Top of the ALPs

Precise tests of the axion coupling to tops

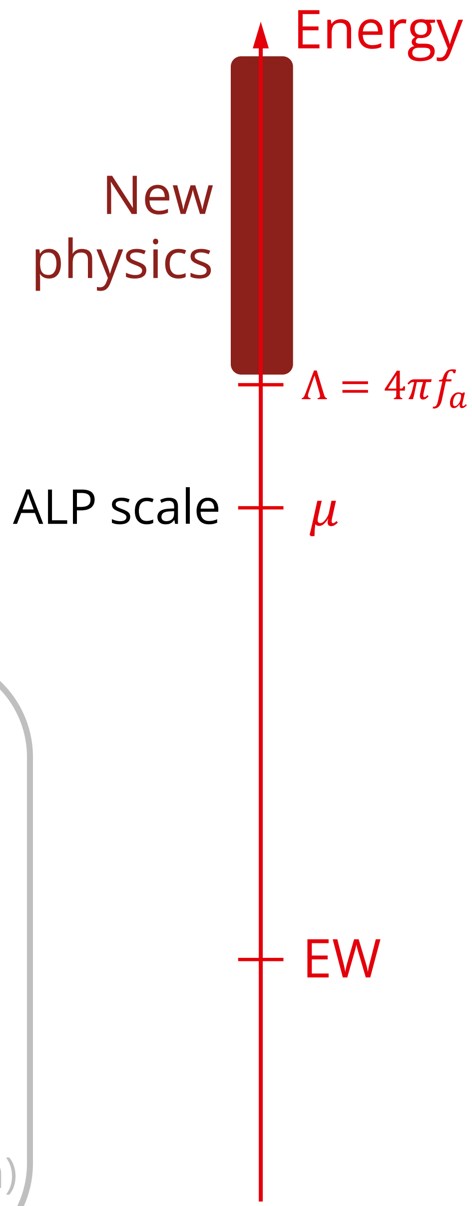
Anh Vu Phan (Vu), Susanne Westhoff, based on JHEP 05 (2024) 075
TOP2024, 24 September 2024

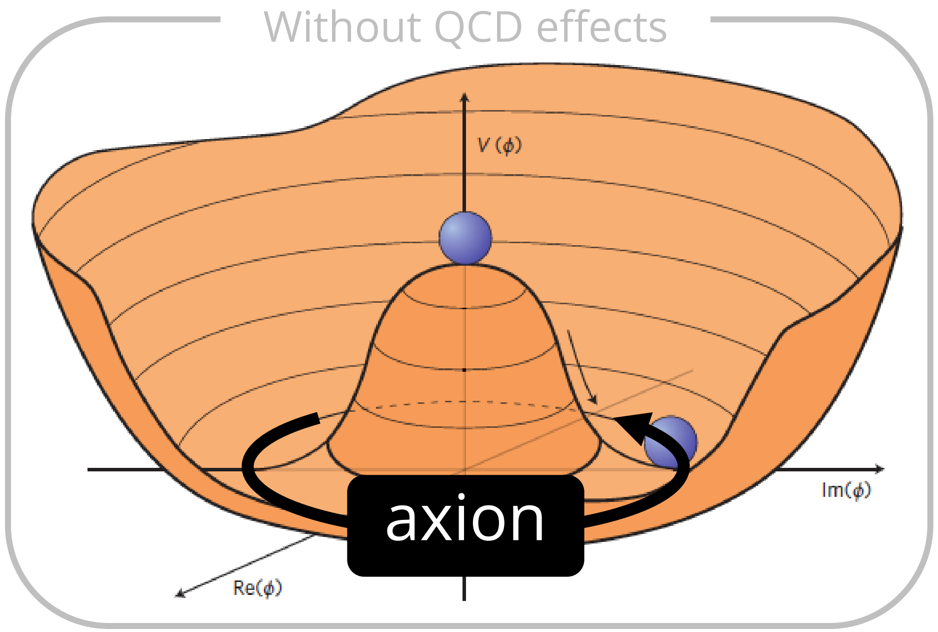
Radboud University
Nikhef

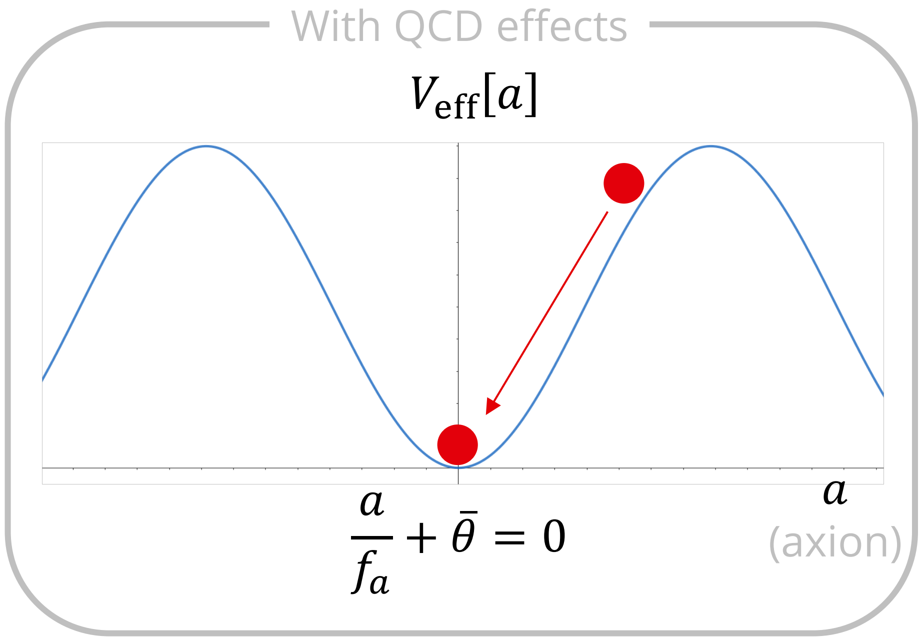
Georgi, Kaplan, and Randall (1986)

AXION-LIKE PARTICLE (ALP)

- Generalization of the axion
  - Pseudoscalar
  - Has shift symmetry $a \to a + 2\pi f_a$
  - Need not solve strong CP problem



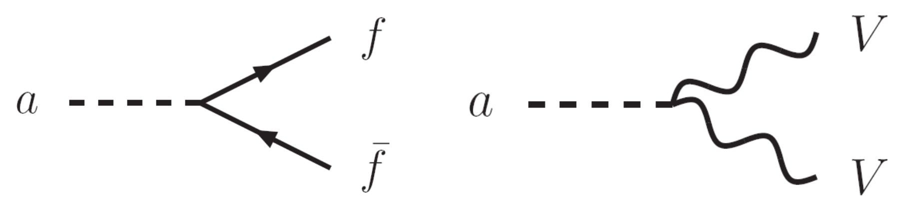




Georgi, Kaplan, and Randall (1986)

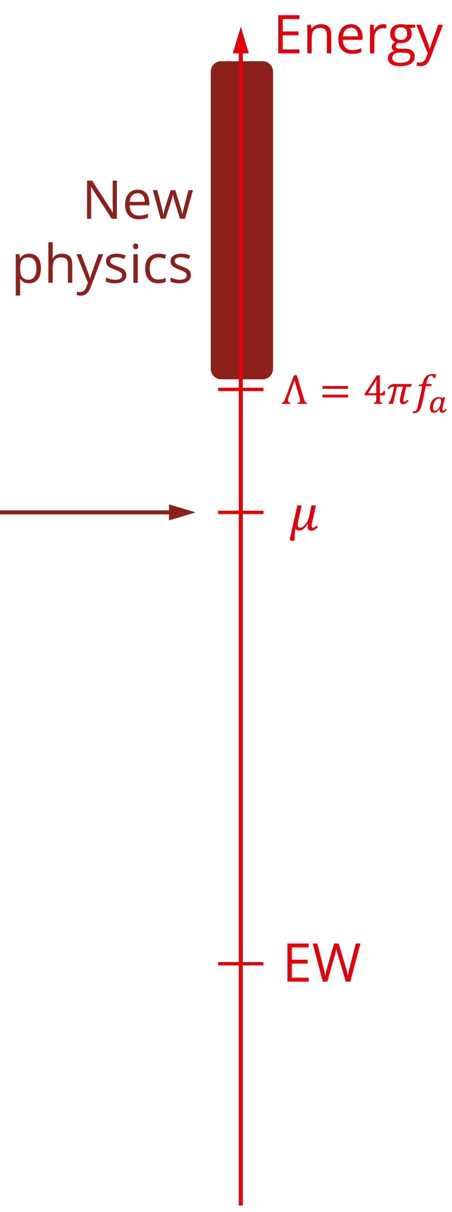
ALP EFFECTIVE THEORY

$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2} a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F} c_F \gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi} V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$



breaks
$a \to a + c$

invariant under $a \to a + 2\pi f_a$



ALP EFFECTIVE THEORY

Why top?

$$\mathcal{L}_{\rm eff}(\mu) \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F}\boldsymbol{c}_F\gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi}V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$

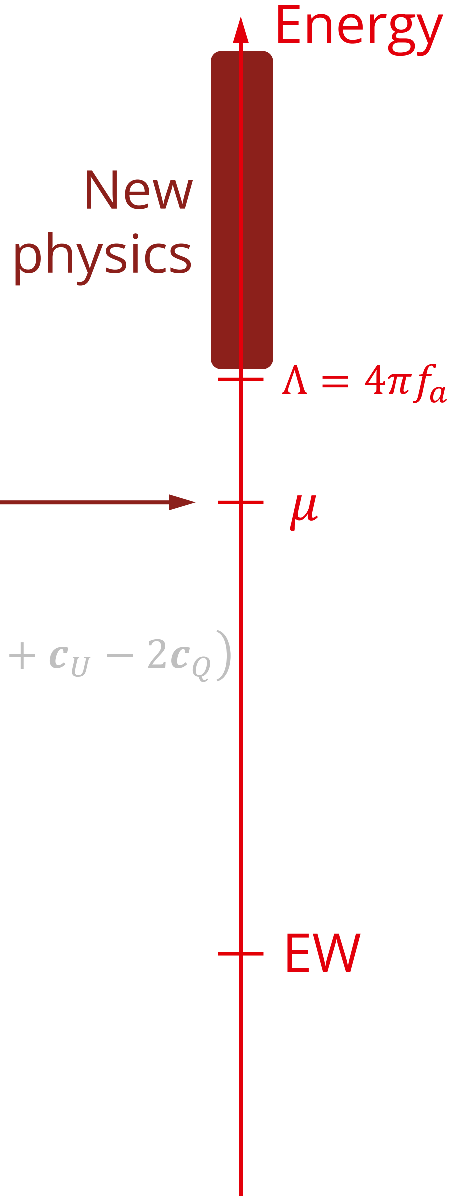
$$Q_L \to e^{-ic_Q\frac{a}{f_a}}Q_L$$

$$u_R \to e^{-ic_U\frac{a}{f_a}}u_R$$

$$c_{qq} = \left(\boldsymbol{c}_U - \boldsymbol{c}_Q\right)_{qq}$$

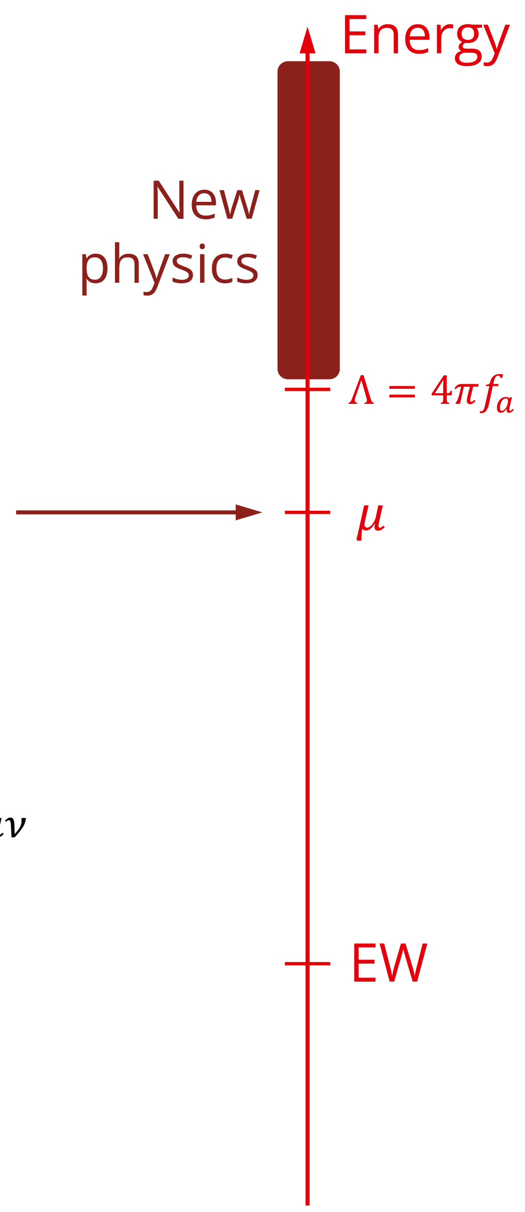
$$\tilde{c}_{GG} = c_{GG} + \frac{1}{2}\mathrm{Tr}\left(\boldsymbol{c}_D + \boldsymbol{c}_U - 2\boldsymbol{c}_Q\right)$$

$$\to \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \sum_f m_f c_{ff}\frac{a}{f_a}\bar{f}i\gamma^5 f + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$



Georgi, Kaplan, and Randall (1986)

AXION-LIKE PARTICLE (ALP)



$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F}\boldsymbol{c}_F\gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$

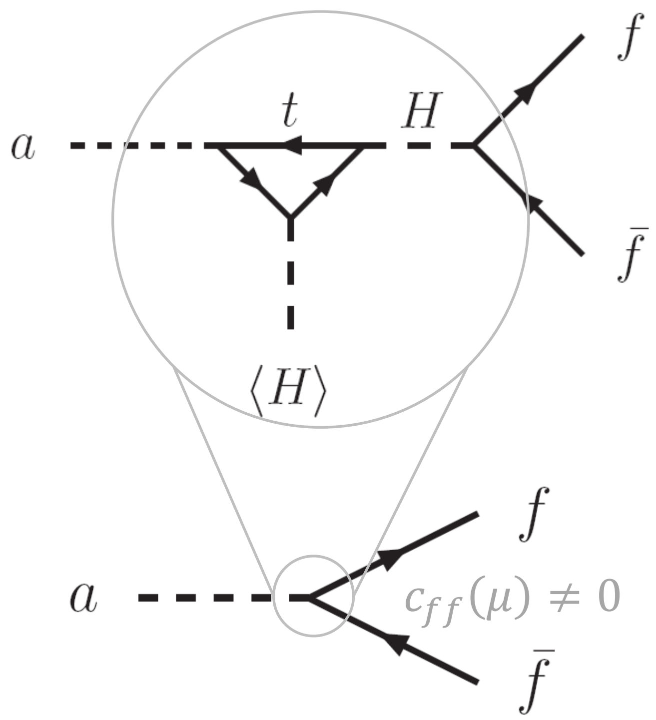
$$\rightarrow \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 + \boxed{\sum_f m_f c_{ff}\frac{a}{f_a}\bar{f}i\gamma^5 f} + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$

top is most sensitive to ALP!

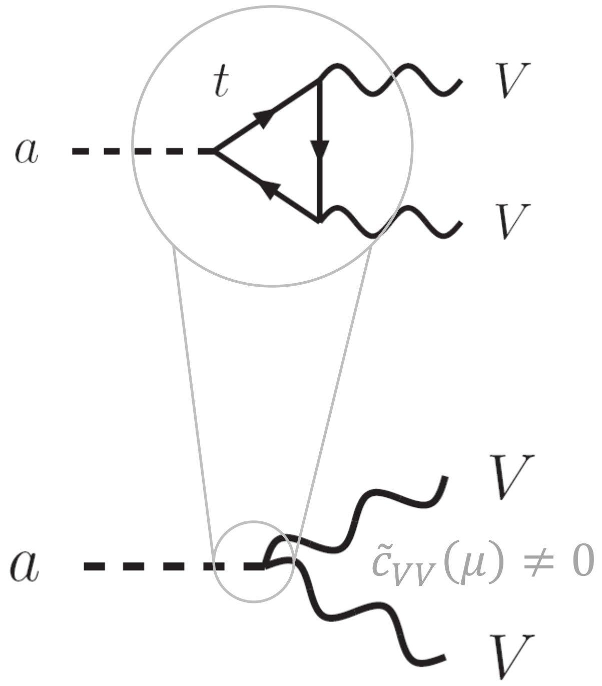
TOP-INDUCED EFFECTIVE COUPLINGS

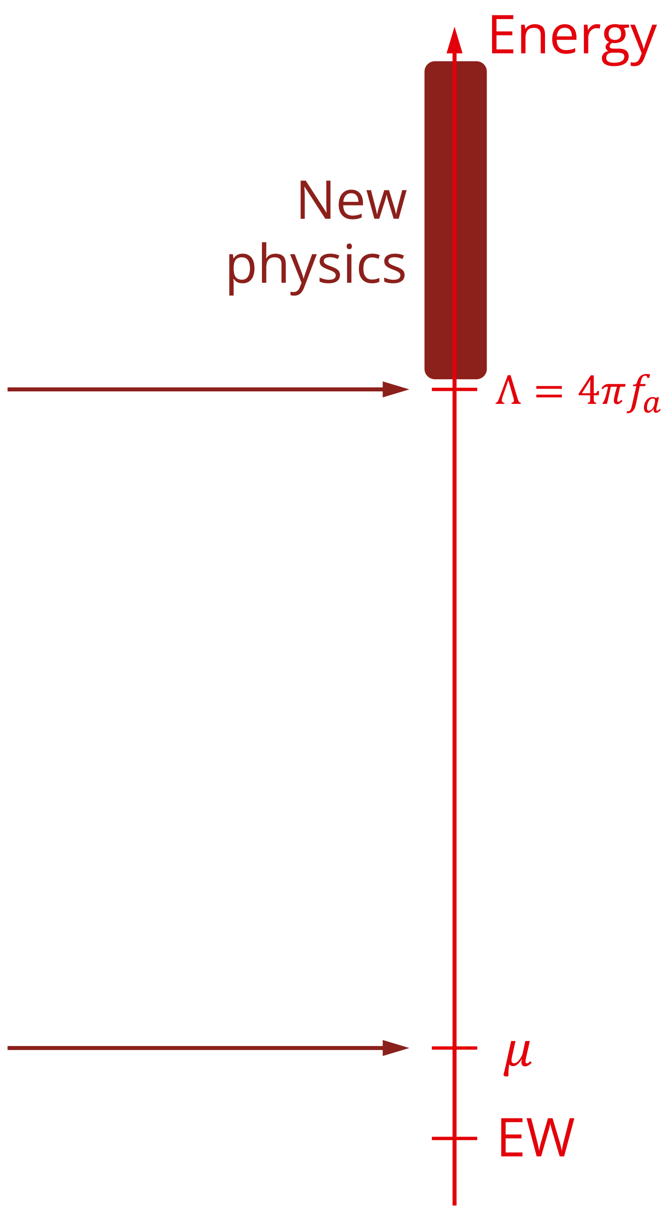
- Tops can induce other couplings via loop corrections

$c_{f\bar{f}}(\Lambda) = 0$ $(f \neq t)$



$\tilde{c}_{VV}(\Lambda) = 0$

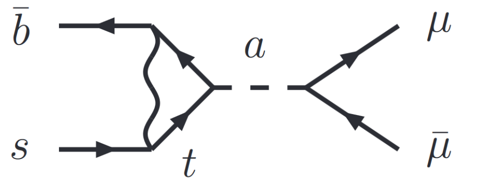




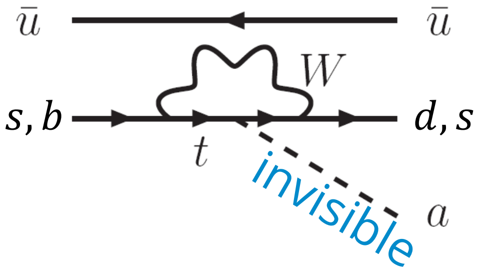
HOW TO FIND ALPS?

In meson decays

$B_s \to \mu^+\mu^-$



$K \to \pi + \text{inv}$
$B \to K + \text{inv}$



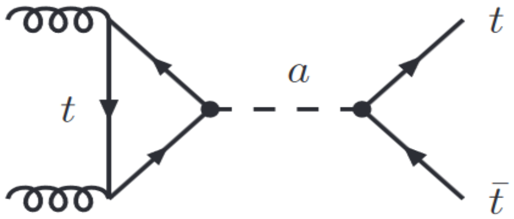
Bauer et al. (2021) [2110.10698]
Rygaard et al. (2023) [2306.08686]

Long-lived ALPs

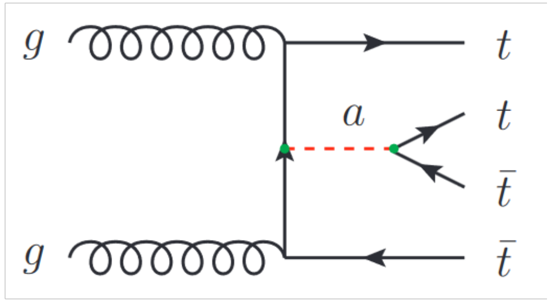
In top observables

virtual corrections

$pp \to t\bar{t}$

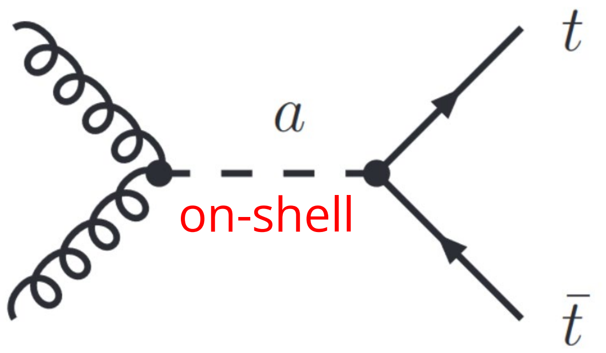


$pp \to t\bar{t}t\bar{t}$



AVP, Westhoff (2023) [2312.00872]
Esser et al. (2024) [2404.08062]
Blasi et al. (2023) [2311.16048]
Bruggisser et al. (2023) [2308.11703]
Biekoetter et al. (2023) [2307.10372]

resonance ALPs



Anuar et al. (2024) [2404.19014]

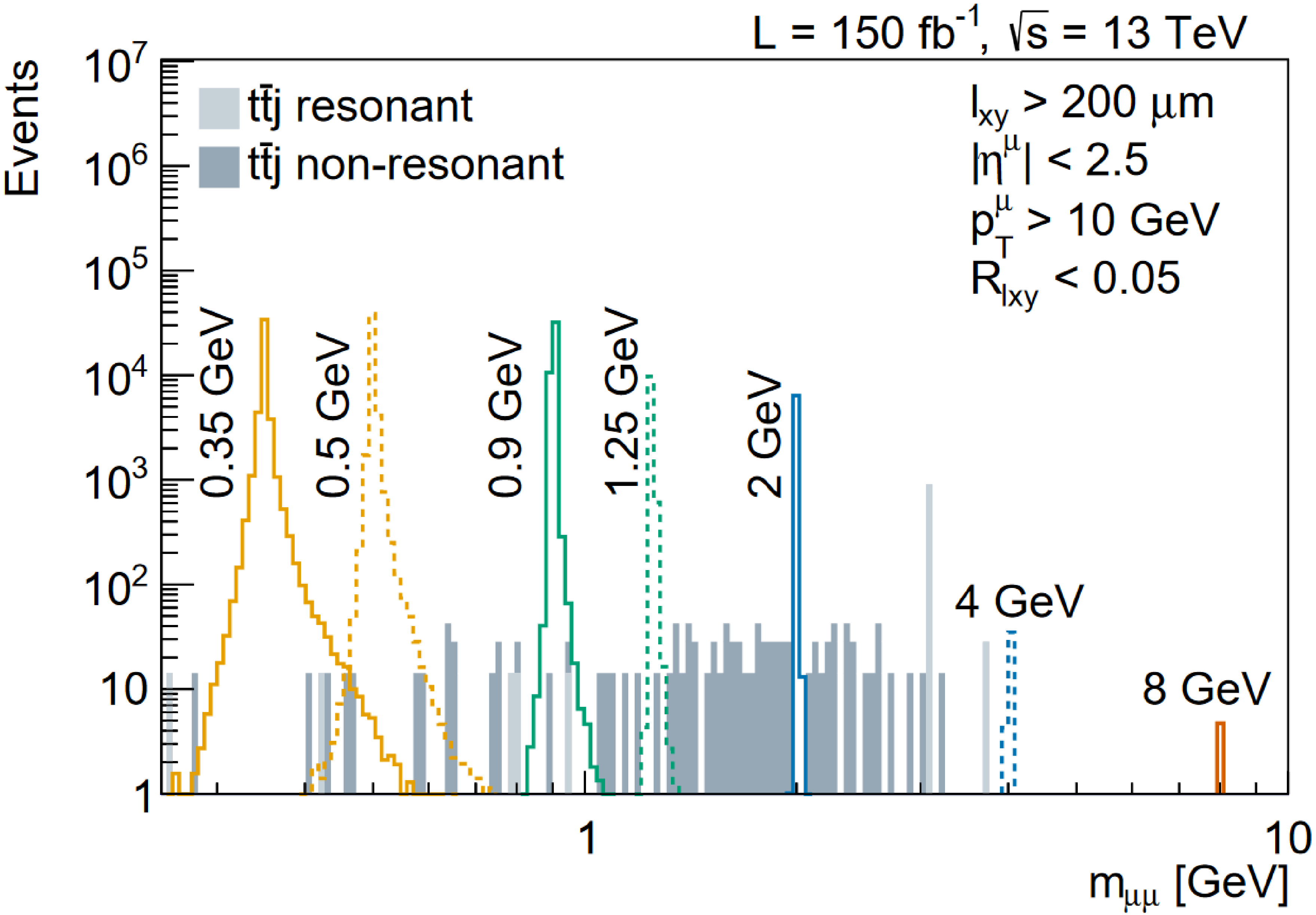
m_a

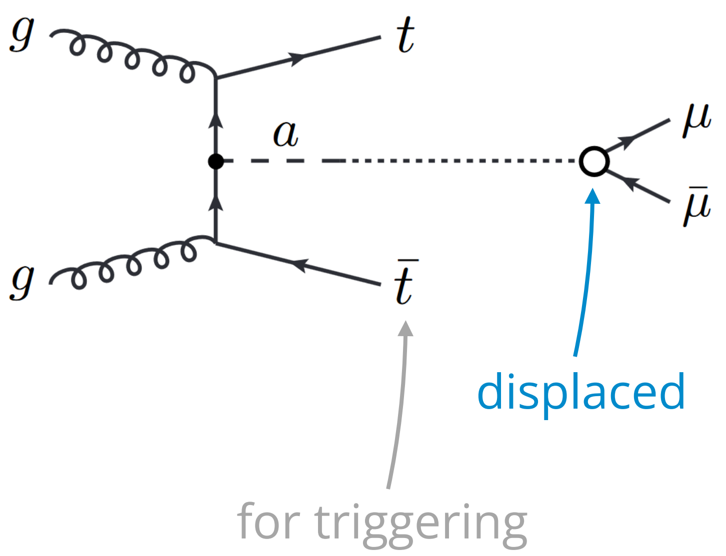
~ 10 GeV

$2m_t = 345$ GeV

DISPLACED ALPS AT THE LHC

Rygaard et al. (2023) [2306.08686]

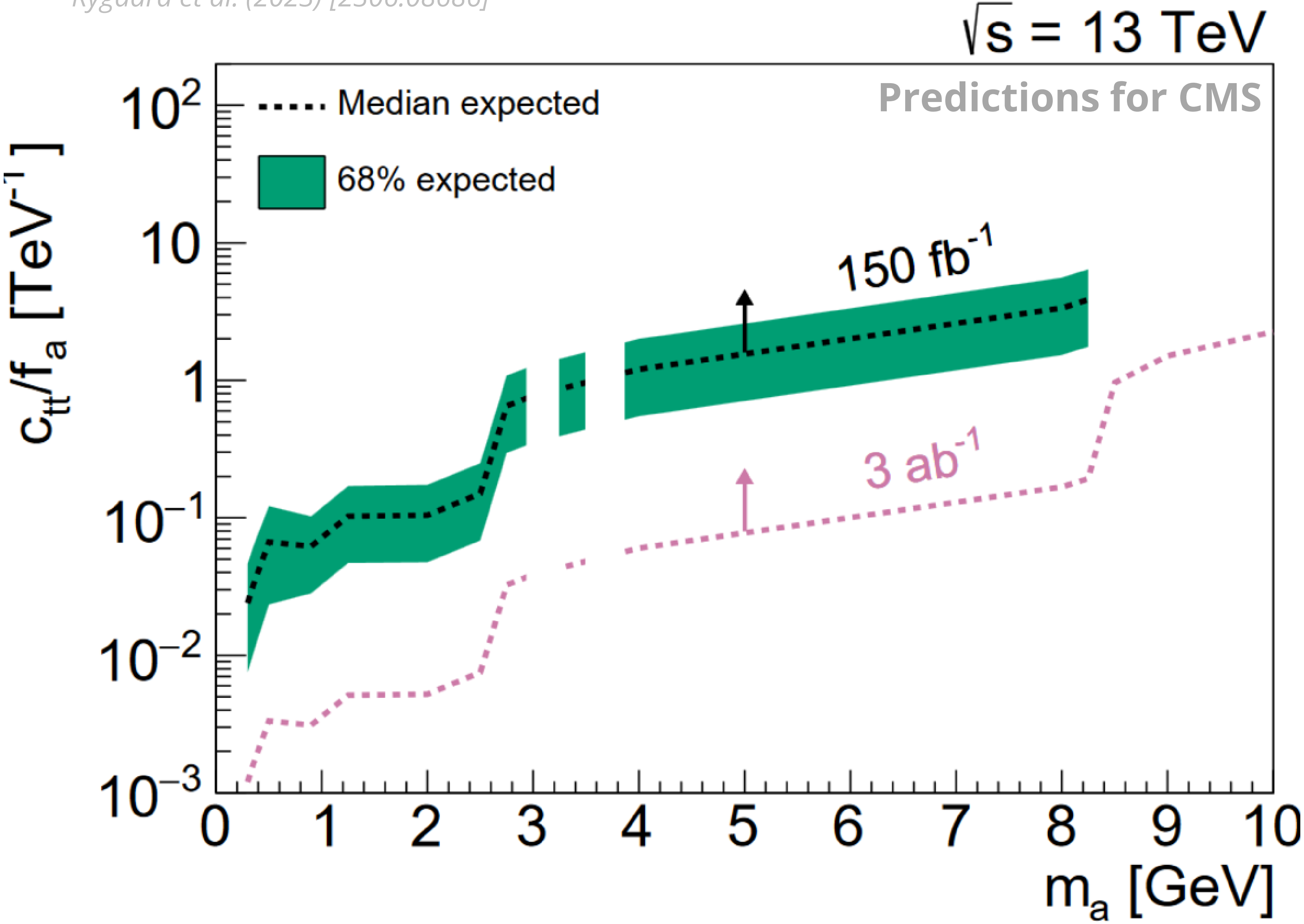


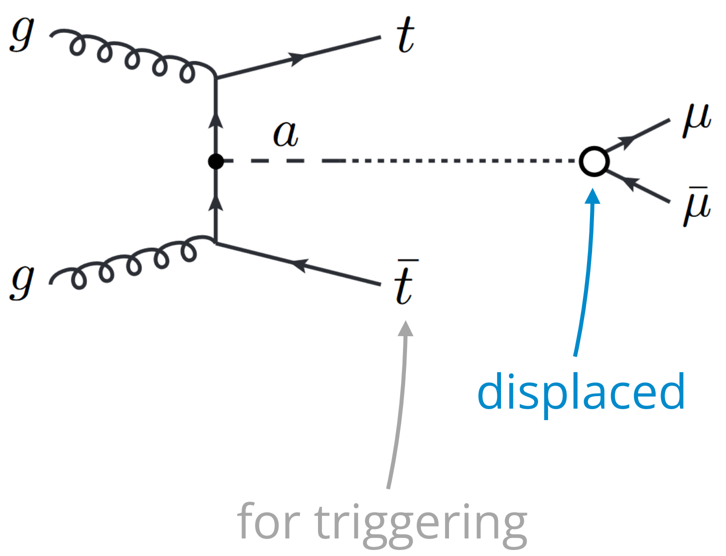


$$\frac{c_{tt}(\Lambda)}{f_a} = \frac{1}{\text{TeV}}, \; c_{\mu\mu}(\Lambda) = 0$$

DISPLACED ALPS

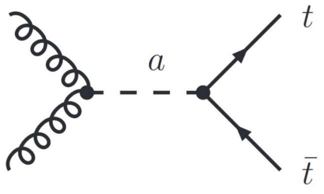
Rygaard et al. (2023) [2306.08686]



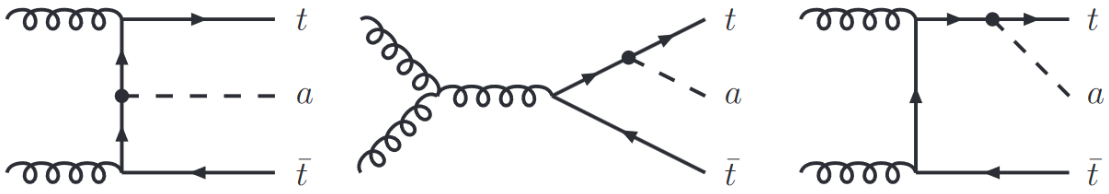


ALPS IN $t\bar{t}$ PRODUCTION

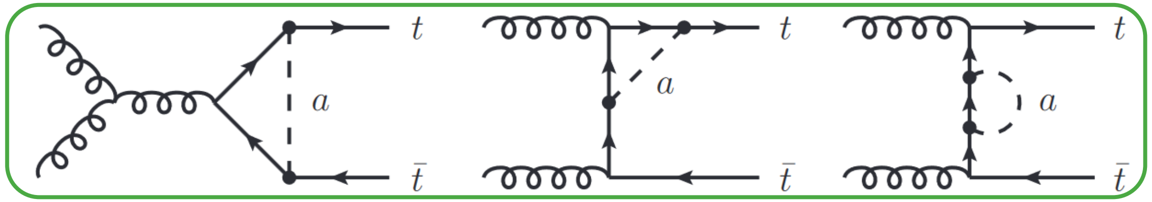
Tree-level

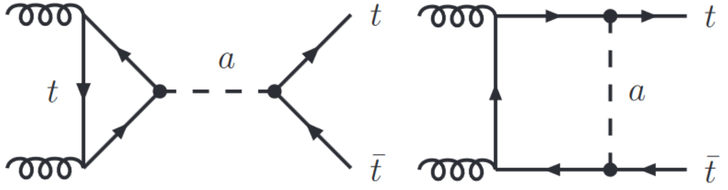


Real ALP radiation



Virtual corrections



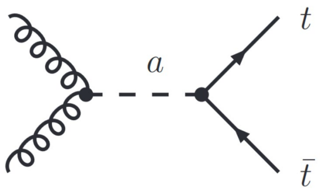


Needs renormalization

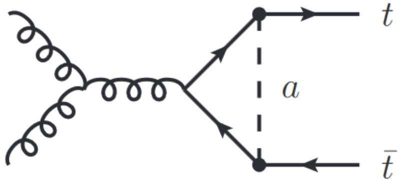
AVP, Westhoff (2023) [2312.00872]

LEADING CONTRIBUTIONS

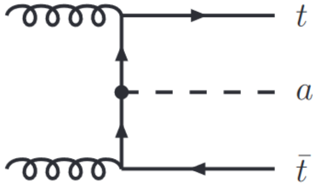
Tree-level



Virtual corrections



Real ALP radiation



tree × SM

|tree|^2

virtual × SM

|radiation|^2

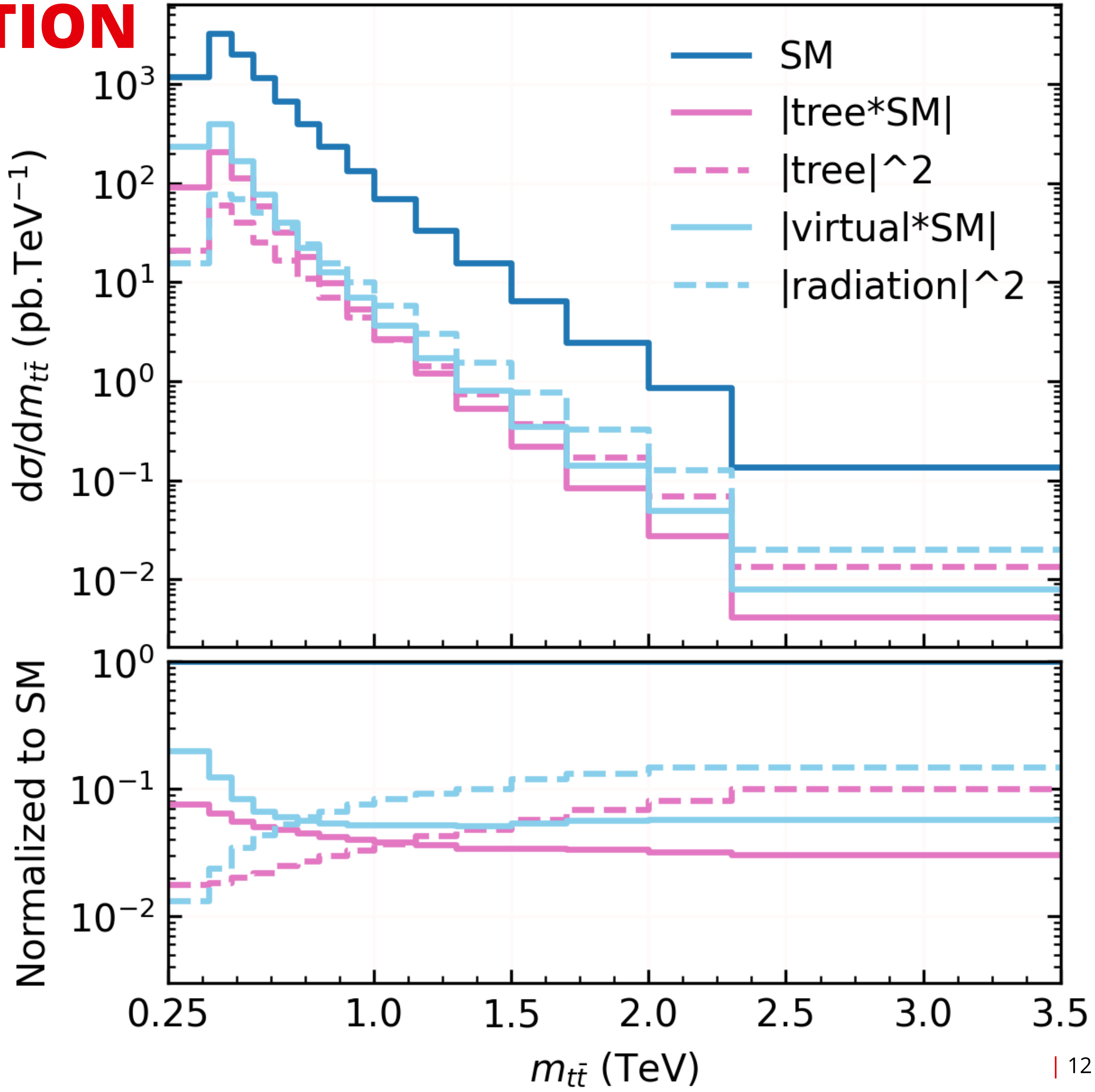
$$\sigma_{t\bar{t}} = \sigma_{SM} + \frac{\alpha_S^2}{4\pi}\frac{\tilde{c}_{GG}\, c_{tt}}{f_a^2}\sigma_{a-SM}^{(t\bar{t},0)} + \frac{\alpha_S^2}{(4\pi)^2}\frac{\tilde{c}_{GG}^2\, c_{tt}^2}{f_a^4}\sigma_{a-a}^{(t\bar{t},0)} + \frac{\alpha_S^2}{4\pi}\frac{c_{tt}^2}{f_a^2}\sigma_{a-SM}^{(t\bar{t},1)} + \frac{\alpha_S^2}{4\pi}\frac{c_{tt}^2}{f_a^2}\sigma_{a-a}^{(t\bar{t}a,0)} + \cdots$$

ALP EFFECTS IN $m_{t\bar{t}}$ DISTRIBUTION

SM: *PRD 104 (2021) 092013*

***AVP**, Westhoff (2023) [2312.00872]*

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \text{GeV}$$



ALP EFFECTS IN $m_{t\bar{t}}$ DISTRIBUTION

SM: *PRD 104 (2021) 092013*
***AVP**, Westhoff (2023) [2312.00872]*

Virtual ALP and tree-level interferences with SM are *negative*

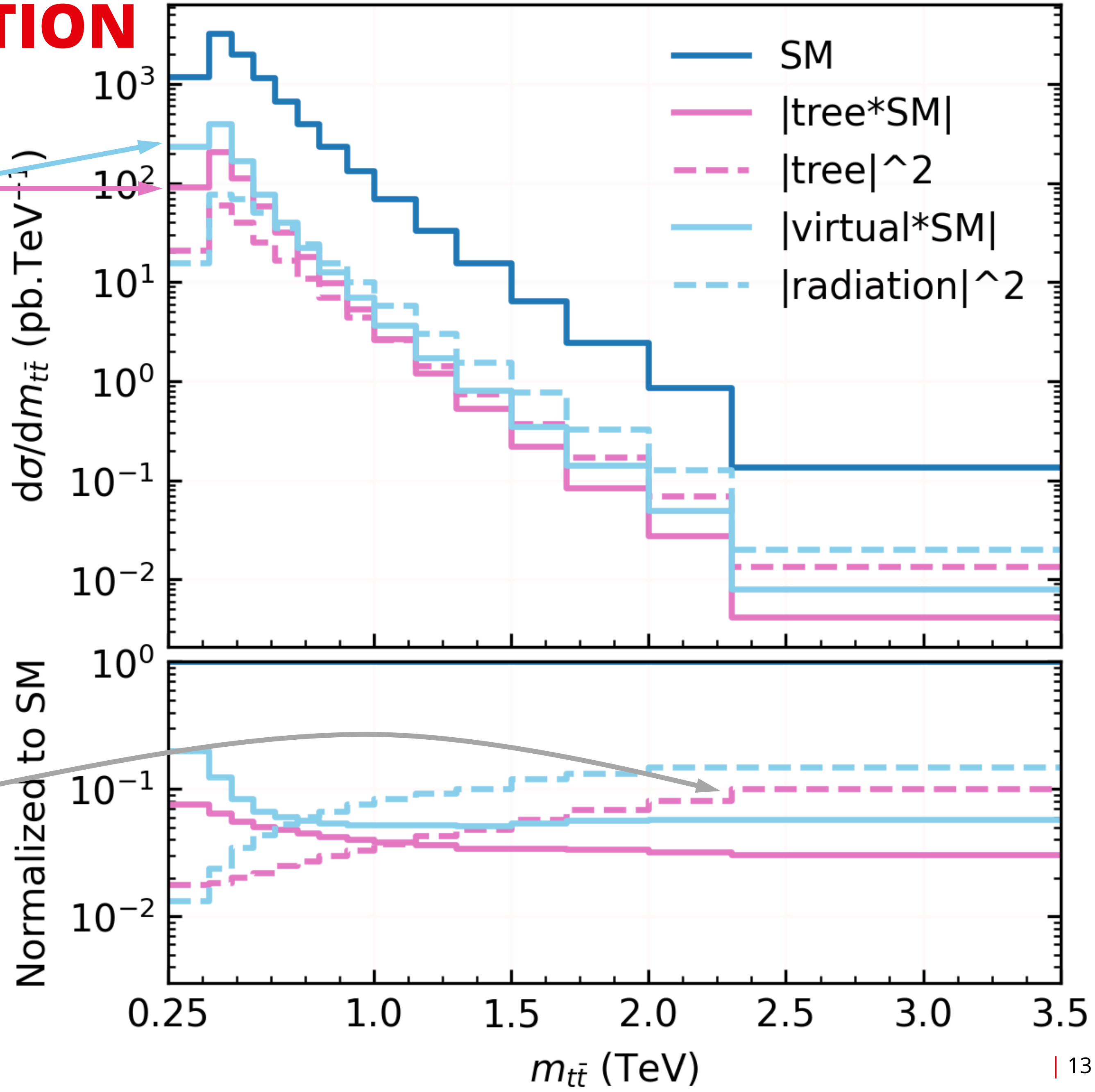
$$c_{GG} = \tilde{c}_{GG} - \frac{1}{2} c_{tt}$$

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \text{GeV}$$

New Physics scale $\Lambda = 4\pi f_a$

Energy enhancement in |tree-level|^2

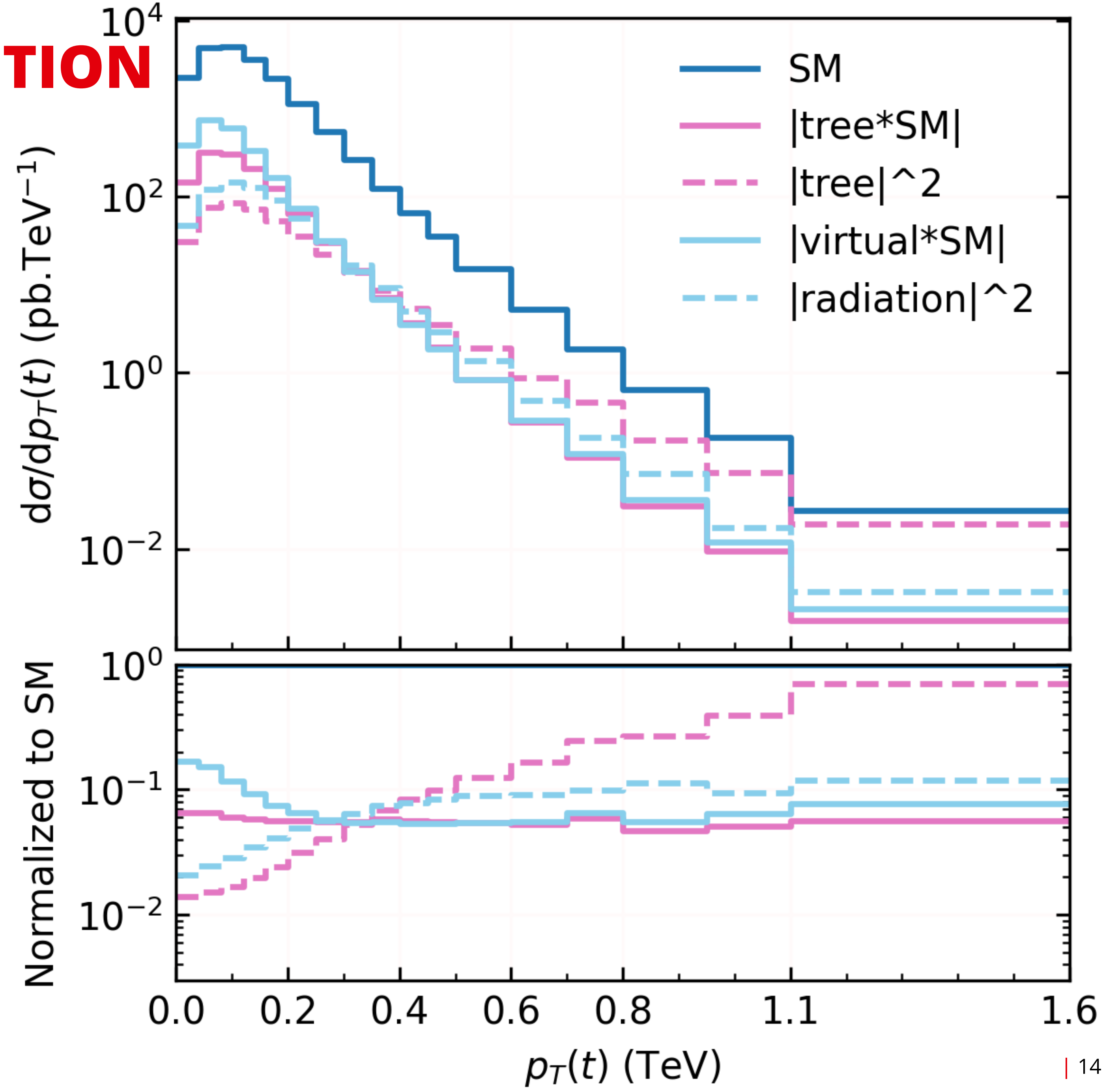
$$\sigma_{|\text{ALP}|^2}(s) \sim \frac{1}{s}\frac{m_t^2 s}{f_a^4}$$



ALP EFFECTS IN p_T DISTRIBUTION

SM: *PRD 104 (2021) 092013*

***AVP**, Westhoff (2023) [2312.00872]*



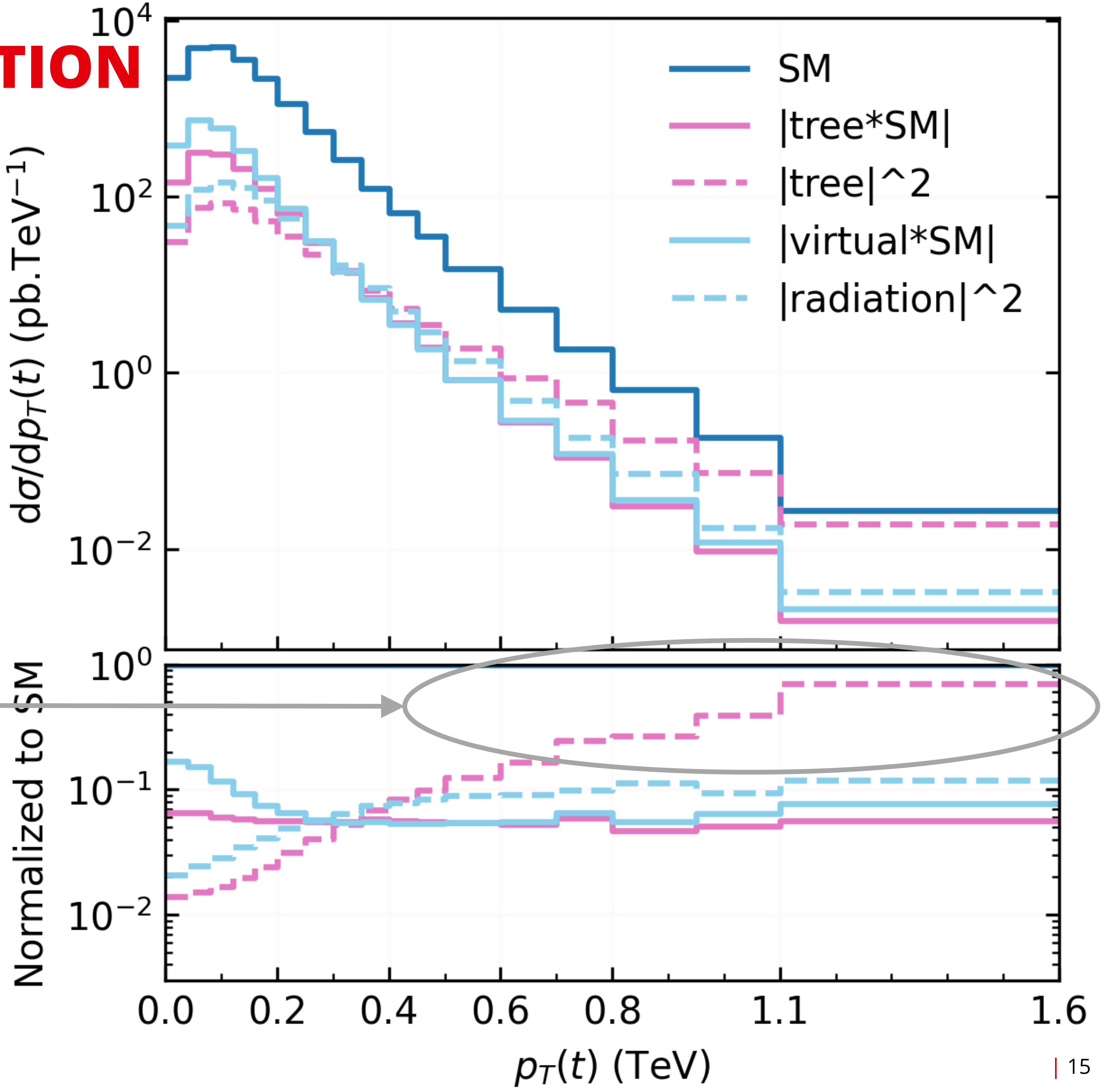
ALP EFFECTS IN p_T DISTRIBUTION

SM: *PRD 104 (2021) 092013*
***AVP**, Westhoff (2023) [2312.00872]*

Large energy enhancement

$$aG^A_{\mu\nu}\tilde{G}^{A,\mu\nu} \sim ap^2G^2_\mu \implies \sigma_{|\mathrm{ALP}|^2}(s) \sim \frac{1}{s}\frac{m_t^2 s}{f_a^4}$$

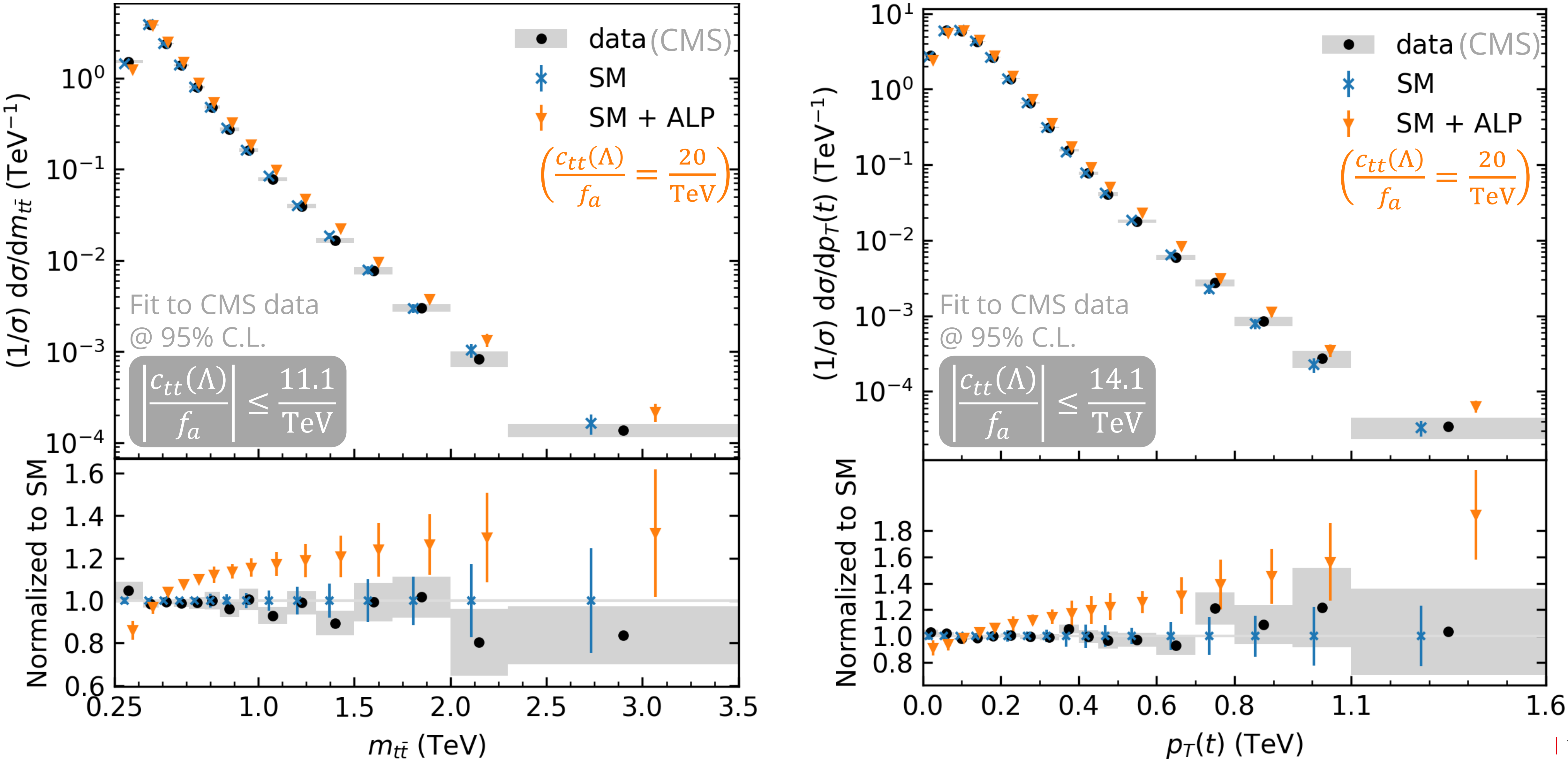
SM ALP



Data: *PRD 104 (2021) 092013*
***AVP**, Westhoff (2023) [2312.00872]*

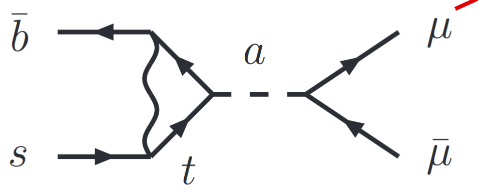
$c_{GG}(\Lambda) = 0\,; m_a = 10\ \text{GeV}$

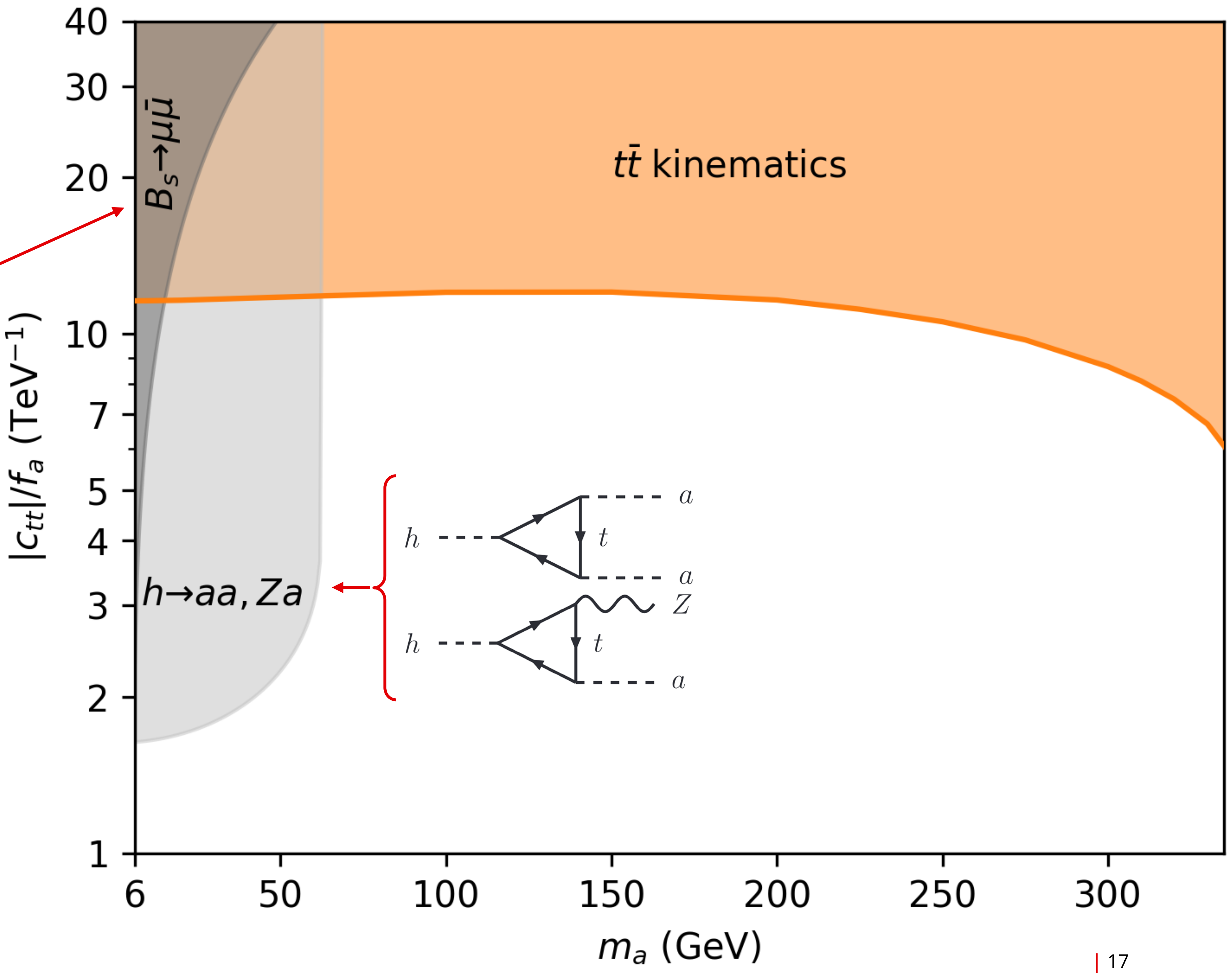
ALP theory uncertainty: 10%



BOUNDS ON c_{tt} FROM VIRTUAL TOP

$c_{GG}(\Lambda) = 0$





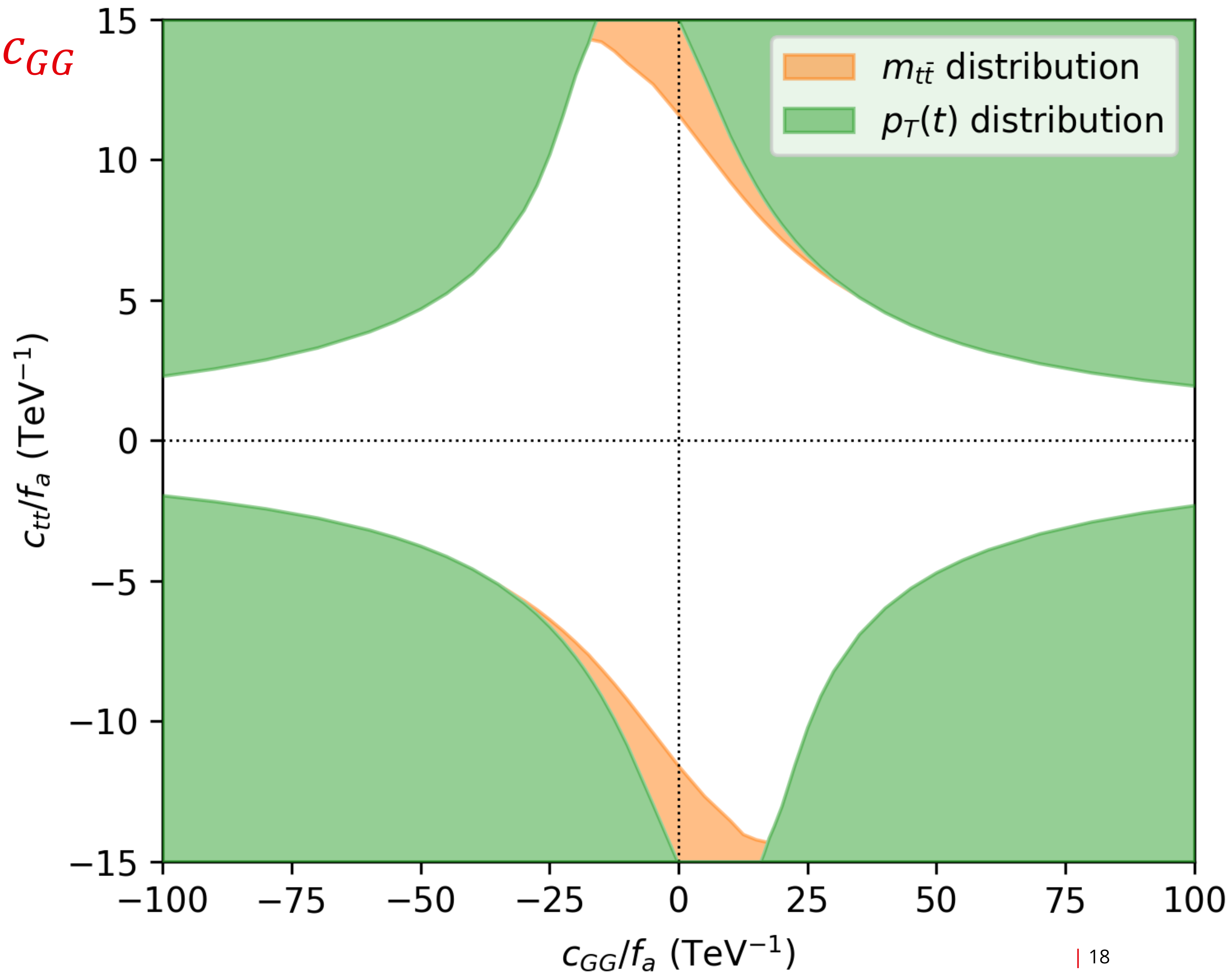
Shaded = excluded at 95% C.L.

__AVP__, Westhoff (2023) [2312.00872], Bauer et al. (2021) [2110.10698], CMS-BPH-21-006 [2212.10311], DESY-14-026 [1403.1582].

BOUNDS ON c_{tt} AND c_{GG}

AVP, Westhoff (2023) [2312.00872]

$m_a = 10$ GeV,
c_{GG}, c_{tt} vary



Conclusions

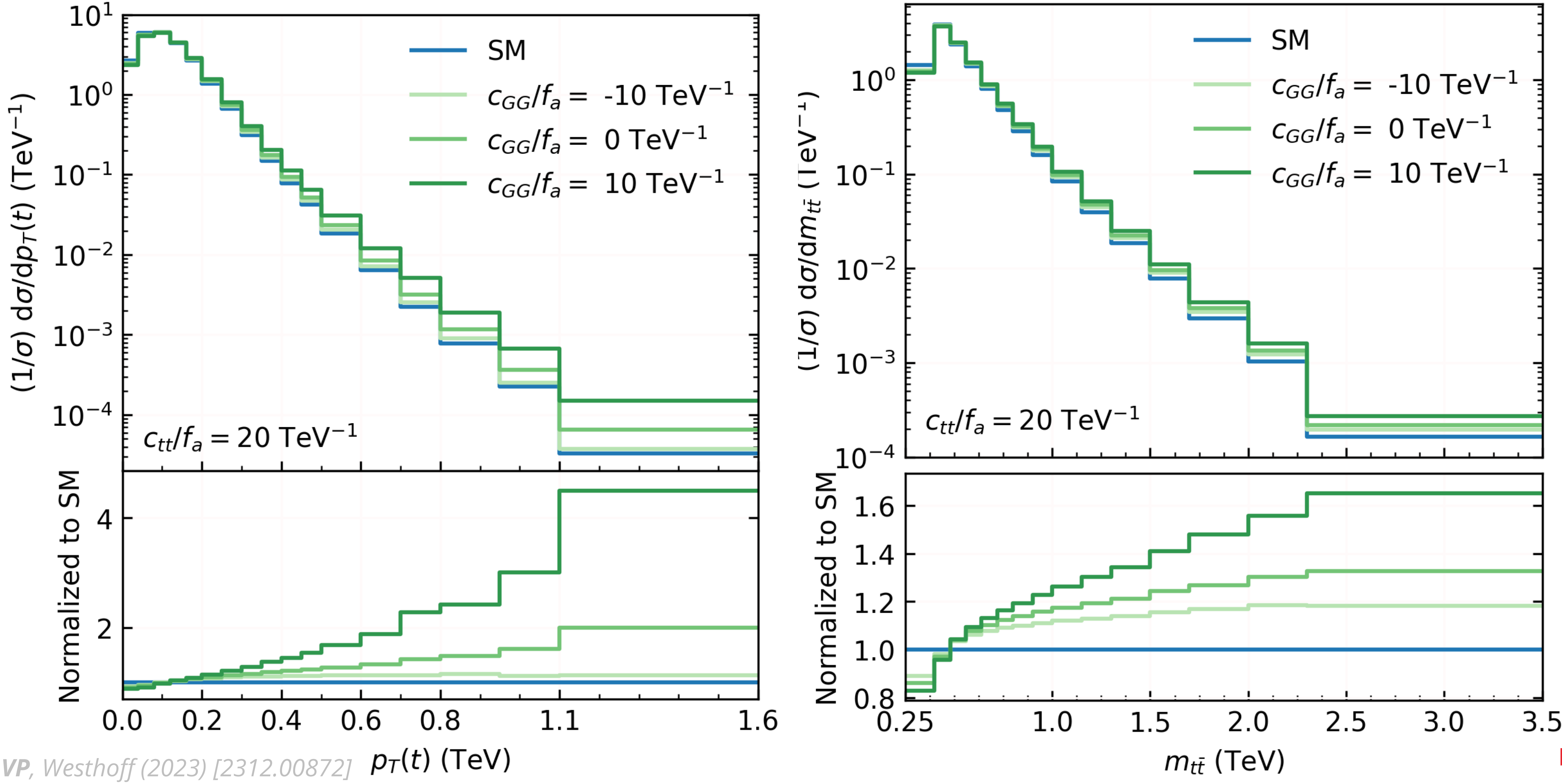
- Among the SM fermions, **top is most sensitive to ALPs**.
- Top **induces all other ALP couplings** ⇒ rich phenomenology.
- Inclusive $t\bar{t}$ measurements give mass-independent bound on ALP-top coupling.

Thank you for listening!

BACKUP SLIDES

$c_{GG}(\Lambda)$ DEPENDENCE

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\,; m_a = 10\ \text{GeV}$$



AVP, Westhoff (2023) [2312.00872]

RESULTS

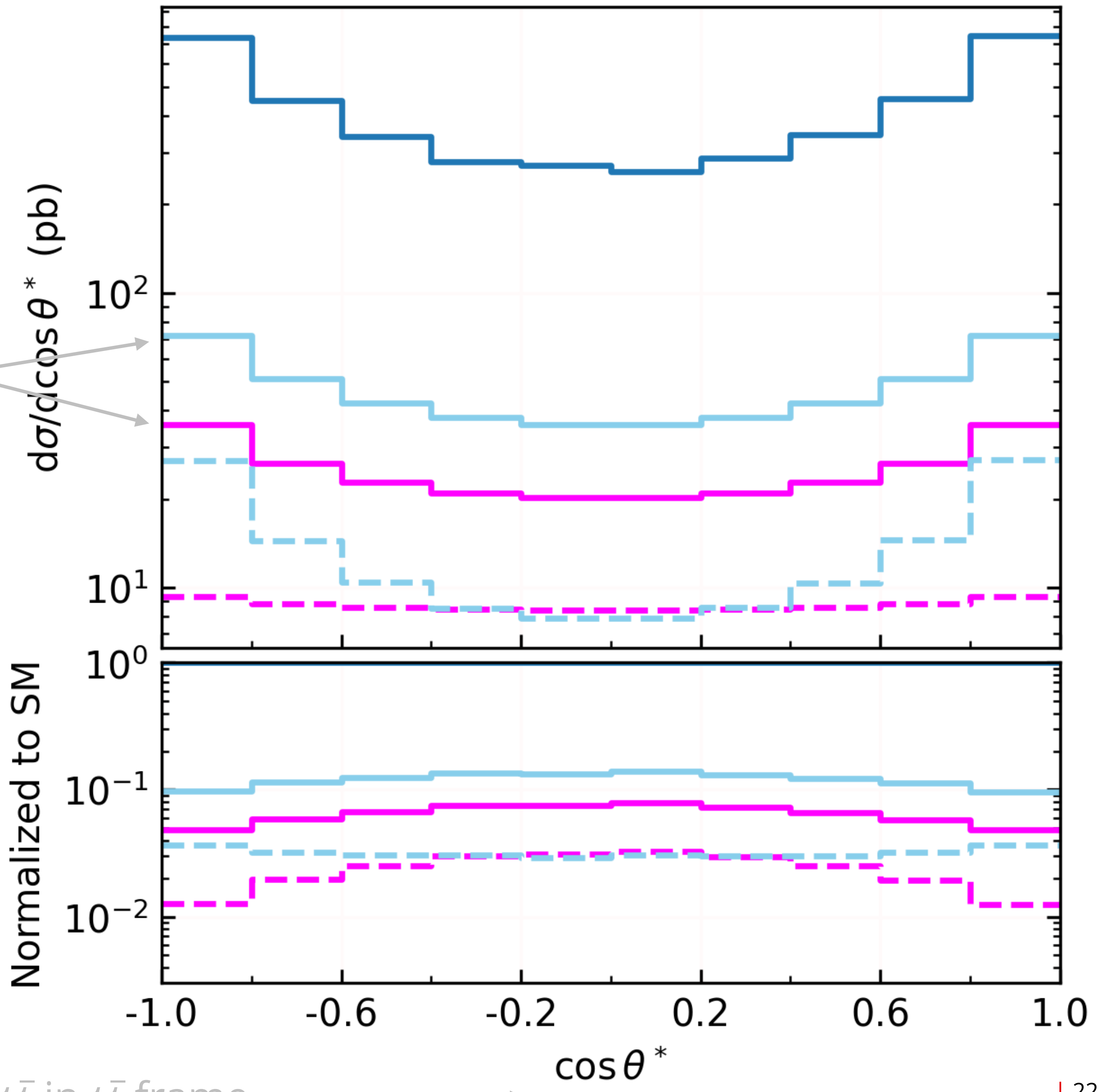
INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

Virtual ALP and tree-level interferences with SM are negative

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$

New Physics scale $\Lambda = 4\pi f_a$

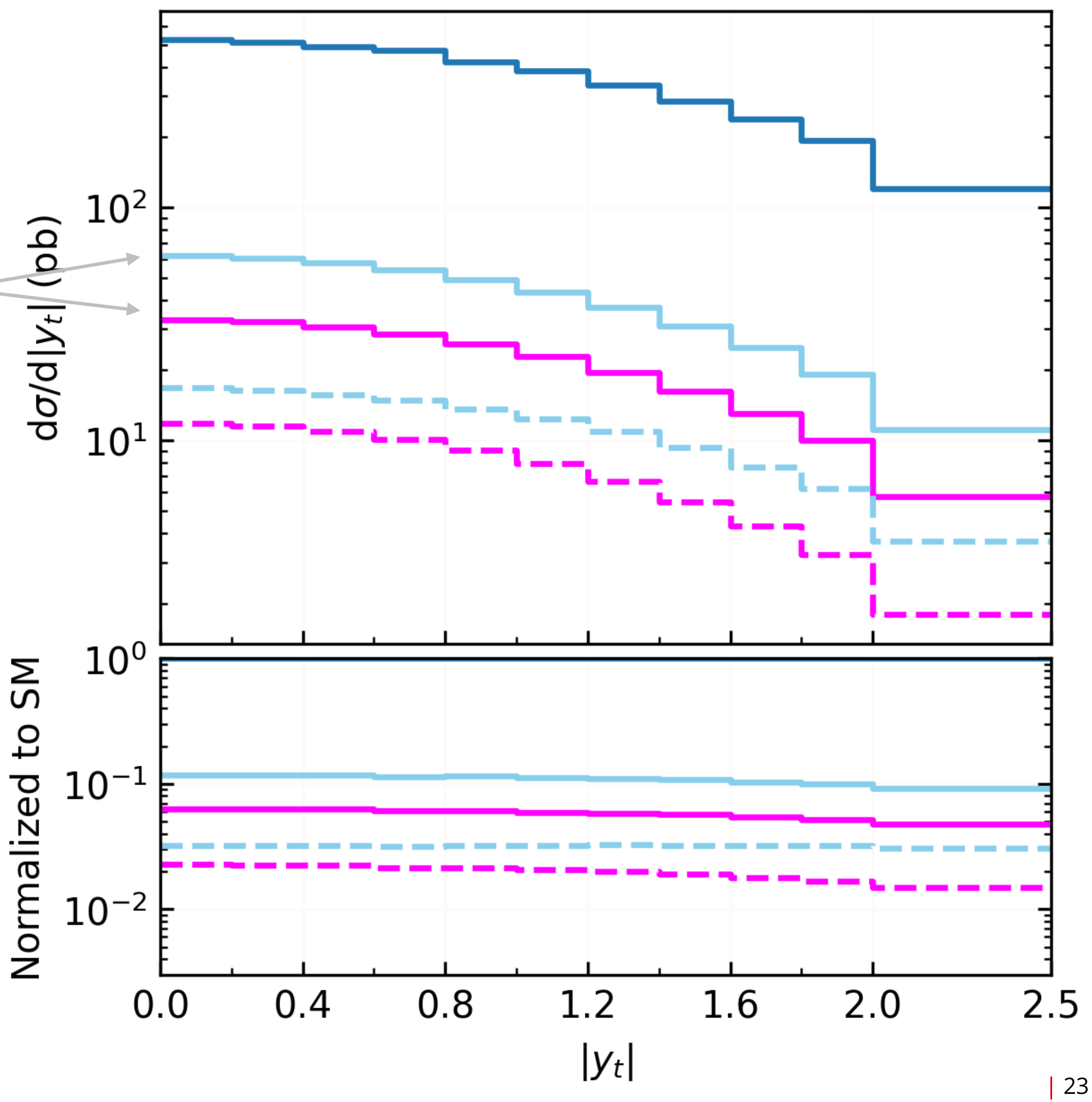


Angle between top and $t\bar{t}$ in $t\bar{t}$ frame

INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

Virtual ALP and tree-level interferences with SM are negative



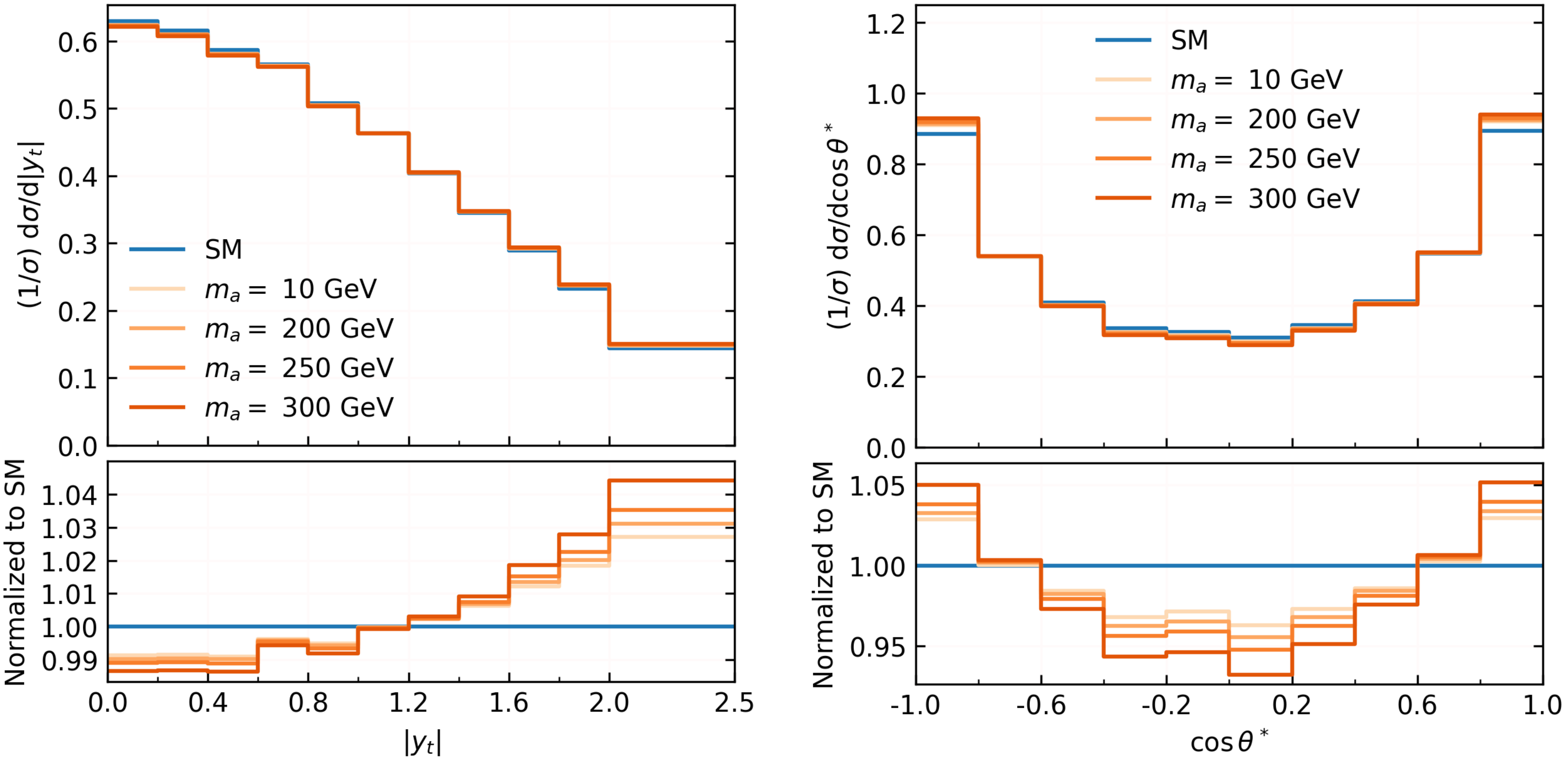
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\ ; c_{GG}(\Lambda) = 0\ ; m_a = 10\ \text{GeV}$$

New Physics scale $\Lambda = 4\pi f_a$

RESULTS

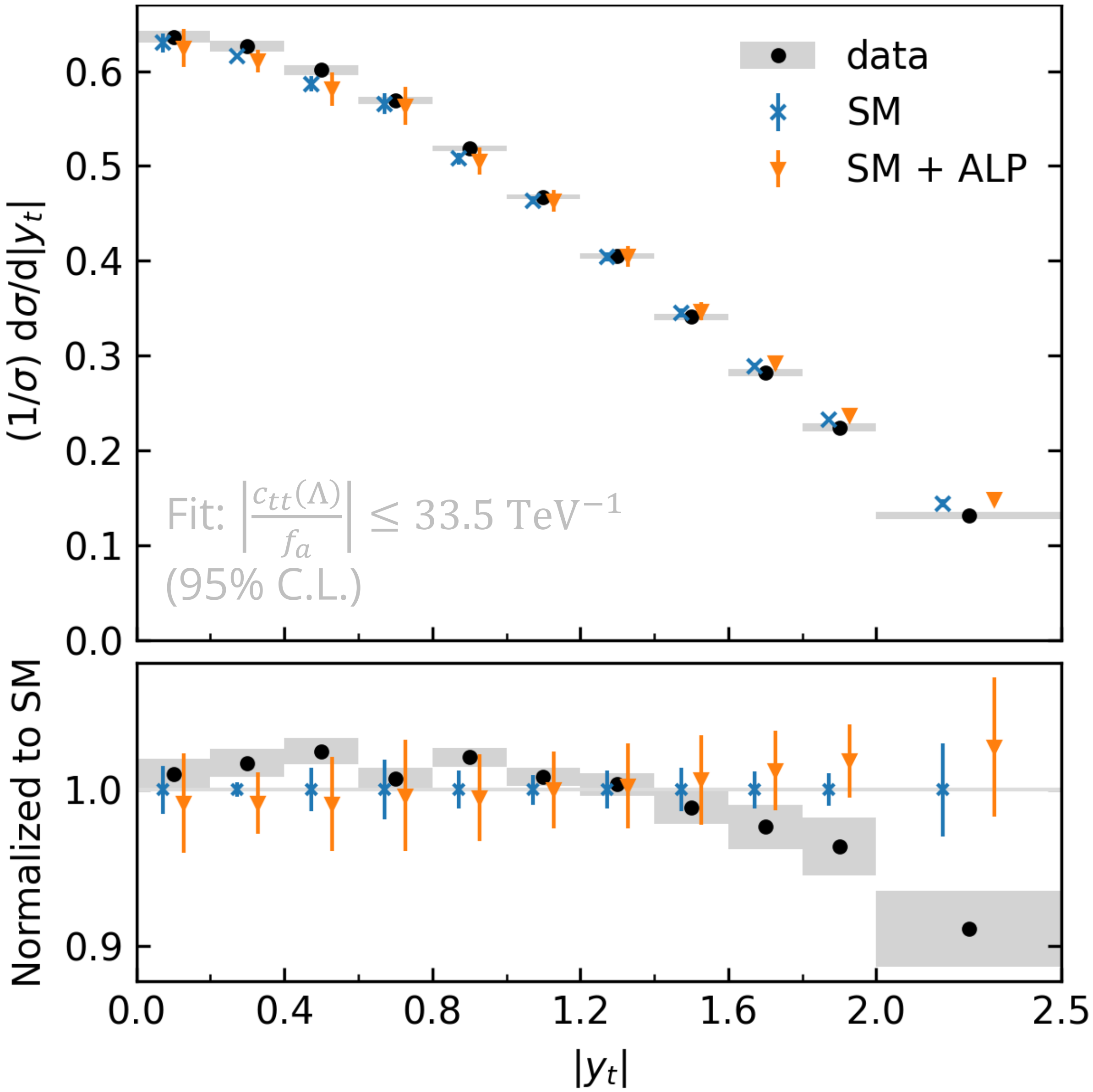
ALP MASS DEPENDENCE

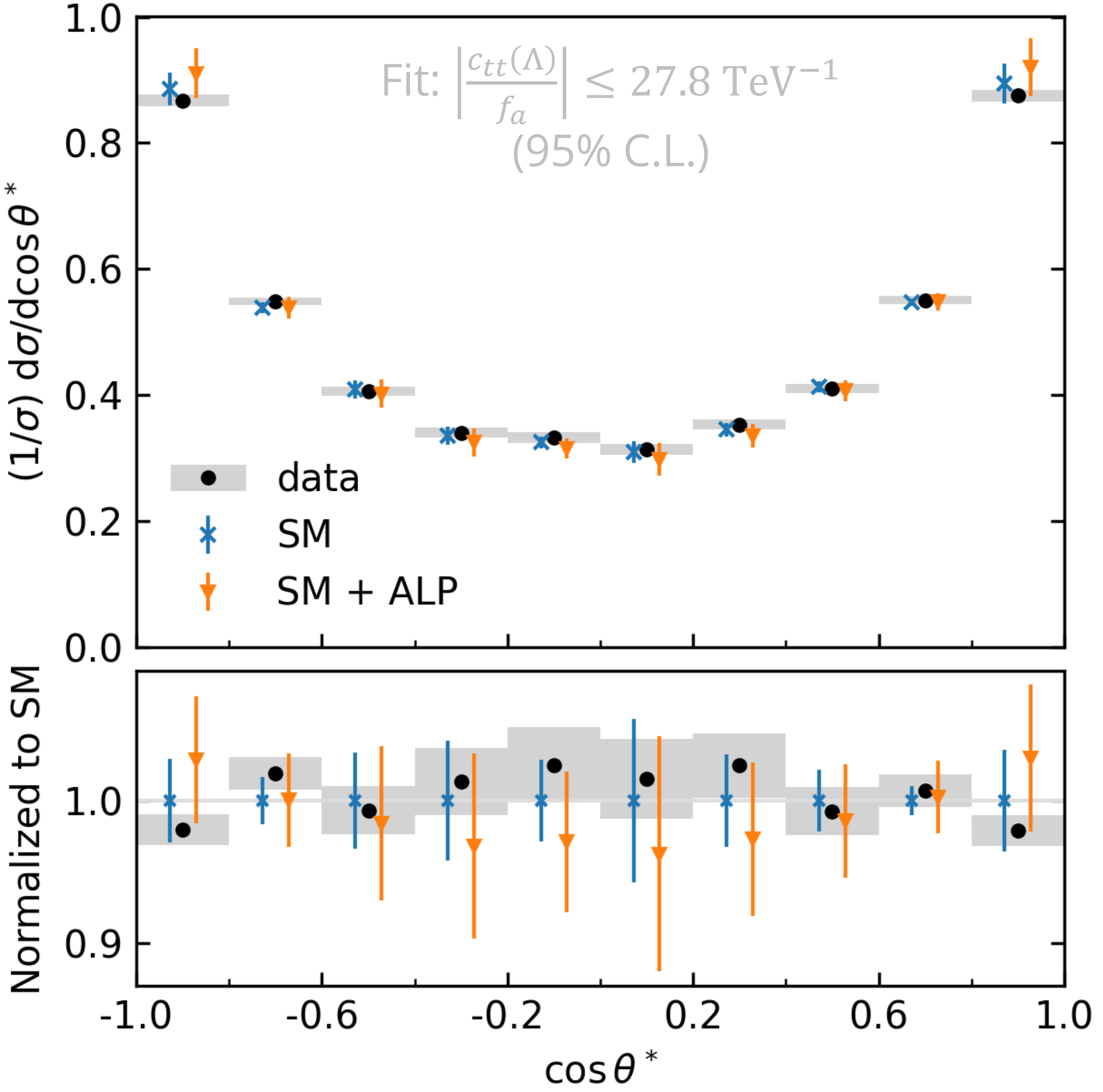
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0$$



Data: PRD 104 (2021) 092013
ALP uncertainty: 10%

$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \text{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \text{GeV}$$

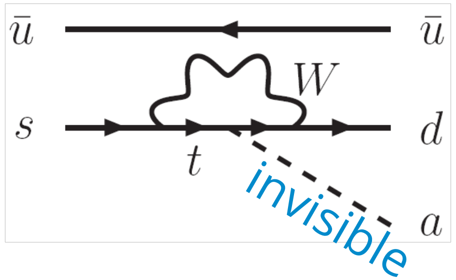


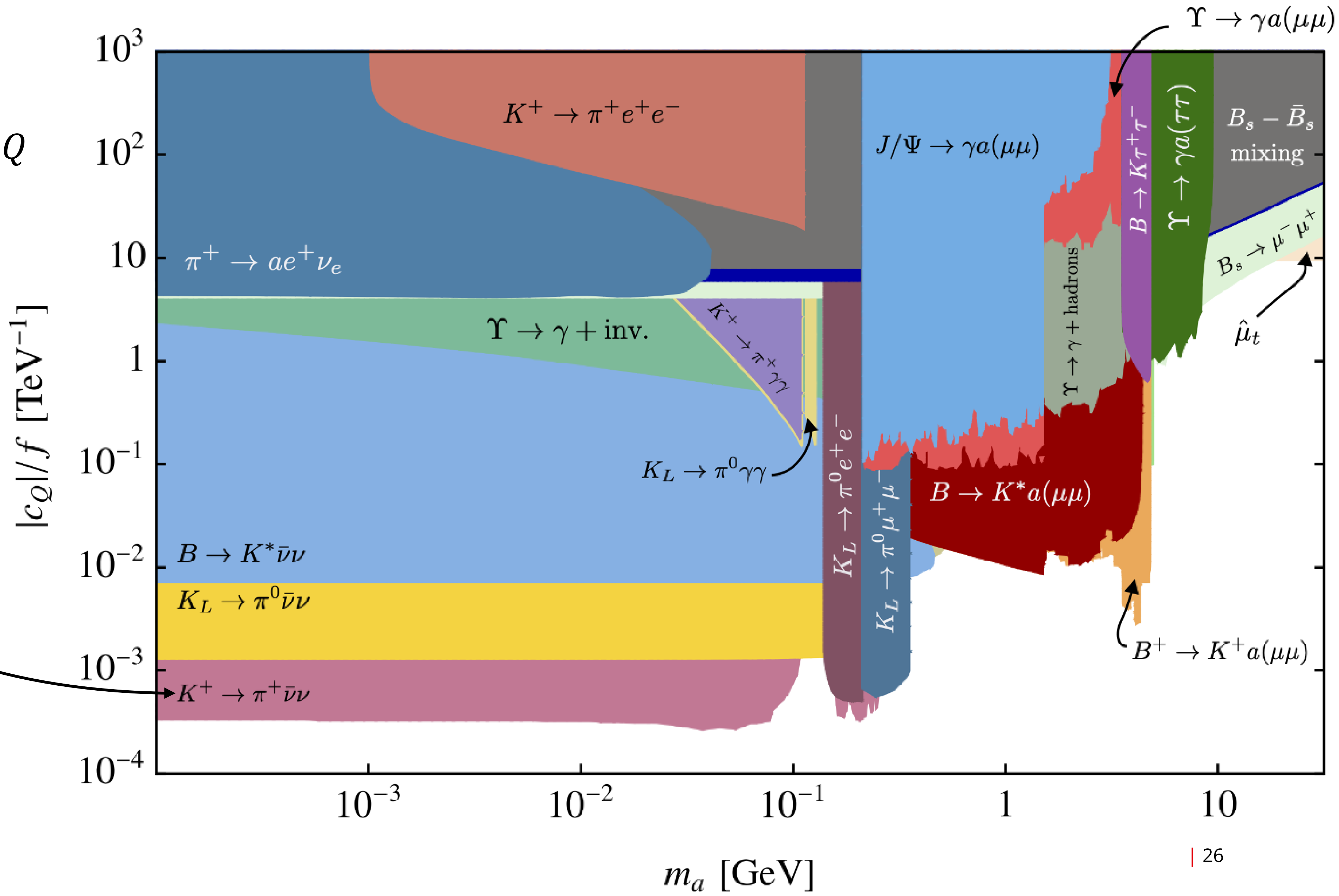


ALPS IN MESON DECAYS

Bauer et al. (2021) [2110.10698]

$$\mathcal{L}_{\text{eff}}(\mu) \supset -\frac{\partial^\mu a}{f_a}\bar{Q}\boldsymbol{c}_Q\gamma_\mu Q$$



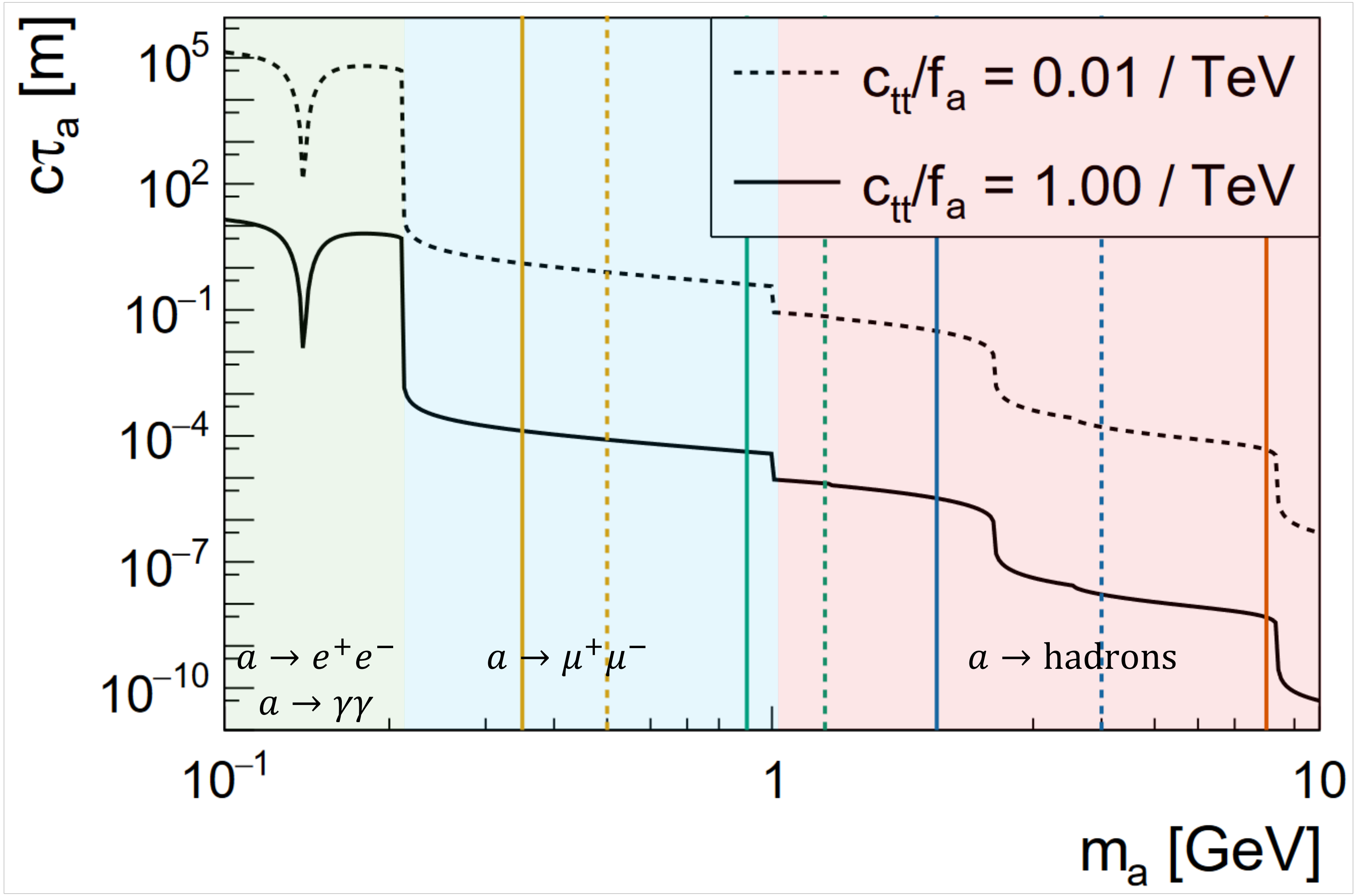


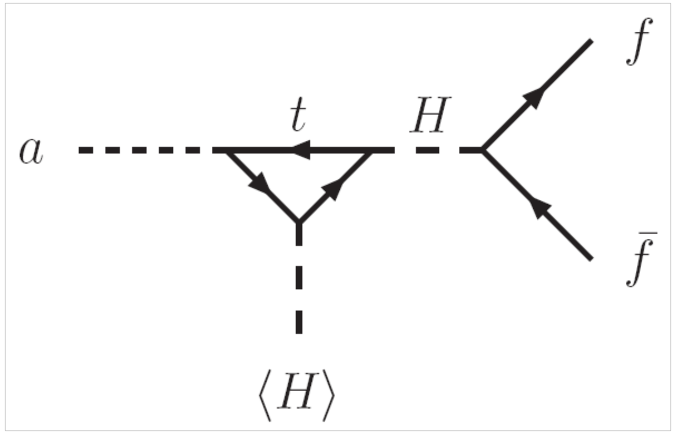
ALP's flavor changing couplings are turned off

ALPS LIFETIME

Rygaard et al. (2023) [2306.08686]

$c_{GG}(\Lambda) = 0, c_{ff\neq tt}(\Lambda) = 0$

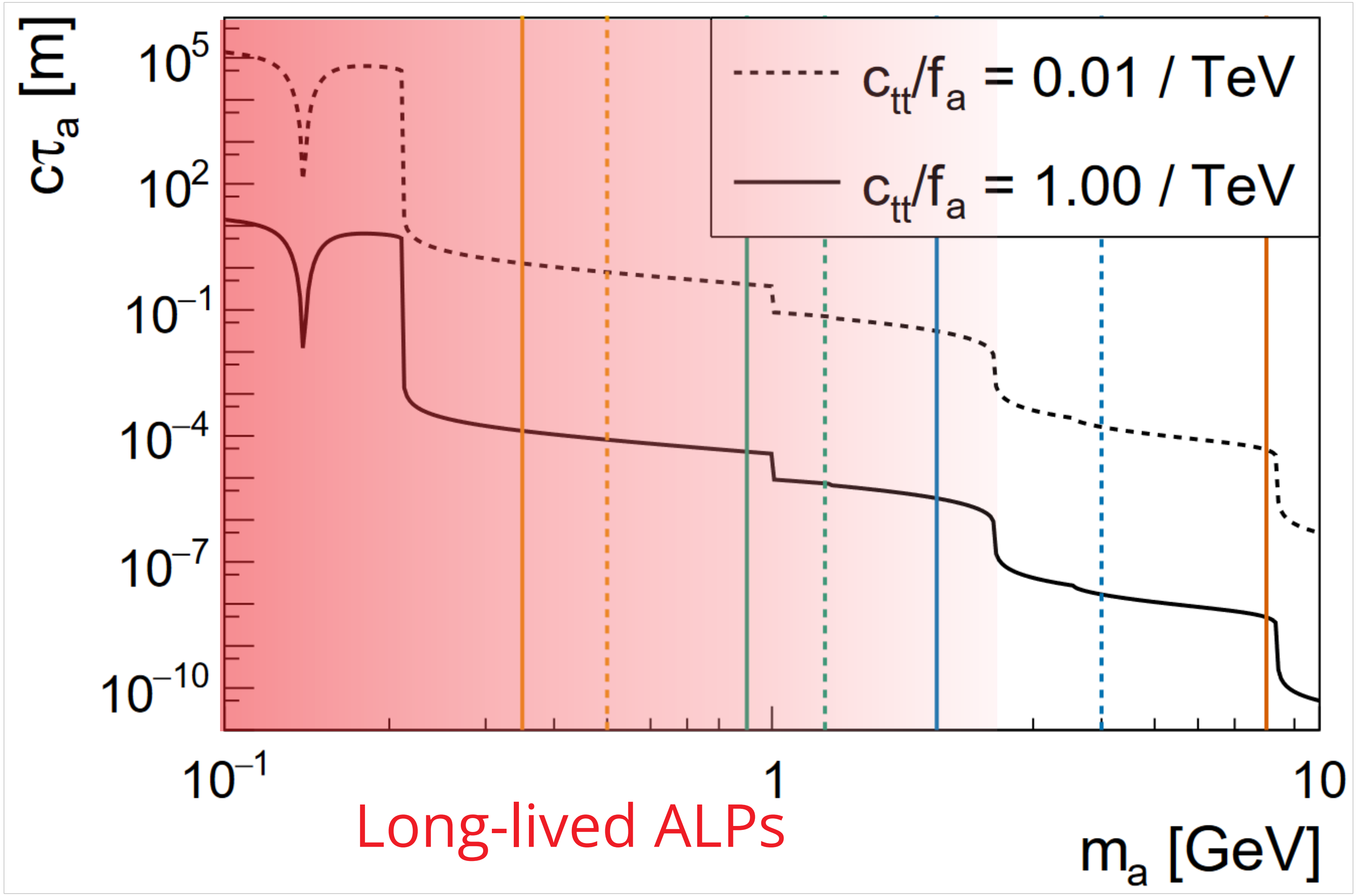




ALPS LIFETIME

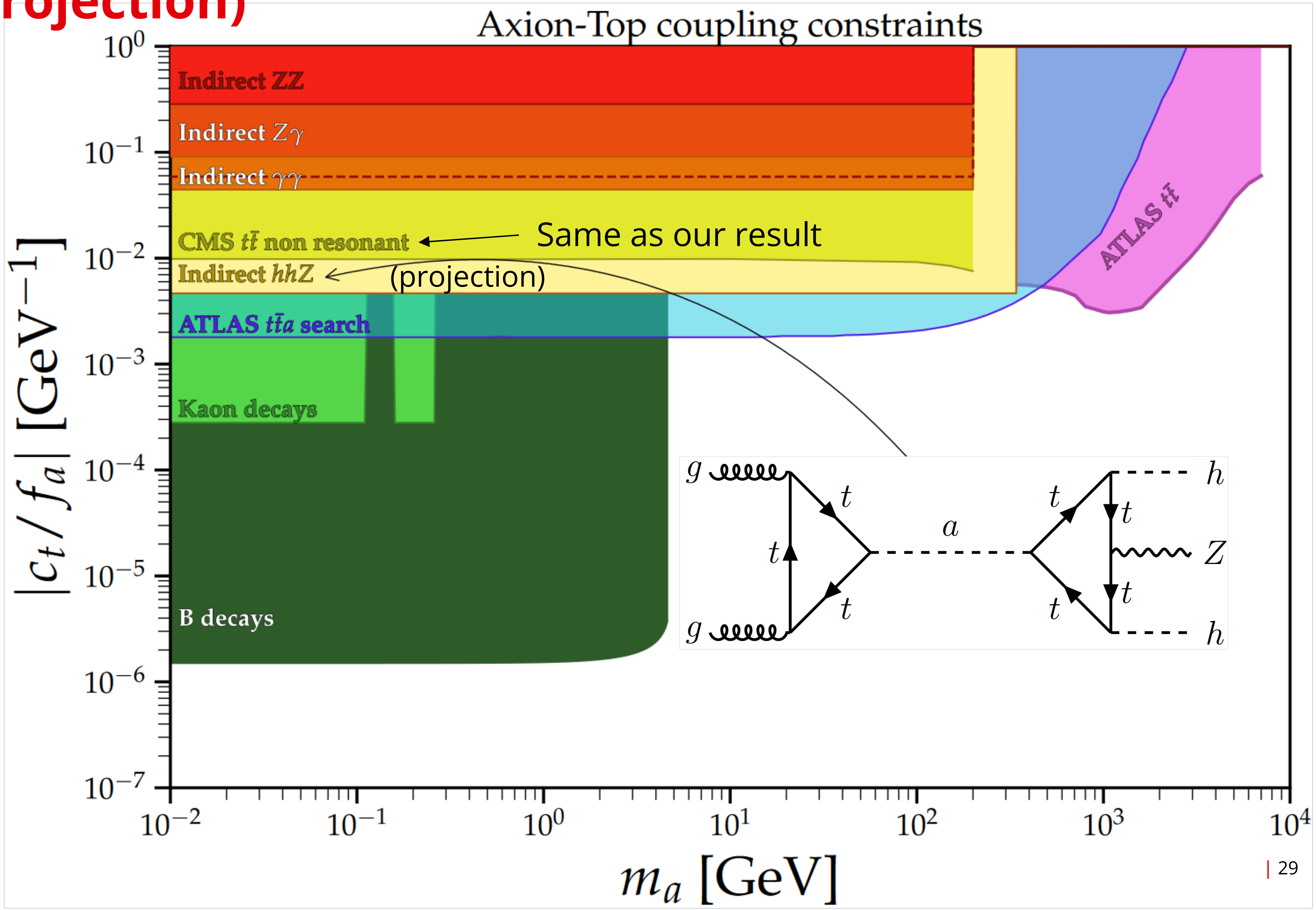
Rygaard et al. (2023) [2306.08686]

$c_{GG}(\Lambda) = 0, c_{ff\neq tt}(\Lambda) = 0$



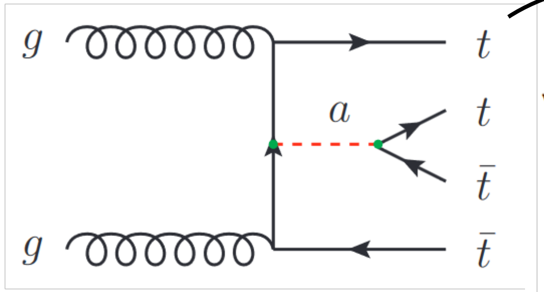
ALPS IN hhZ (projection)

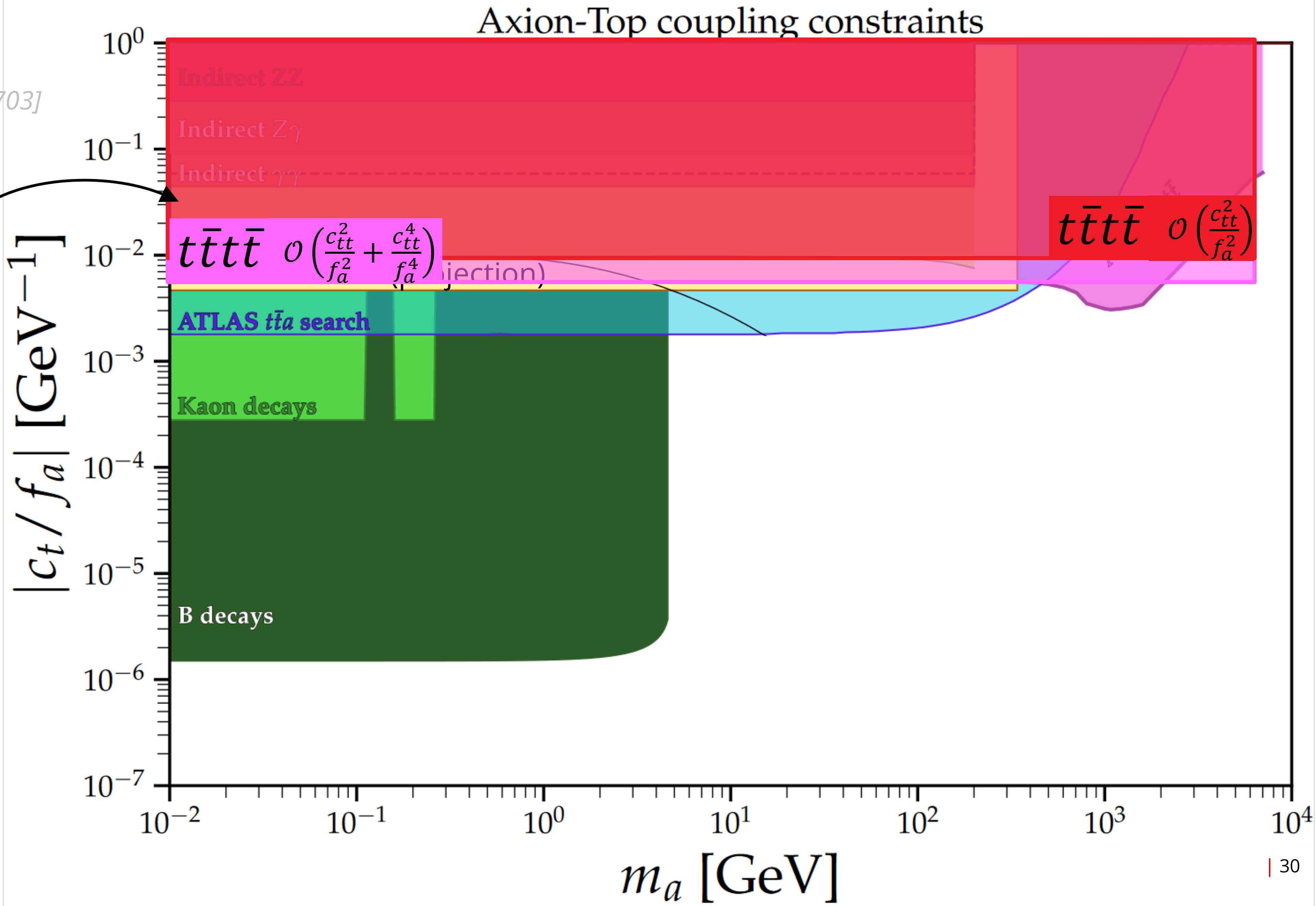
Esser et al. (2024) [2404.08062]



ALPS IN $t\bar{t}t\bar{t}$

Esser et al. (2024) [2404.08062],
Blasi et al. (2023) [2311.16048],
Bruggisser et al. (2024) [2308.11703]





RESONANCE SEARCHES

Anuar et al. (2024) [2404.19014]