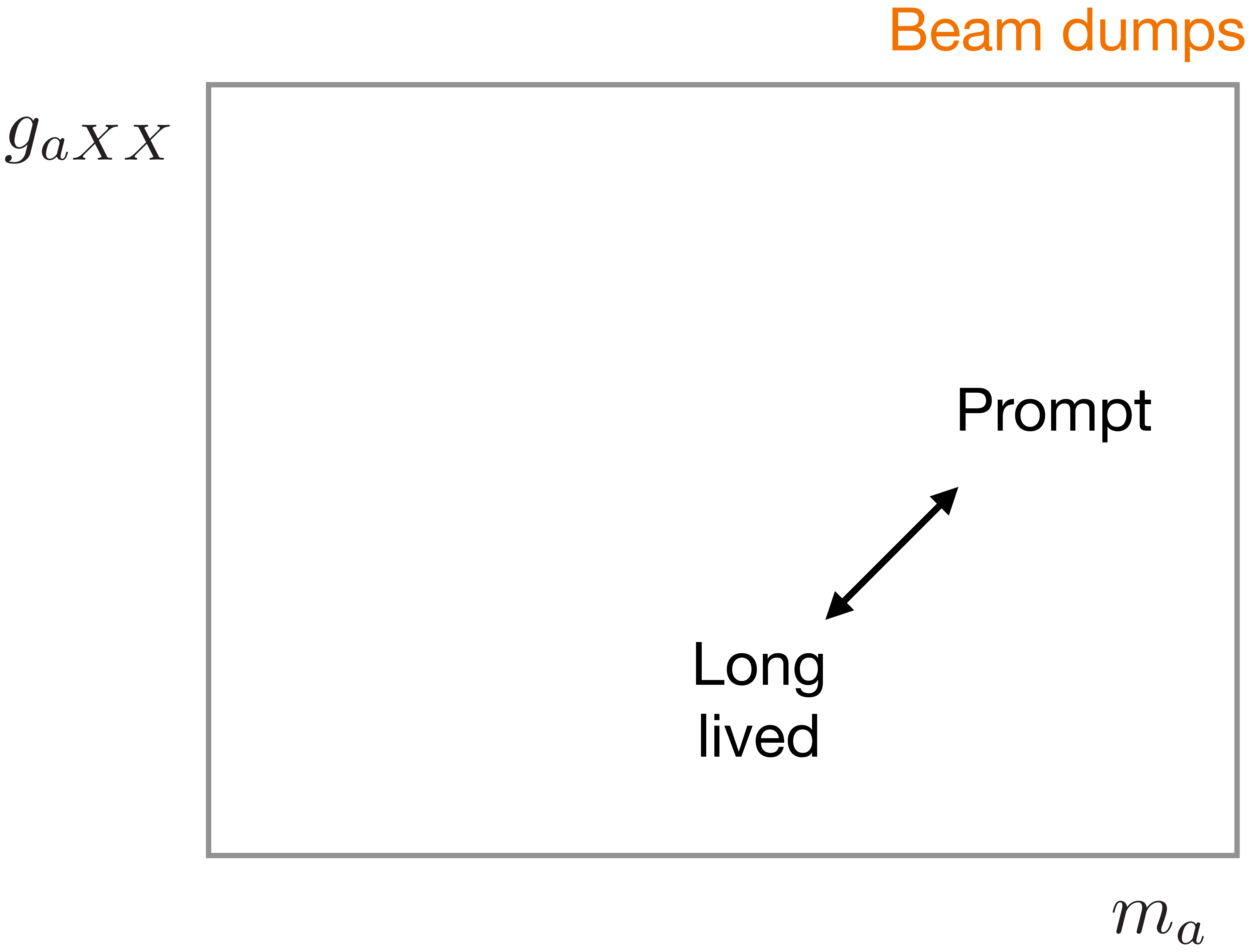
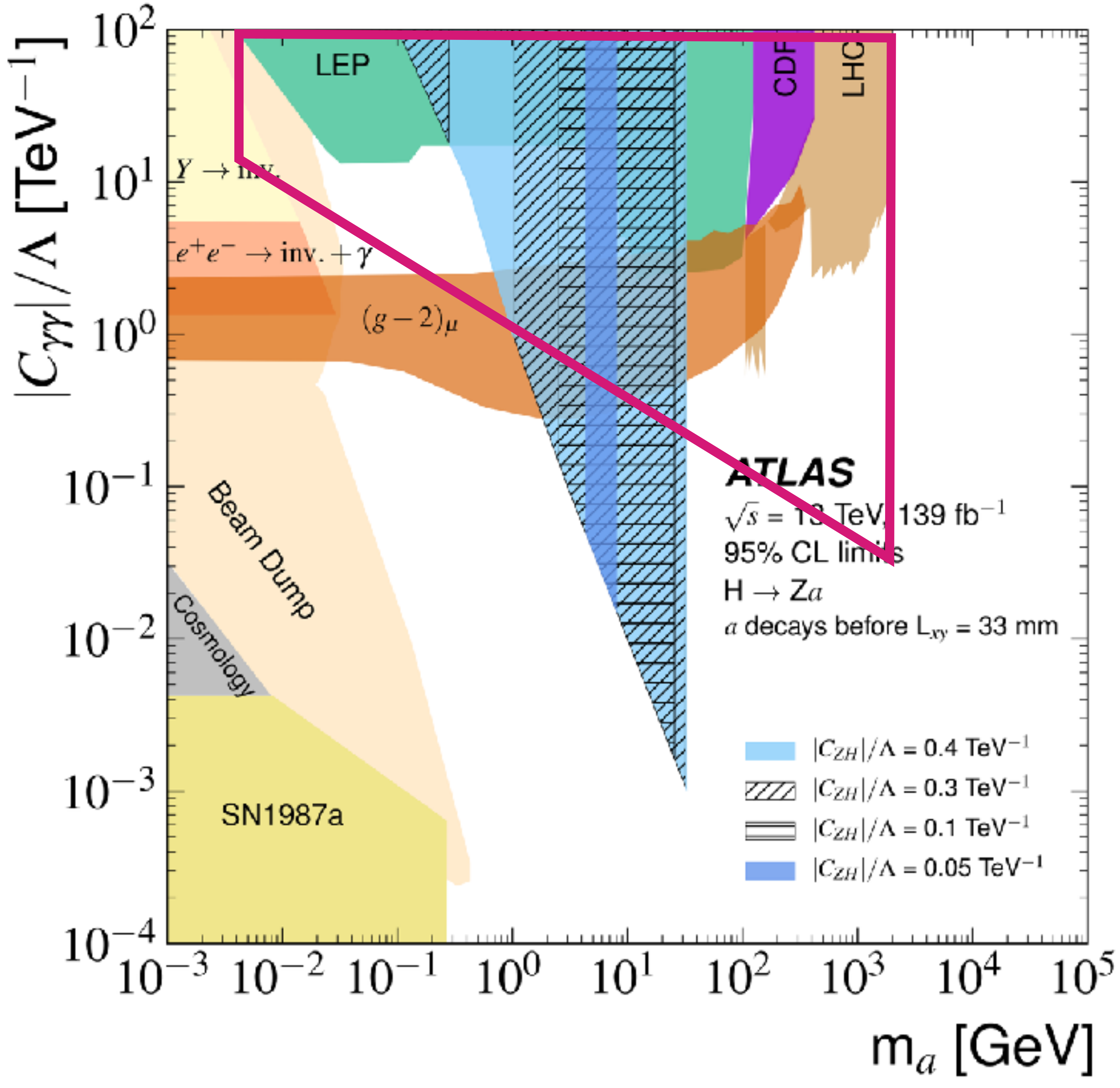


ALPs at colliders



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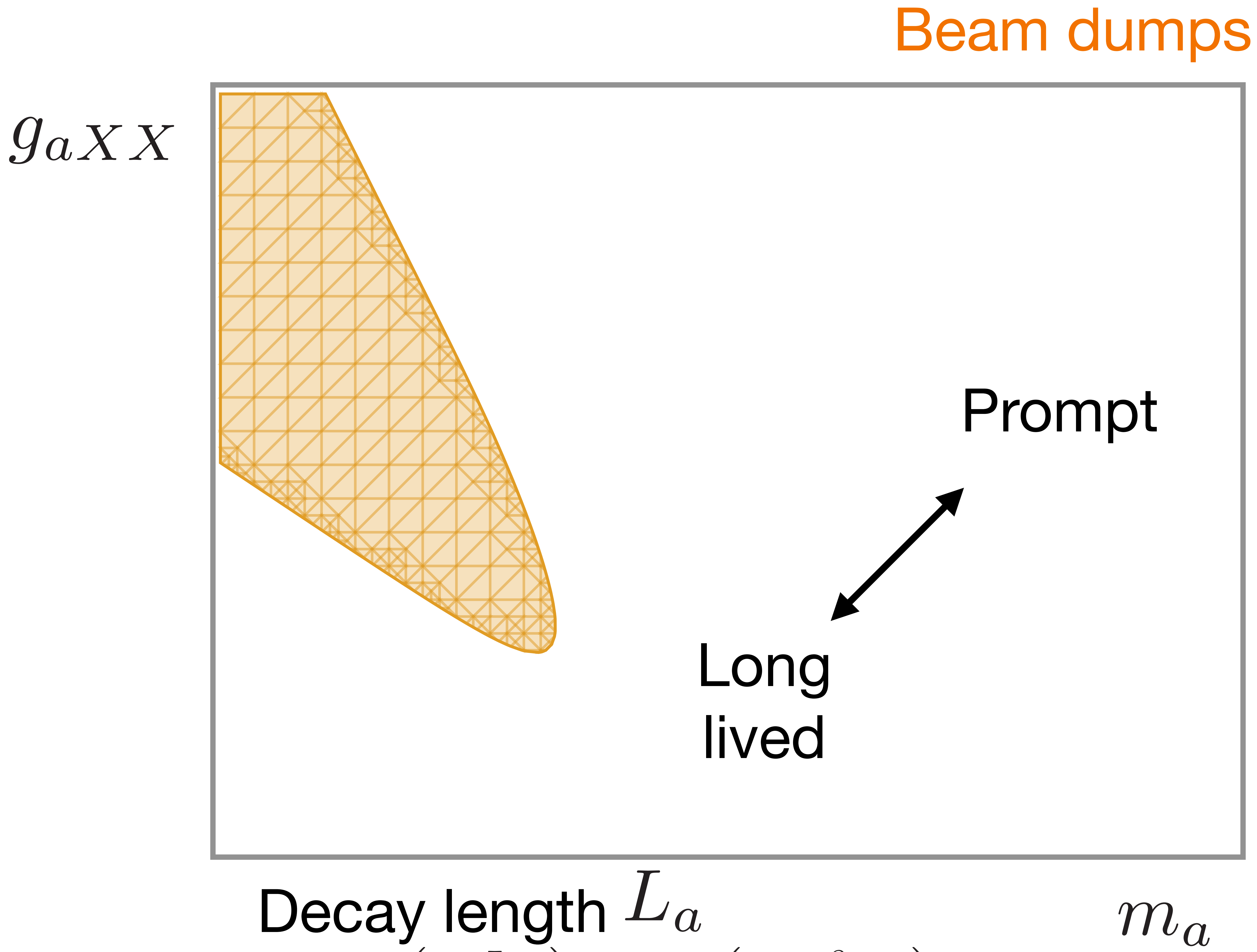
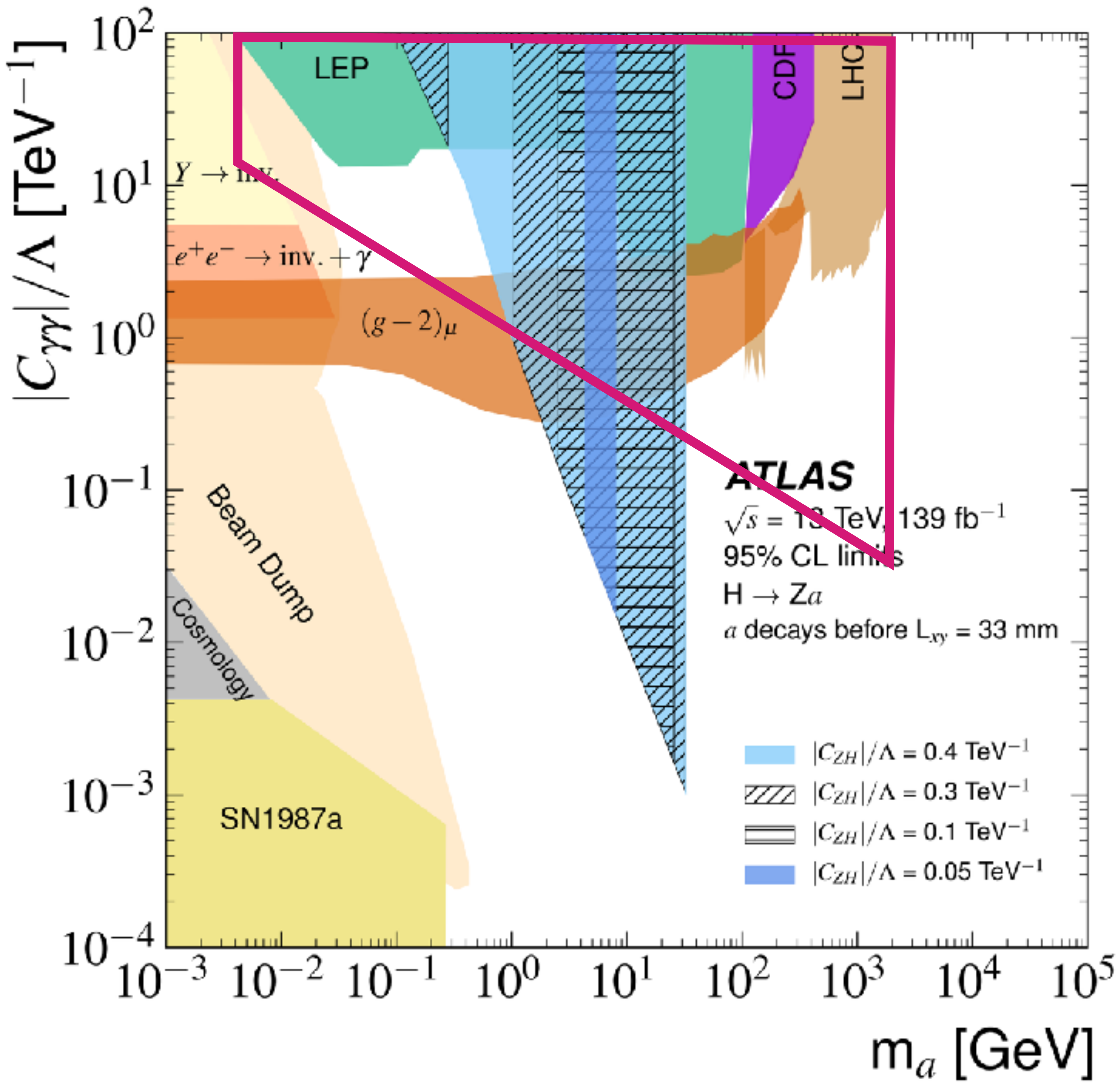


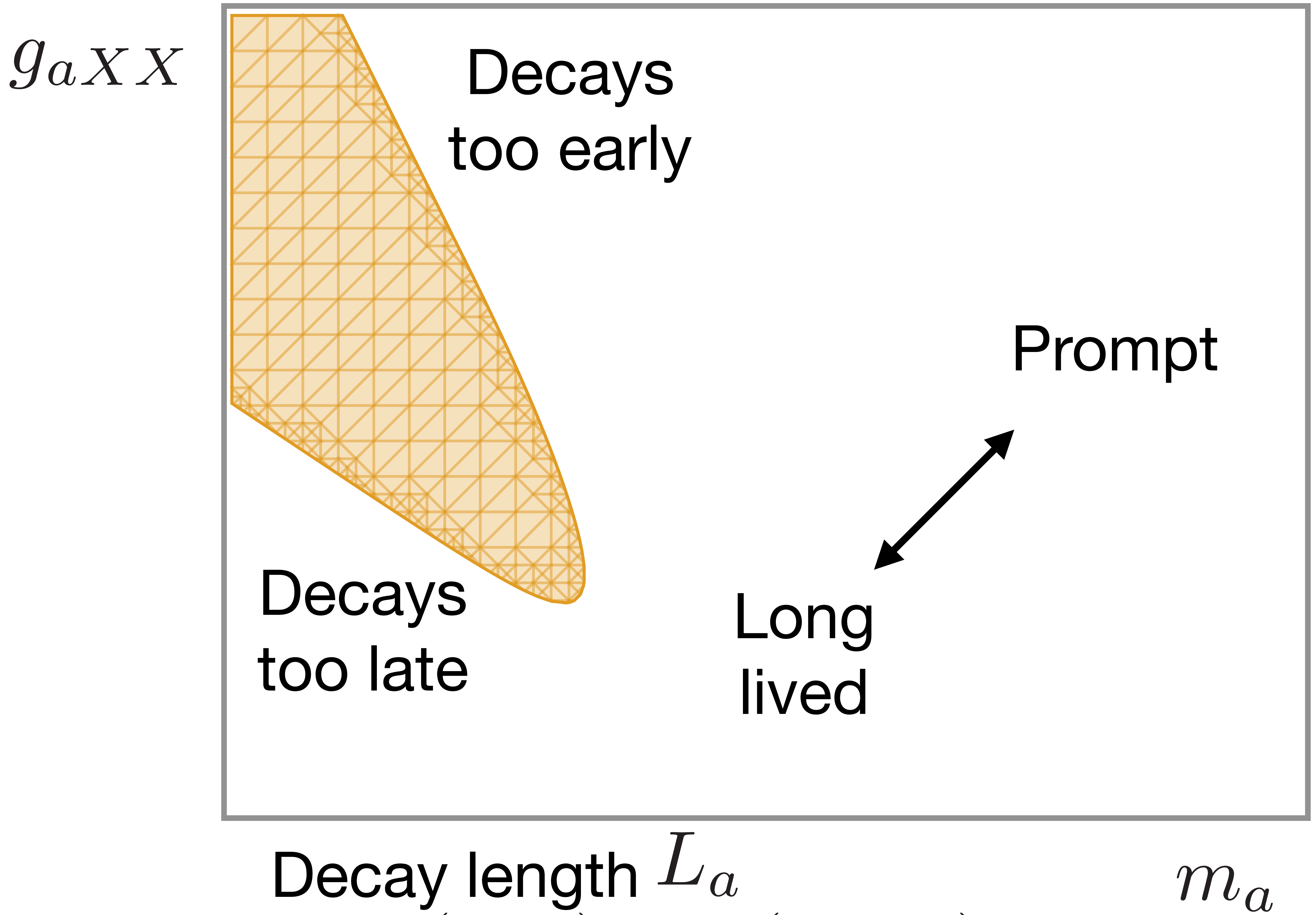
$$\exp\left(-\frac{L_a}{L_{\text{det}}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\text{det}}}\right)$$

ALPs at colliders



[ATLAS (2312.01942)]

Beam dumps



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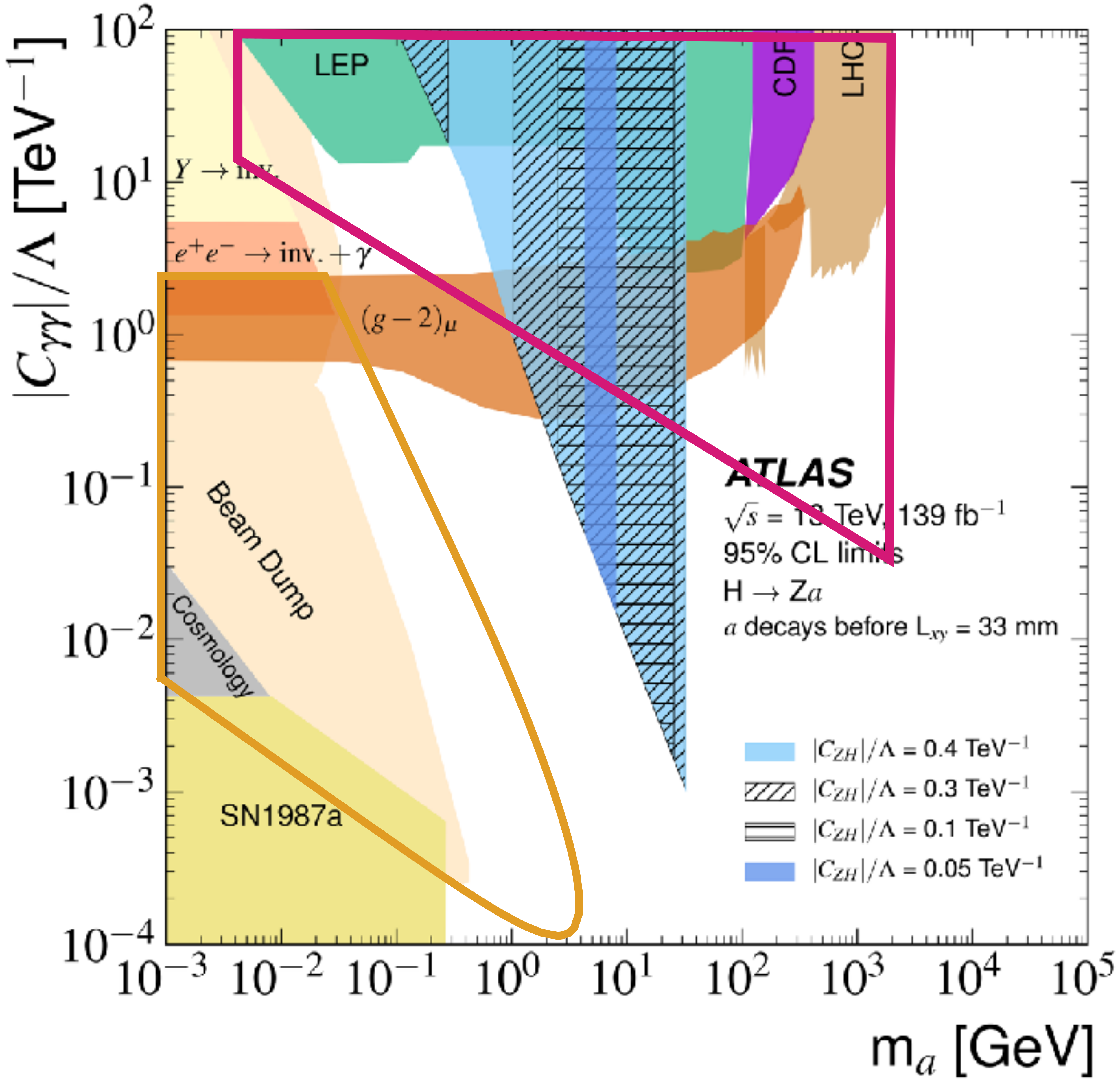
ALPs at colliders



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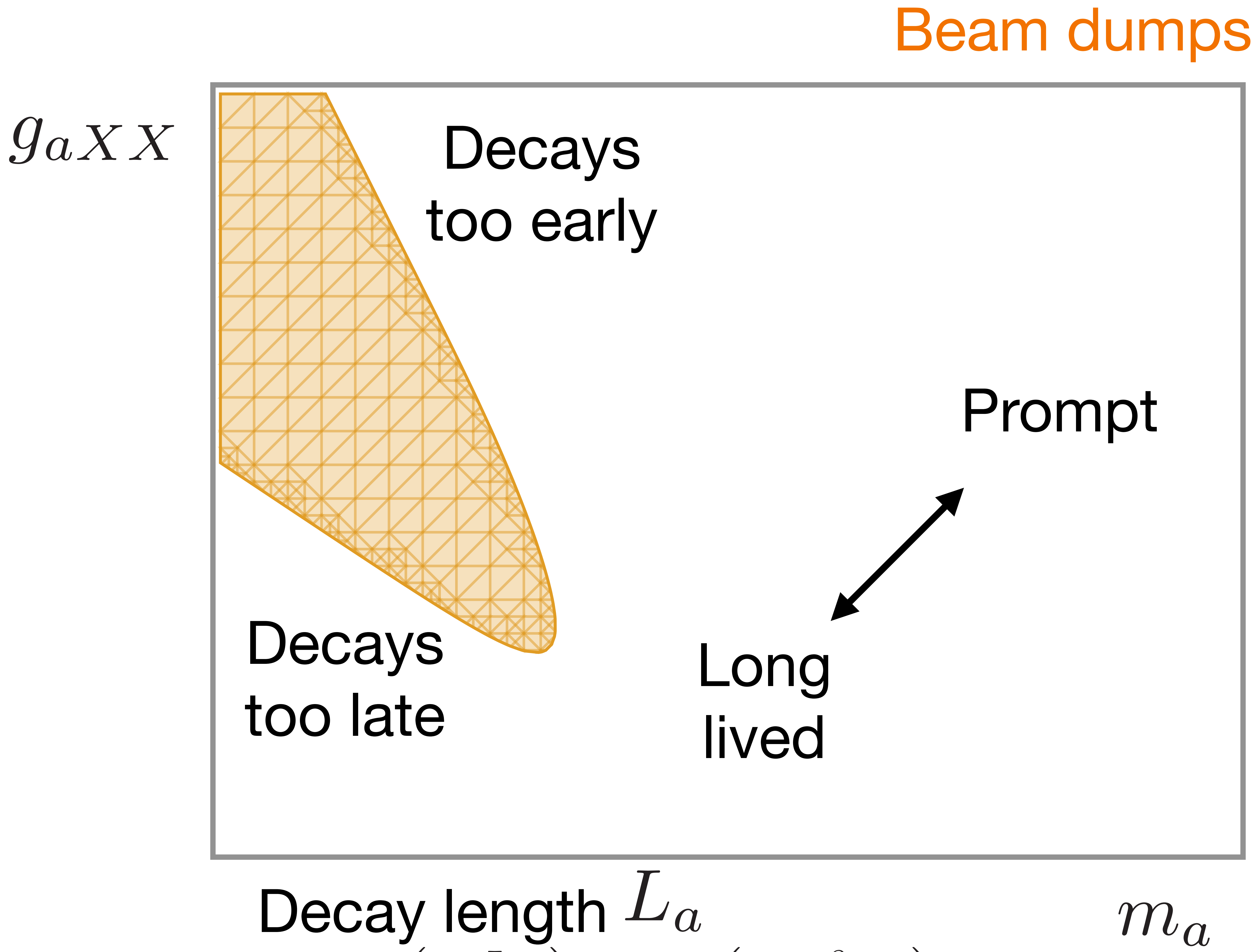


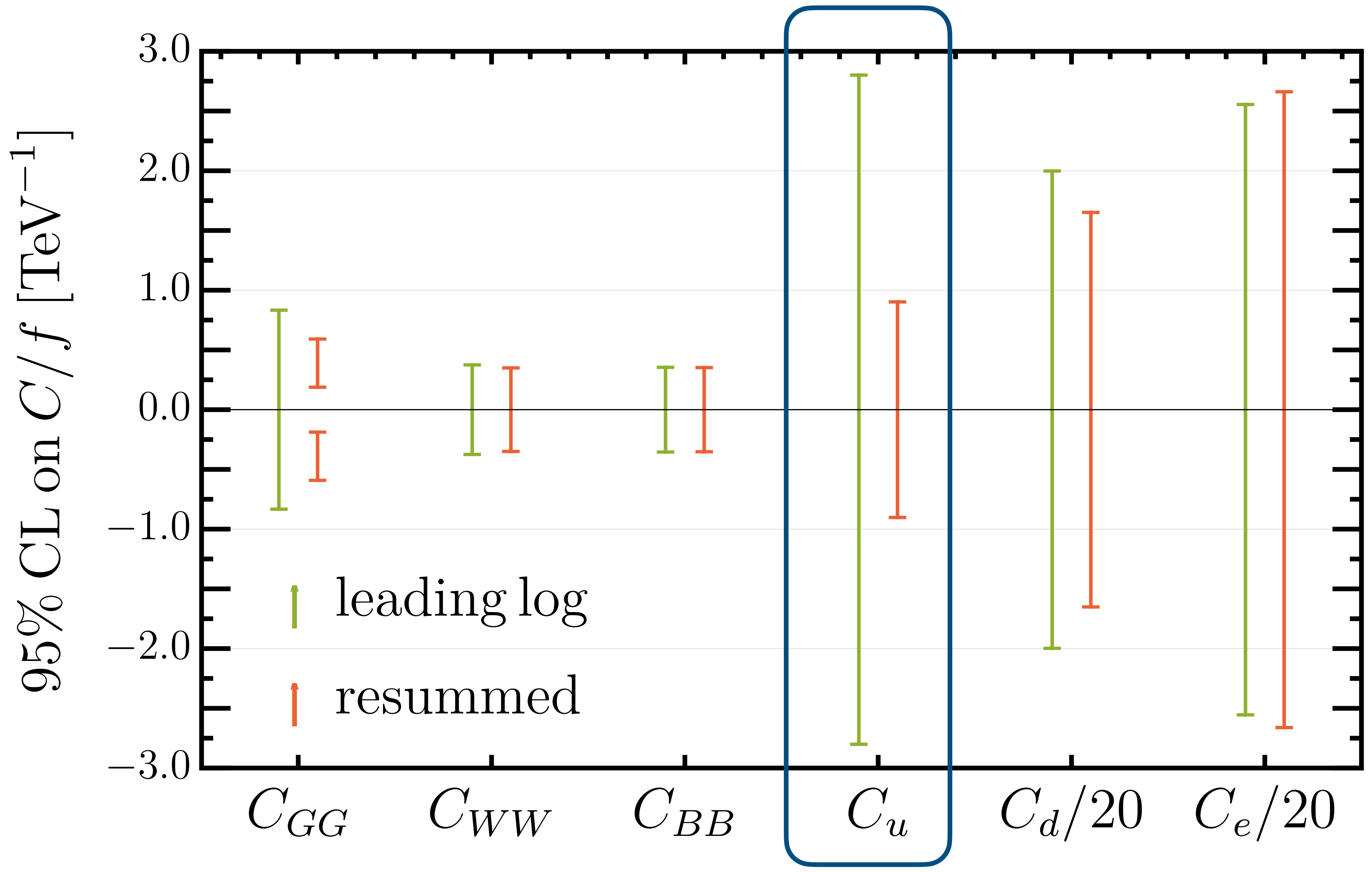
$$\exp\left(-\frac{L_a}{L_{\text{det}}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\text{det}}}\right)$$

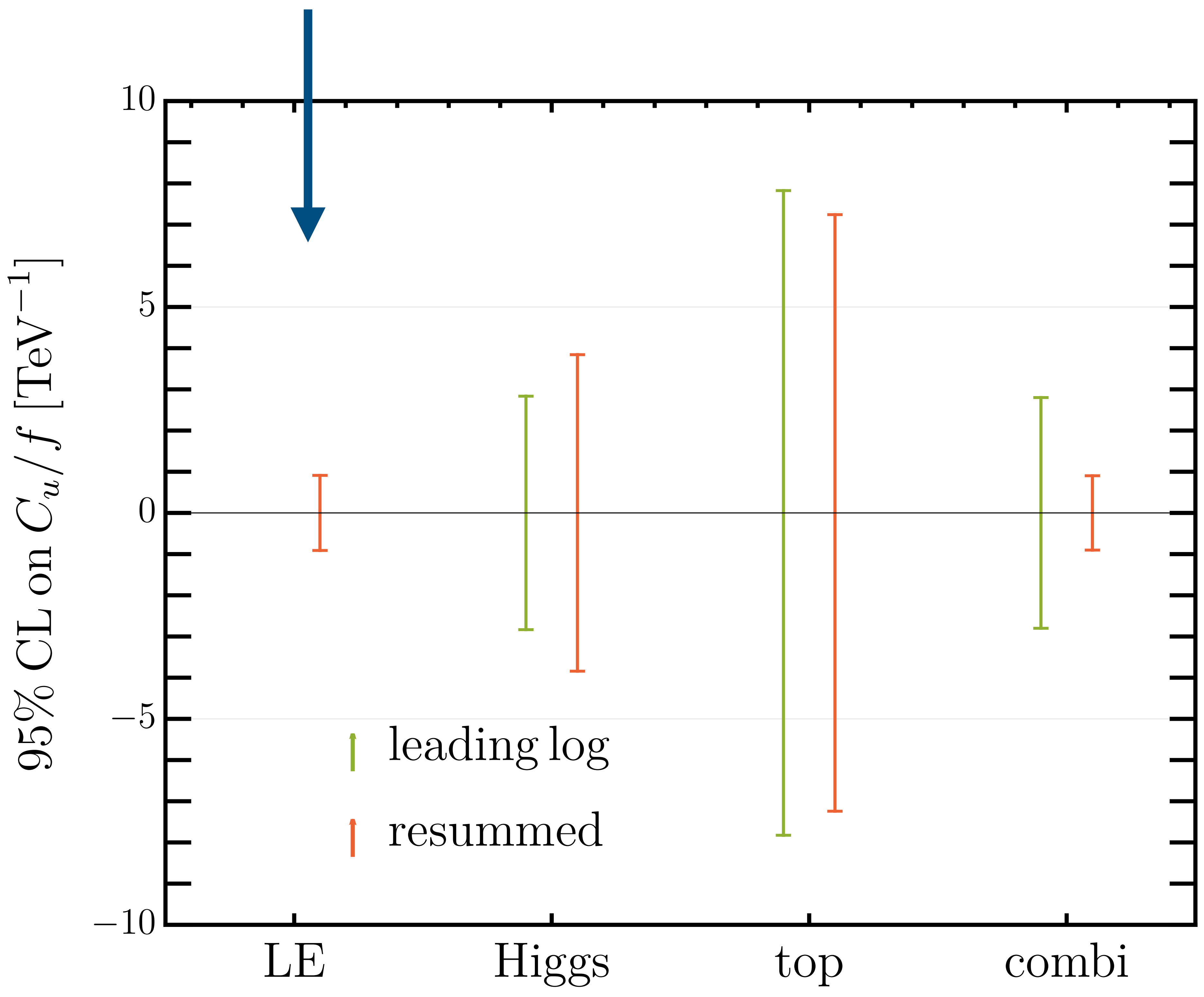
[AB, Fuentes Martín, Galda, Neubert (2307.10372)]

LL approximation

Strongest bound from low energy

Absent at LL order





$$C_i^{\text{SMEFT}}(\mu) \approx \frac{S_i}{(4\pi f)^2} \log\left(\frac{\mu}{\Lambda}\right)$$

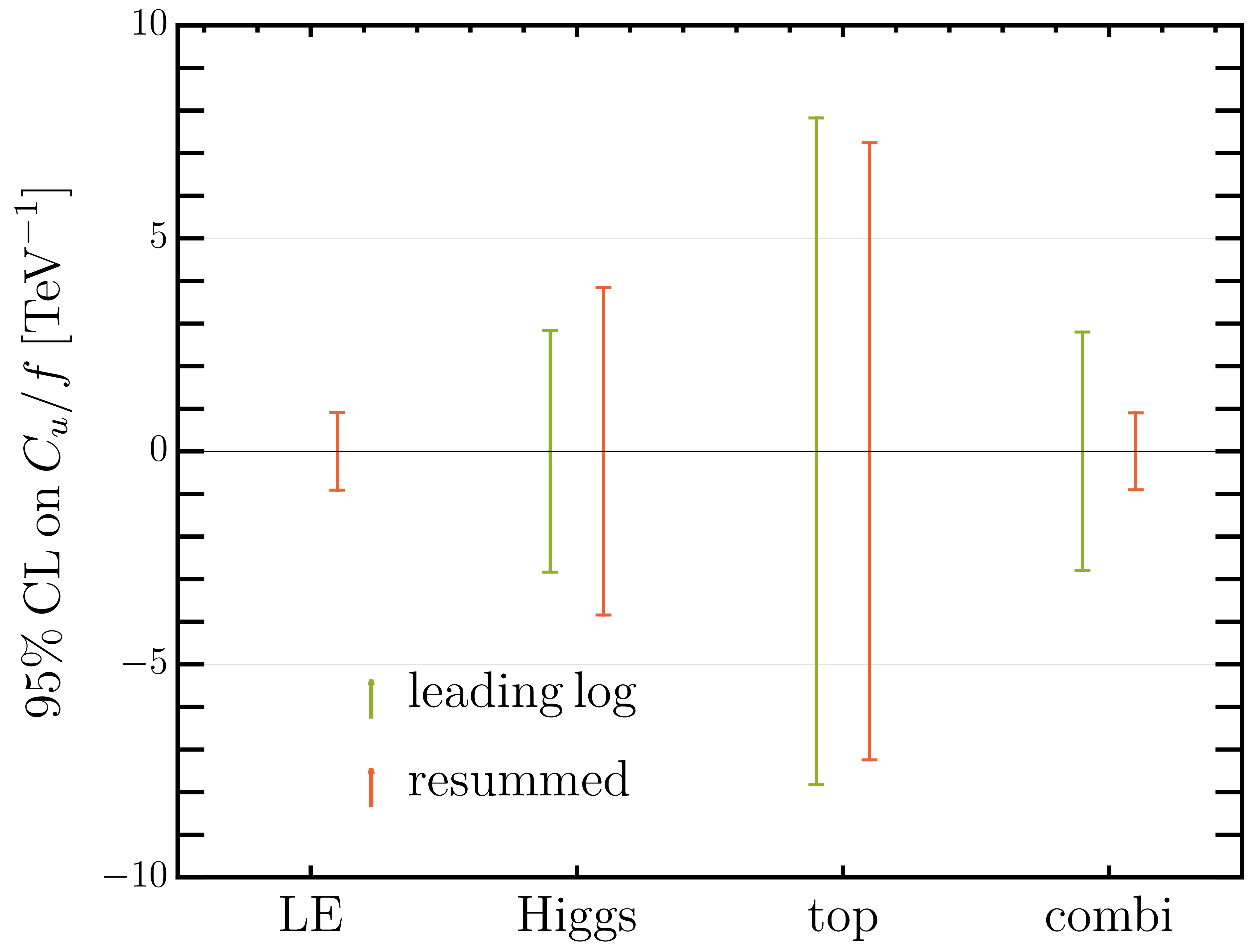
LL approximation - Cu

$$\frac{d}{d\ln\mu} C_{HD} = \left(\frac{3\,\alpha_t}{\pi} + \frac{3\,\lambda}{8\pi^2}\right) C_{HD} + \frac{6\,\alpha_t}{\pi}[C^{(1)}_{Hq}]_{33} - \frac{6\,\alpha_t}{\pi}[C_{Hu}]_{33}$$

$$\frac{d}{d\ln\mu}[C^{(1)}_{Hq}]_{33} = -\pi\,\alpha_t\,C_u^2 + \cdots$$

$$\frac{d}{d\ln\mu}[C_{Hu}]_{33} = 2\pi\,\alpha_t\,C_u^2 + \cdots$$

$$C_{HD}(\mu) = -9\,\alpha_t^2\,C_u^2\,\ln^2\frac{\mu}{\Lambda}$$



CHD strongly constrained from measurement of W boson mass

Reinterpreting the limits for UV axion models

Matching a UV model onto an EFT would lead to additional SMEFT operators. What is the influence of those?

[Arias-Aragón, Quevillon, Smith (2211.04489)]

KSVZ

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

Vector-like quark + Scalar singlet

Boson-philic ALP

DFSZ

[Dine-Fischler-Srednicki-Zhitnitsky (1980, 1981)]

2HDM + Scalar singlet

Fermion-philic ALP

KSVZ model

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

$$\mathcal{L}_{Qq} = -y_q^p\, \bar{q}_L^p H Q_R + \text{h.c.}$$

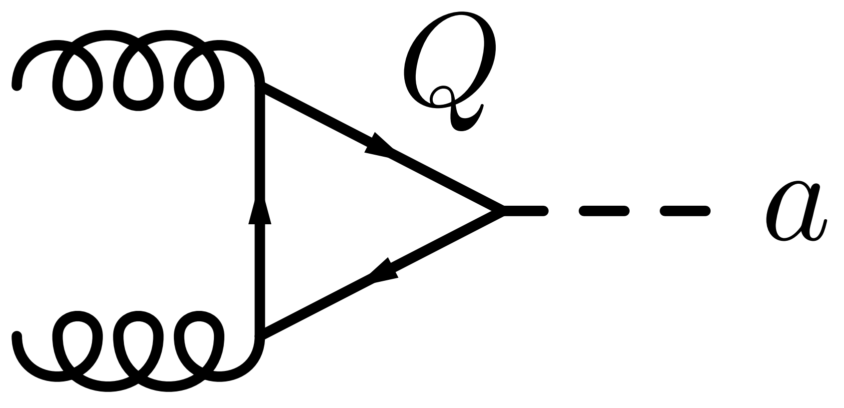
$$Q_{L,R} \sim (\mathbf{3},\mathbf{1})_{-1/3}$$

$$\mathcal{L}_{\text{KSVZ}} = \mathcal{L}_{\text{SM}} + |\partial_\mu S|^2 + \bar{Q}\, i \not{D}\, Q - y_Q \left(S\, \bar{Q}_L Q_R + \text{h.c.}\right)$$
$$+ \mu_S |S|^2 - \frac{\lambda_S}{2}|S|^2 - \lambda_{SH}|S|^2(H^\dagger H) + \mathcal{L}_{Qq}$$

VLQ decay

Vector-like quark Q

Singlet scalar S $\quad S(x) = \frac{1}{\sqrt{2}}\left[f + \rho(x)\right] e^{\frac{i a(x)}{f}}\,,$



Heavy particles Q and ρ

$M_Q = y_Q\, f/\sqrt{2},\; M_\rho^2 = \lambda_S f^2$

Integrate out

KSVZ model - EFT

$$\mathcal{L}_{Qq} = -y_q^p \, \bar{q}_L^p H Q_R + \text{h.c.}$$

$$\mathcal{L}_{\text{EFT}} \supset +\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 \, a^2 \boxed{- \frac{\alpha_s}{8\pi}} \frac{a}{f} G_{\mu\nu}^A \widetilde{G}^{\mu\nu \, A} \boxed{- \frac{1}{3} \frac{\alpha_Y}{4\pi}} \frac{a}{f} B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

$$\boxed{- \frac{\lambda_{SH}^2 f^2}{2 M_\rho^4} Q_{H\Box}} + \boxed{\frac{y_q^p y_q^{r\,*}}{2 M_Q^2} \left(\mathbf{Y}_d^{rs} \, [Q_{dH}]^{ps} - \frac{1}{2} \, [Q_{Hq}^{(1)}]^{pr} - \frac{1}{2} \, [Q_{Hq}^{(3)}]^{pr} + \text{h.c.} \right)}$$

At scale Λ: ALP couplings and SMEFT contributions

➡ Limits on f can be obtained for fixed CGG and CBB from one-parameter ALP fit

Additional Limits on scalar parameters and portal

$$\lambda_S^2 \, f / \lambda_{SH} > 2.8 \, \text{TeV}$$

$$|y_q / M_Q| < 0.1 \text{TeV}^{-1}$$

DFSZ model

Two-Higgs doublet model + scalar singlet

$$S(x) = \frac{1}{\sqrt{2}} [f + \rho(x)] \, e^{\frac{i a(x)}{f}} \,,$$

Two options for relation to SM Yukawas

$$\begin{aligned}\mathcal{L}_{\text{DFSZ}} \supset & |D_\mu H_1|^2 + |D_\mu H_2|^2 + |\partial_\mu S|^2 - (\bar{q}\, \tilde{H}_1 \, \mathbf{\Gamma}_u \, u_R + \bar{q}\, H_2 \, \mathbf{\Gamma}_d \, d_R + \boxed{\bar{\ell}\, H_i \, \mathbf{\Gamma}_e \, e_R} + \text{h.c.}) \\ & - m_1^2 \, |H_1|^2 - m_2^2 \, |H_2|^2 - \frac{\lambda_1}{2} \, |H_1|^4 - \frac{\lambda_2}{2} \, |H_2|^4 - \lambda_3 \, |H_1|^2 |H_2|^2 - \lambda_4 \, |H_1^\dagger H_2|^2 \\ & + \mu_S \, |S|^2 - \frac{\lambda_S}{2} \, |S|^4 - \lambda_{SH_1} \, |S|^2 |H_1|^2 - \lambda_{SH_2} \, |S|^2 |H_2|^2 - \lambda_{SH_{12}} \left[(H_1^\dagger H_2) S^2 + \text{h.c.} \right]\end{aligned}$$

Heavy particles Φ and ρ

DFSZ model - EFT

Mixing angle α

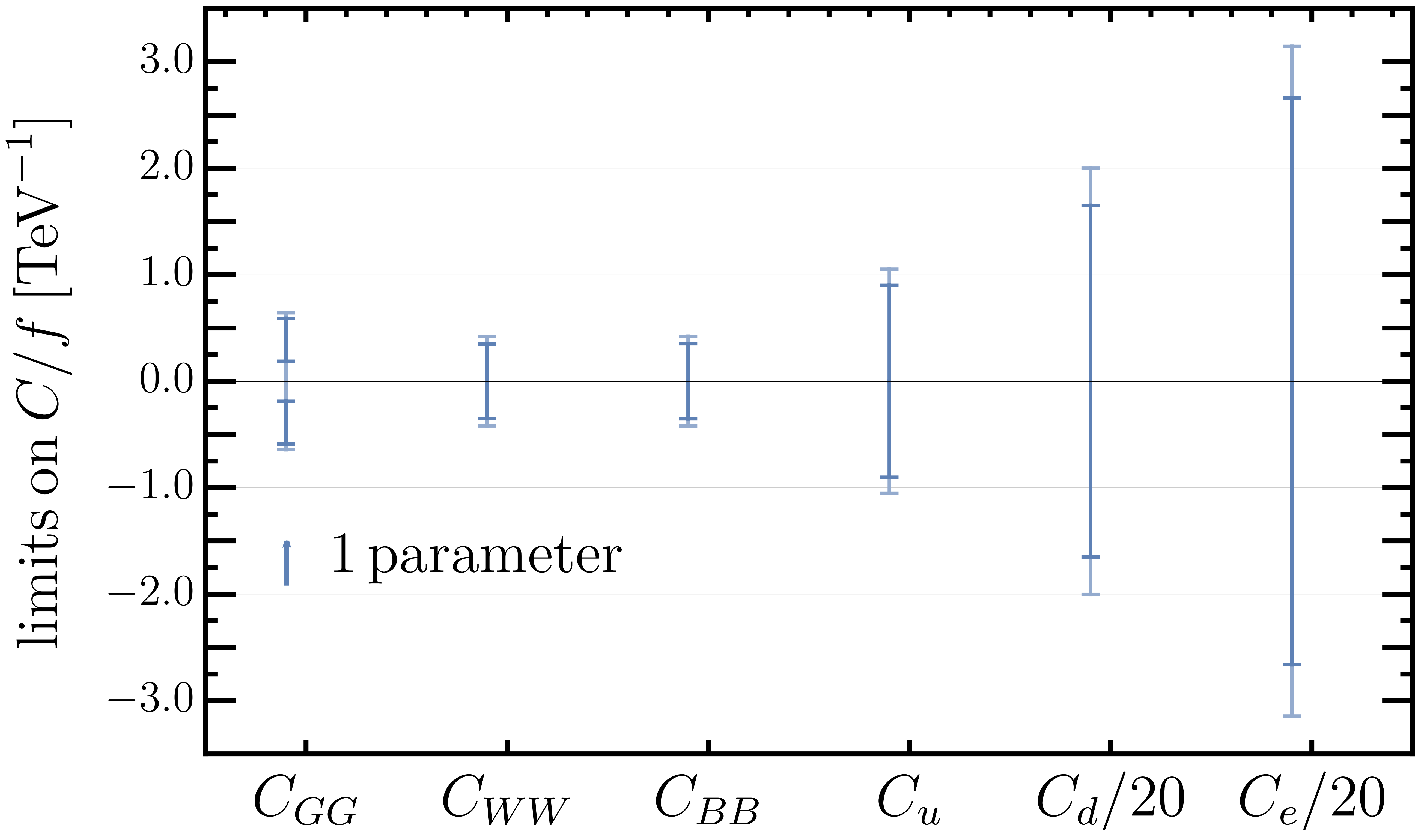
$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$|C_u|/f < 1/\mathrm{TeV}$

$C_u = -2s_\alpha^2$ $\quad$ $C_d = -2c_\alpha^2$

DFSZ I $\quad$ $C_e = -2s_\alpha^2$

DFSZ II $\quad$ $C_e = -2c_\alpha^2$



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Mixing angle α

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$$\begin{aligned}
\mathcal{L}_{\text{EFT}} \supset & -\frac{C_{\psi H}}{M_\Phi^2} \left(t_\alpha [\boldsymbol{Y}_u]^{pr} [Q_{uH}]^{pr} - t_\alpha^{-1} [\boldsymbol{Y}_d]^{pr} [Q_{dH}]^{pr} - \eta_\alpha [\boldsymbol{Y}_e]^{pr} [Q_{eH}]^{pr} + \text{h.c.} \right) \\
& - \frac{[\boldsymbol{Y}_u^*]^{sr} [\boldsymbol{Y}_u]^{pt}\, t_\alpha^2}{M_\Phi^2} \left(\frac{1}{6} [Q_{qu}^{(1)}]^{prst} + [Q_{qu}^{(8)}]^{prst} \right) - \frac{[\boldsymbol{Y}_d^*]^{sr} [\boldsymbol{Y}_d]^{pt}\, t_\alpha^{-2}}{M_\Phi^2} \left(\frac{1}{6} [Q_{qd}^{(1)}]^{prst} + [Q_{qd}^{(8)}]^{prst} \right) \\
& - \frac{[\boldsymbol{Y}_e^*]^{sr} [\boldsymbol{Y}_e]^{pt}\, \eta_\alpha^2}{2M_\Phi^2} [Q_{le}]^{prst} - \frac{1}{M_\Phi^2} \left([\boldsymbol{Y}_u]^{pr} [\boldsymbol{Y}_d]^{st} [Q_{quqd}^{(1)}]^{prst} - [\boldsymbol{Y}_u]^{st} [\boldsymbol{Y}_e]^{pr}\, t_\alpha \eta_\alpha [Q_{lequ}^{(1)}]^{prst} \right. \\
& \left. - [\boldsymbol{Y}_d^*]^{st} [\boldsymbol{Y}_e]^{pr}\, t_\alpha^{-1} \eta_\alpha [Q_{ledq}]^{prst} + \text{h.c.} \right) + \frac{C_H}{M_\Phi^2} Q_H - \frac{\lambda_{SH}^2 f^2}{2M_\rho^4} Q_{H\Box}\,,
\end{aligned}$$

Yukawa suppressed

DFSZ model - EFT

Mixing angle α

$|C_u|/f < 1/\mathrm{TeV}$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$C_u = -2s_\alpha^2$ $\quad$ $C_d = -2c_\alpha^2$

DFSZ I $\quad C_e = -2s_\alpha^2$

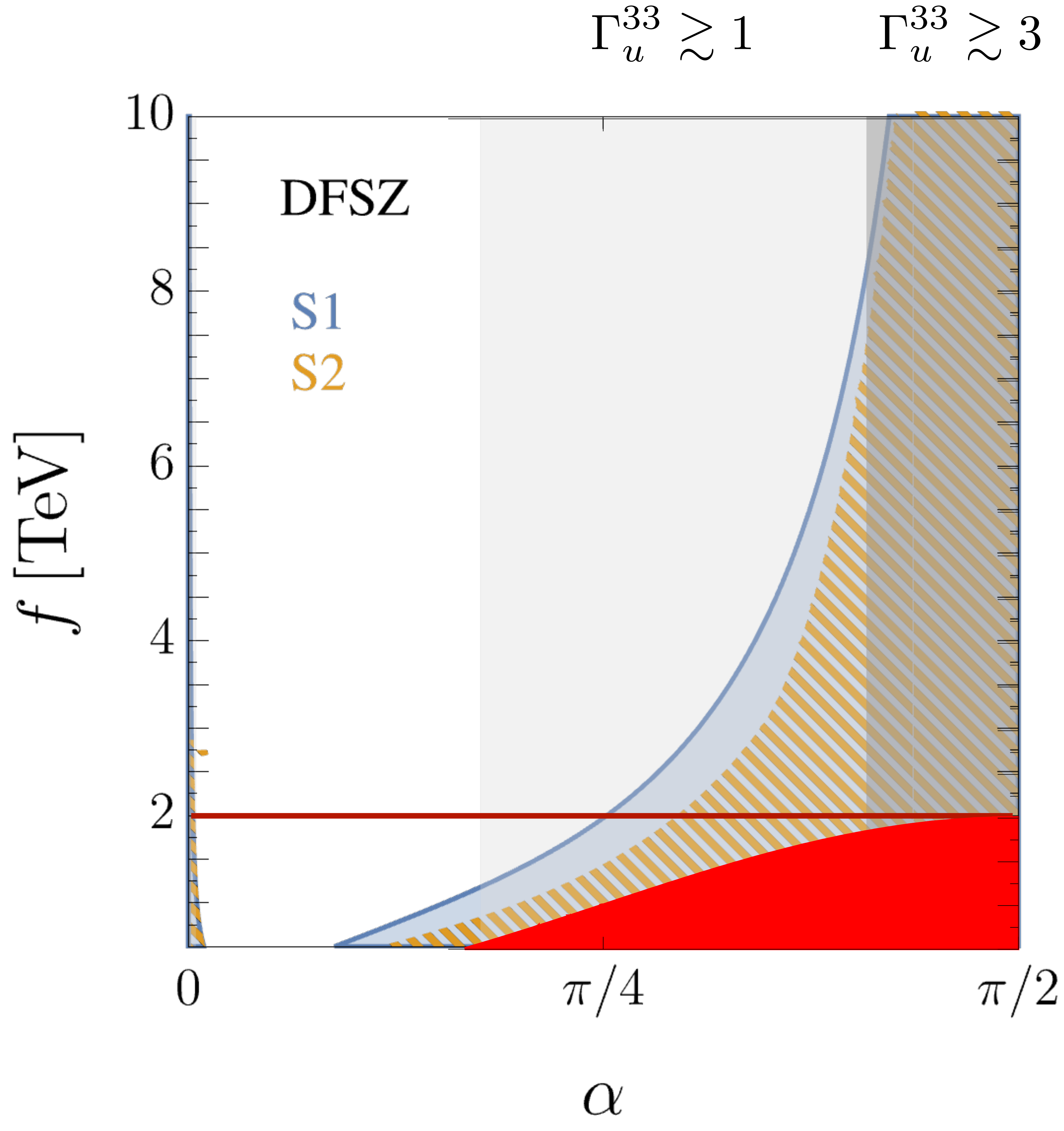
DFSZ II $\quad C_e = -2c_\alpha^2$

$$\mathcal{L}_{\mathrm{EFT}} \supset -\frac{C_{\psi H}}{M_\Phi^2}\left(t_\alpha\,[\boldsymbol{Y}_u]^{pr}\,[Q_{uH}]^{pr} - t_\alpha^{-1}\,[\boldsymbol{Y}_d]^{pr}\,[Q_{dH}]^{pr} - \eta_\alpha\,[\boldsymbol{Y}_e]^{pr}\,[Q_{eH}]^{pr} + \mathrm{h.c.}\right)$$
$$-\frac{[\boldsymbol{Y}_u^*]^{sr}\,[\boldsymbol{Y}_u]^{pt}\,t_\alpha^2}{M_\Phi^2}\left(\frac{1}{6}\,[Q_{qu}^{(1)}]^{prst} + [Q_{qu}^{(8)}]^{prst}\right) - \frac{[\boldsymbol{Y}_d^*]^{sr}\,[\boldsymbol{Y}_d]^{pt}\,t_\alpha^{-2}}{M_\Phi^2}\left(\frac{1}{6}\,[Q_{qd}^{(1)}]^{prst} + [Q_{qd}^{(8)}]^{prst}\right)$$
$$-\frac{[\boldsymbol{Y}_e^*]^{sr}\,[\boldsymbol{Y}_e]^{pt}\,\eta_\alpha^2}{2M_\Phi^2}\,[Q_{le}]^{prst} - \frac{1}{M_\Phi^2}\left([\boldsymbol{Y}_u]^{pr}\,[\boldsymbol{Y}_d]^{st}\,[Q_{quqd}^{(1)}]^{prst} - [\boldsymbol{Y}_u]^{st}\,[\boldsymbol{Y}_e]^{pr}\,t_\alpha\eta_\alpha\,[Q_{lequ}^{(1)}]^{prst}\right.$$
$$\left.-[\boldsymbol{Y}_d^*]^{st}\,[\boldsymbol{Y}_e]^{pr}\,t_\alpha^{-1}\eta_\alpha\,[Q_{ledq}]^{prst} + \mathrm{h.c.}\right) + \frac{C_H}{M_\Phi^2}\,Q_H - \frac{\lambda_{SH}^2 f^2}{2M_\rho^4}\,Q_{H\Box}\,,$$

Yukawa suppressed

ALP couplings and SMEFT operators depend on same parameters α and f

DFSZ models - results



$C_u = -2s_\alpha^2$

$|C_u|/f < 1/\mathrm{TeV}$

S1: negligible scalar parameters

S2: profiling of scalar parameters

Limits on f dominated by SMEFT contributions