Precise tests of the axion coupling to tops

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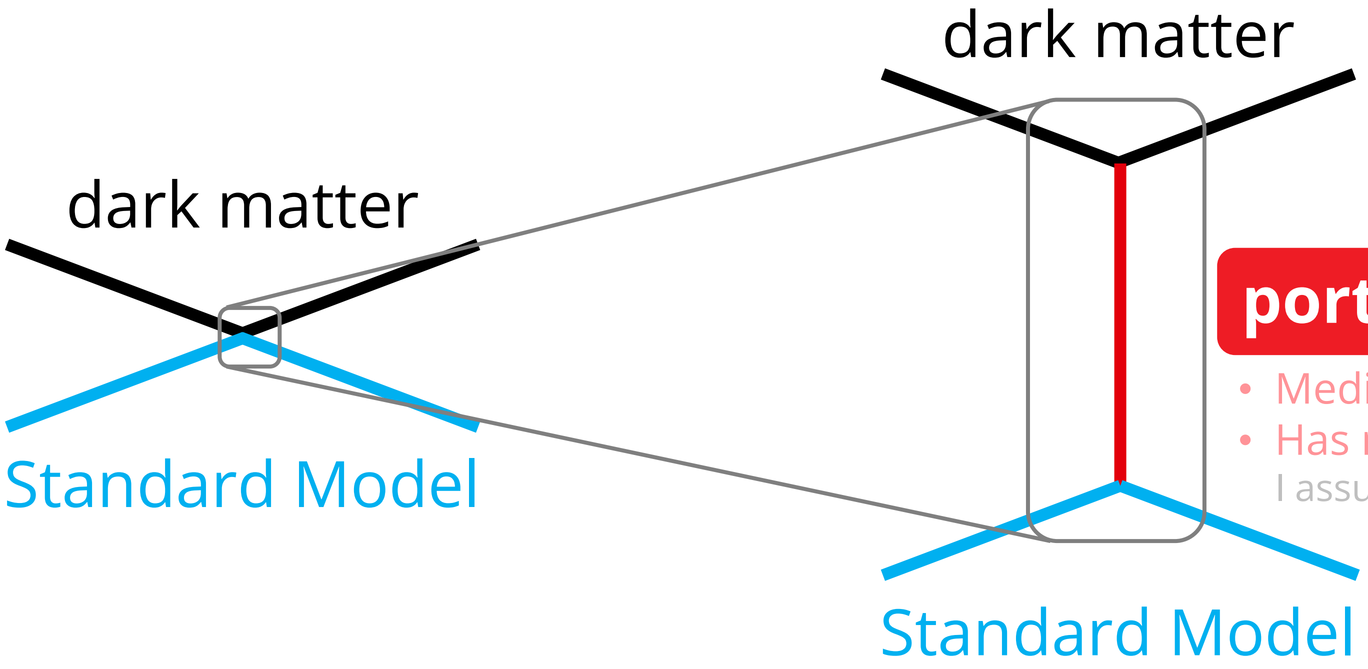
LDMA 2025, 09 April 2025

Radboud University

Nikhef

DARK MATTER DETECTION

For more on ALP-mediated dark matter:
Buttazzo, Panci, Teresi, Ziegler (2020) [2011.08919]
Fitzpatrick, Hochberg, Kuflik, Ovadia, Soreq (2023) [2306.03128]
Dror, Gori, Munbodh (2023) [2306.03145]



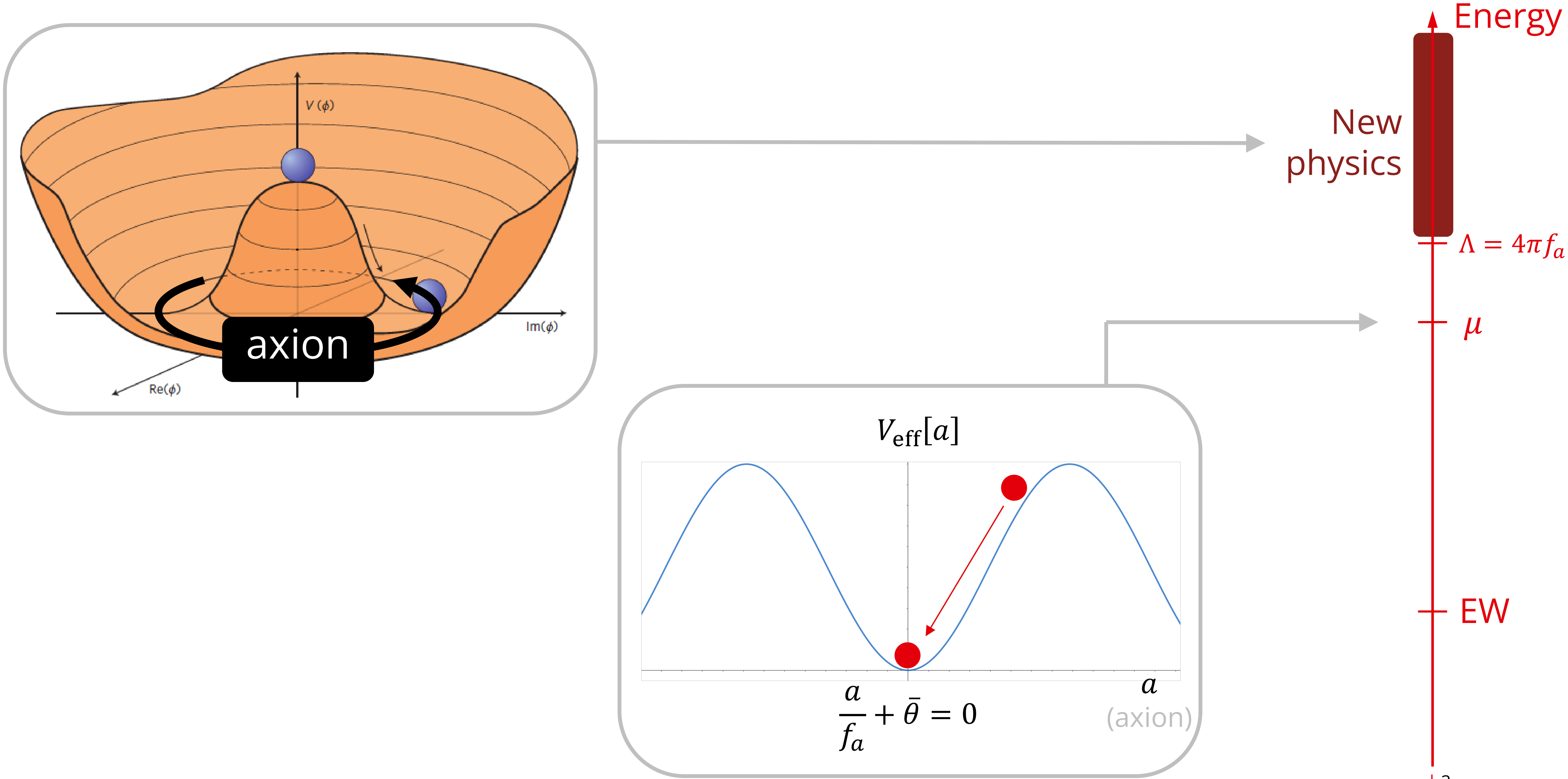
portal

- Mediator between DM and SM
- Has no SM charge

I assume $m_a < 2m_{\rm DM}$ throughout the talk

Georgi, Kaplan, Randall (1986)

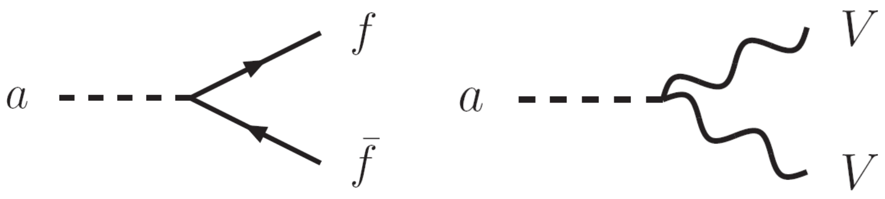
AXION-LIKE PARTICLE (ALP) EFFECTIVE THEORY



Georgi, Kaplan, Randall (1986)

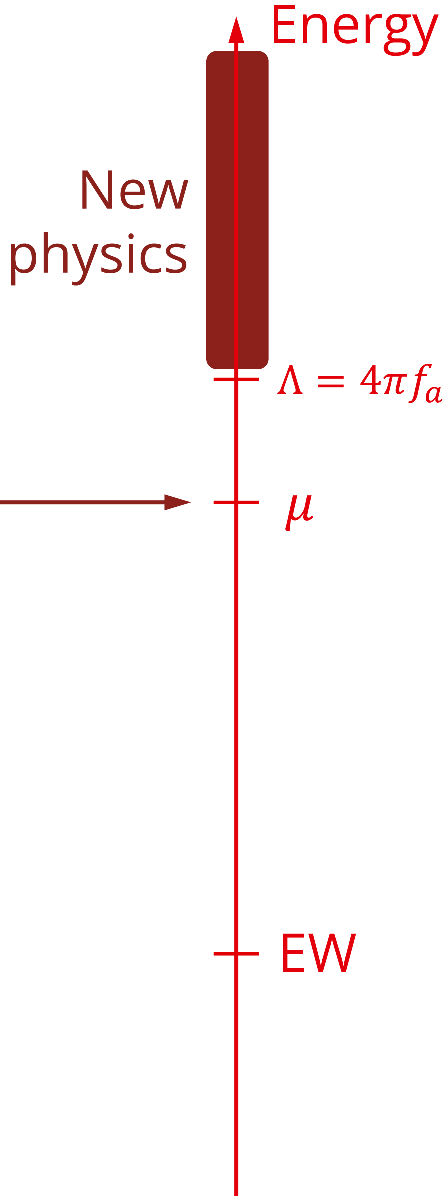
ALP EFFECTIVE THEORY

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



breaks
$a \to a + c$

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



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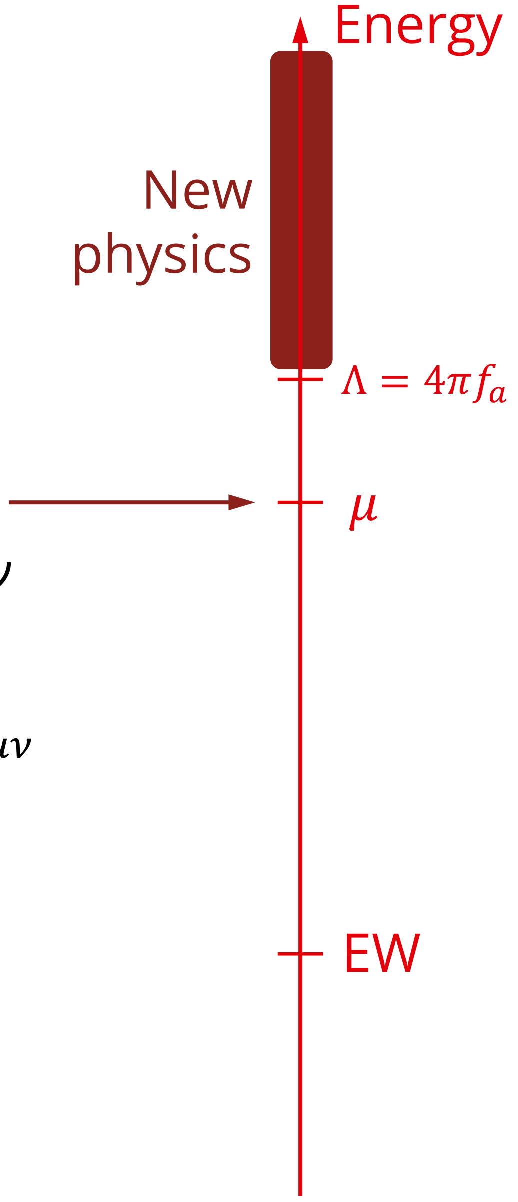
$$- \sum_f m_f c_{ff} \frac{a}{f_a} \bar{f} i \gamma^5 f + \frac{a}{f_a} \sum_V \tilde{c}_{VV} \frac{\alpha_V}{4\pi} V_{\mu\nu}^A \tilde{V}^{A,\mu\nu}$$



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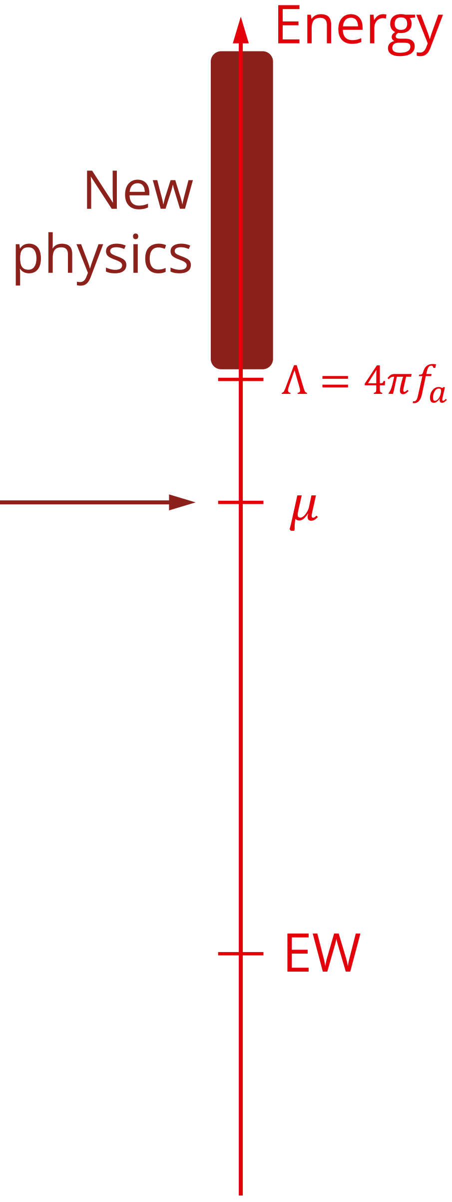
$$-\sum_f m_f c_{ff}\frac{a}{f_a}\bar{f} i\gamma^5 f + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$

top is most sensitive to ALP!



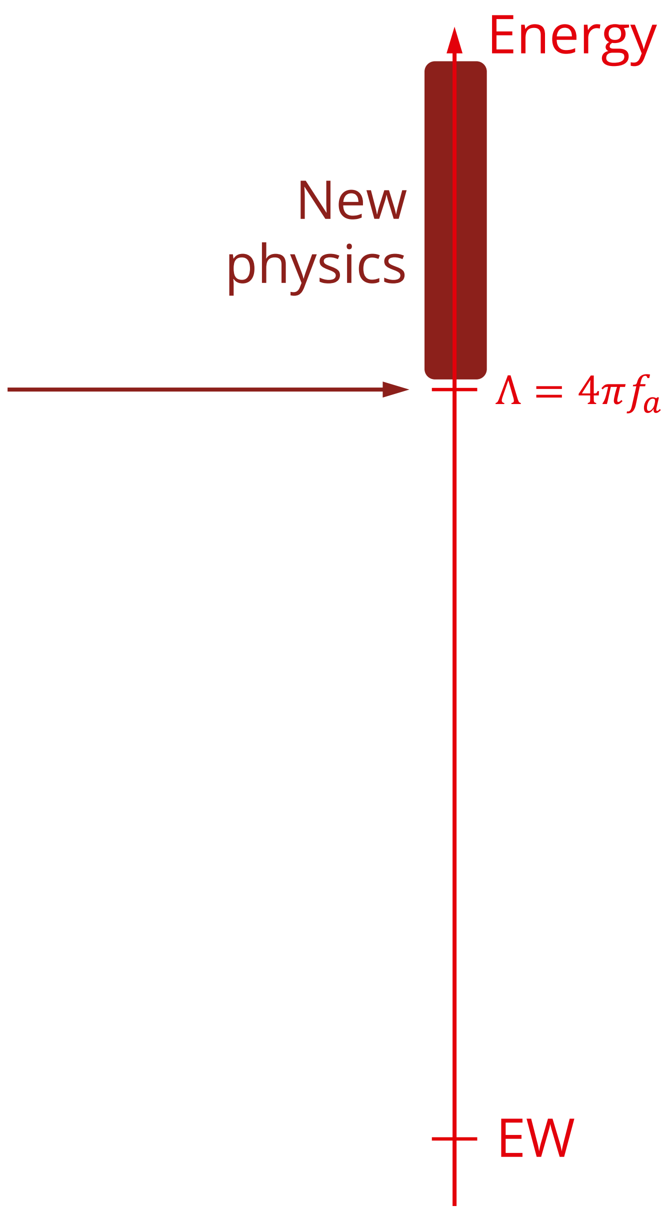
Bauer et al. (2021) [2012.12272]

TOP-INDUCED EFFECTIVE COUPLINGS

- Tops can induce other couplings via loop corrections

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

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



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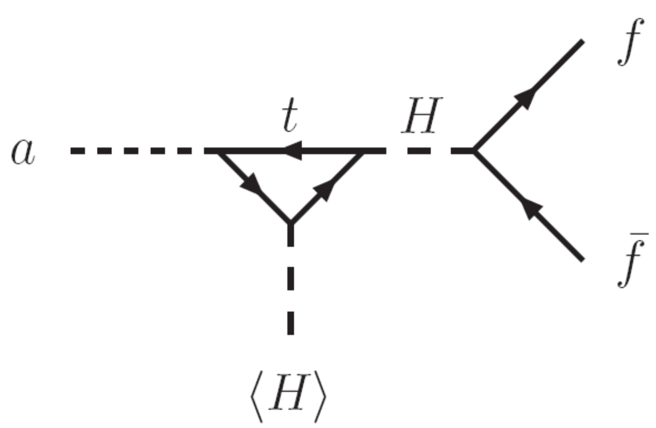

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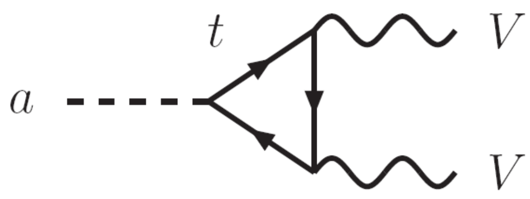

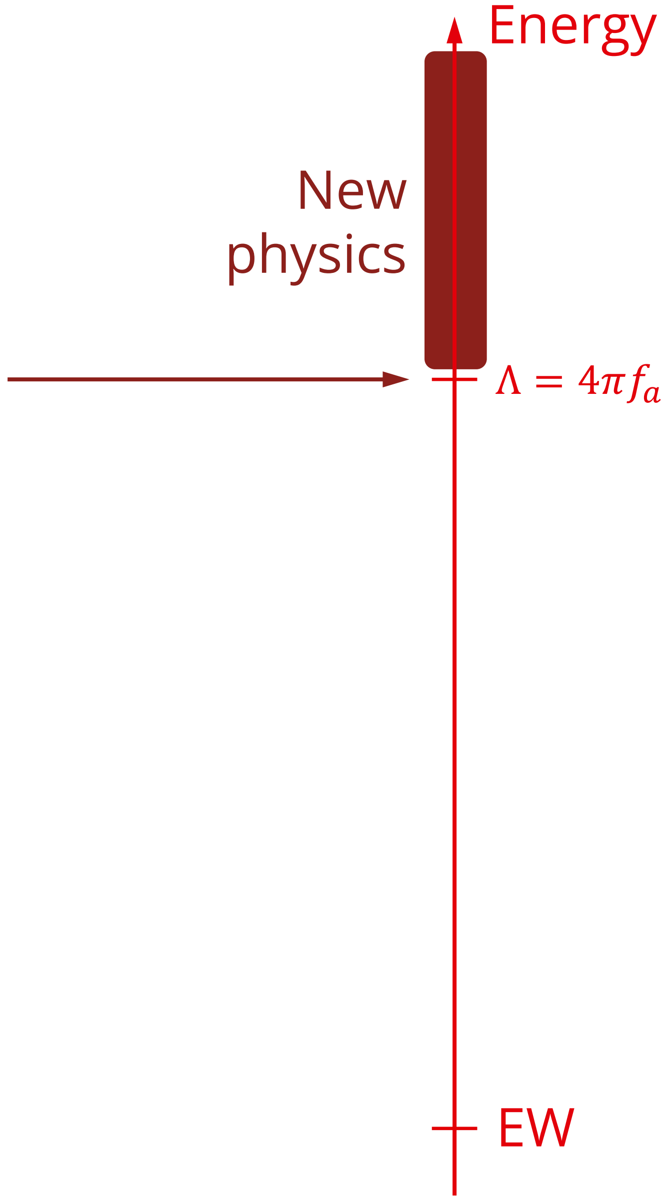

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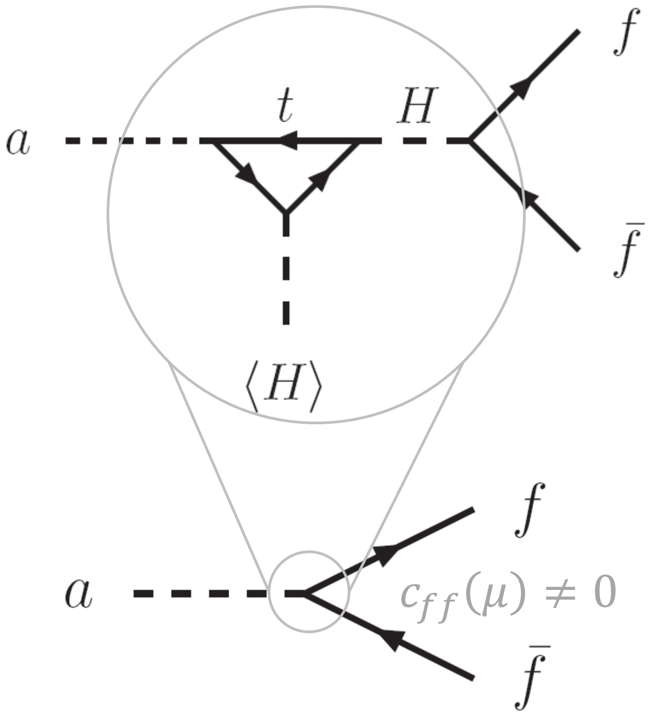
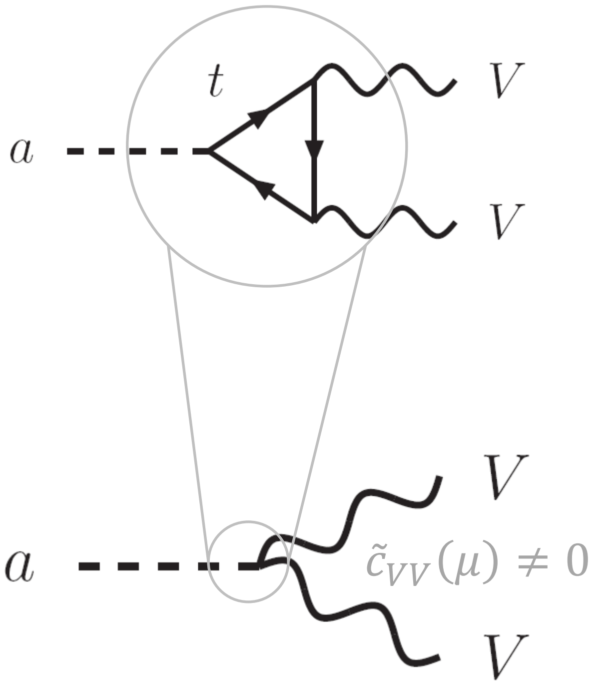
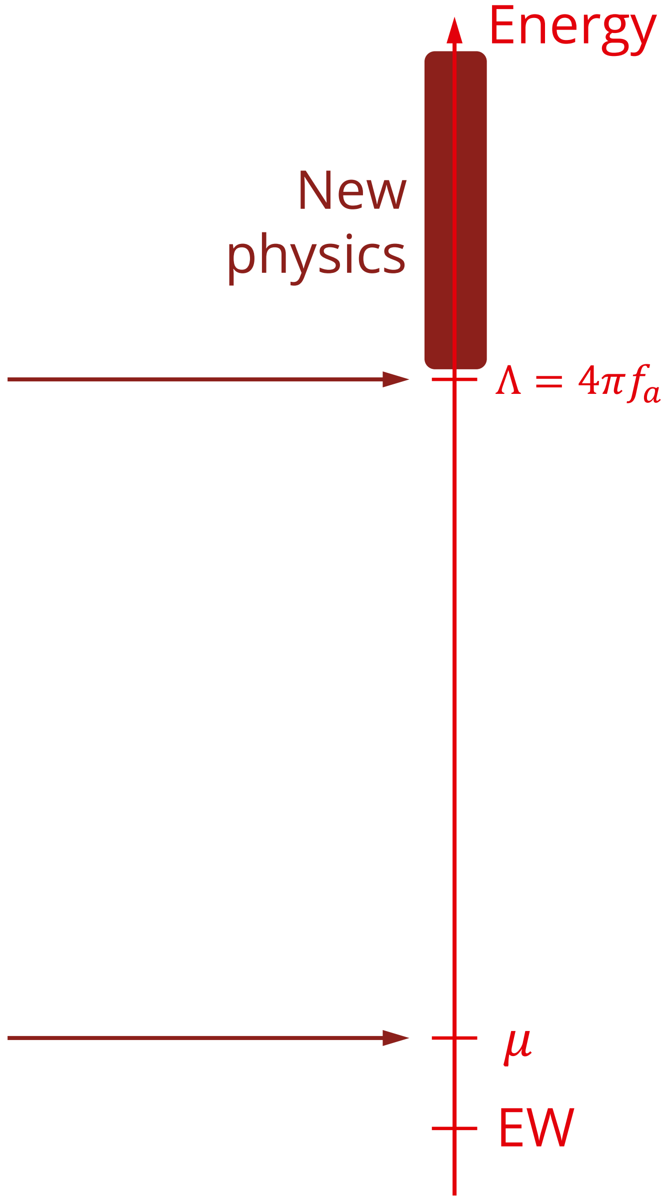


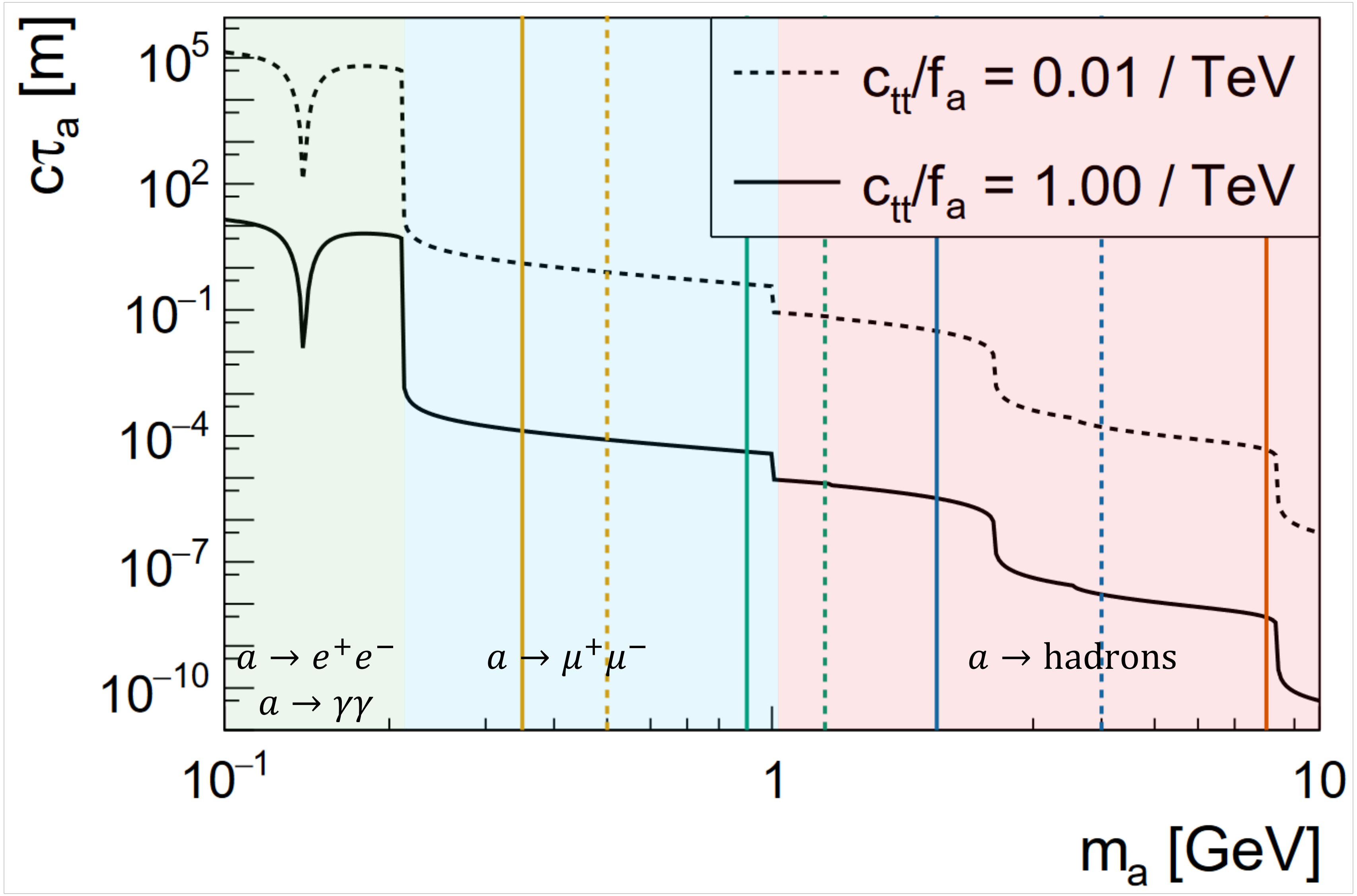


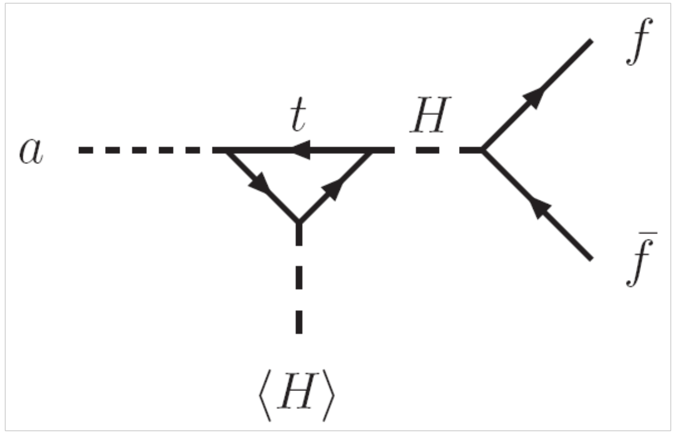


ALP LIFETIME

Rygaard et al. (2023) [2306.08686]

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





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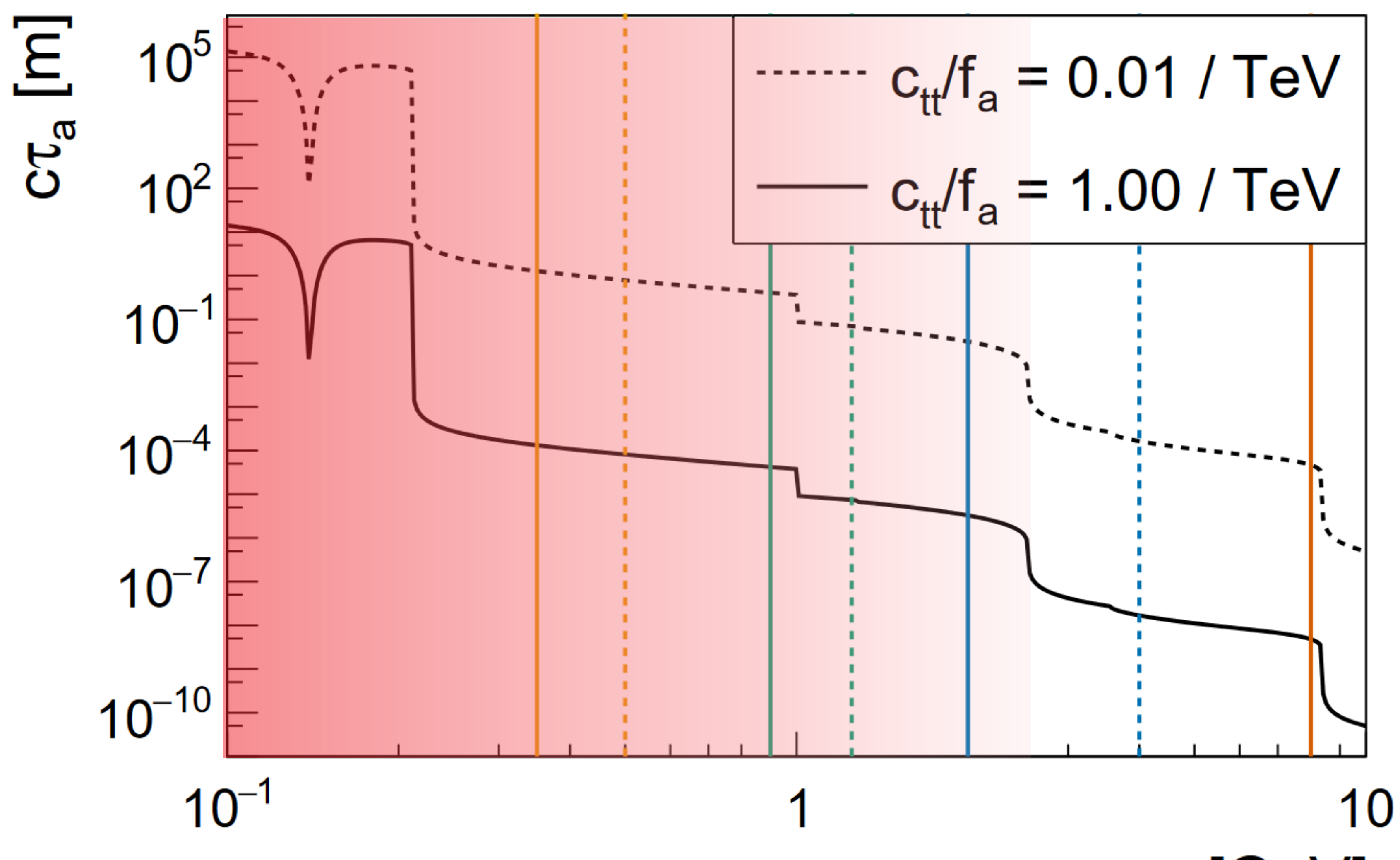
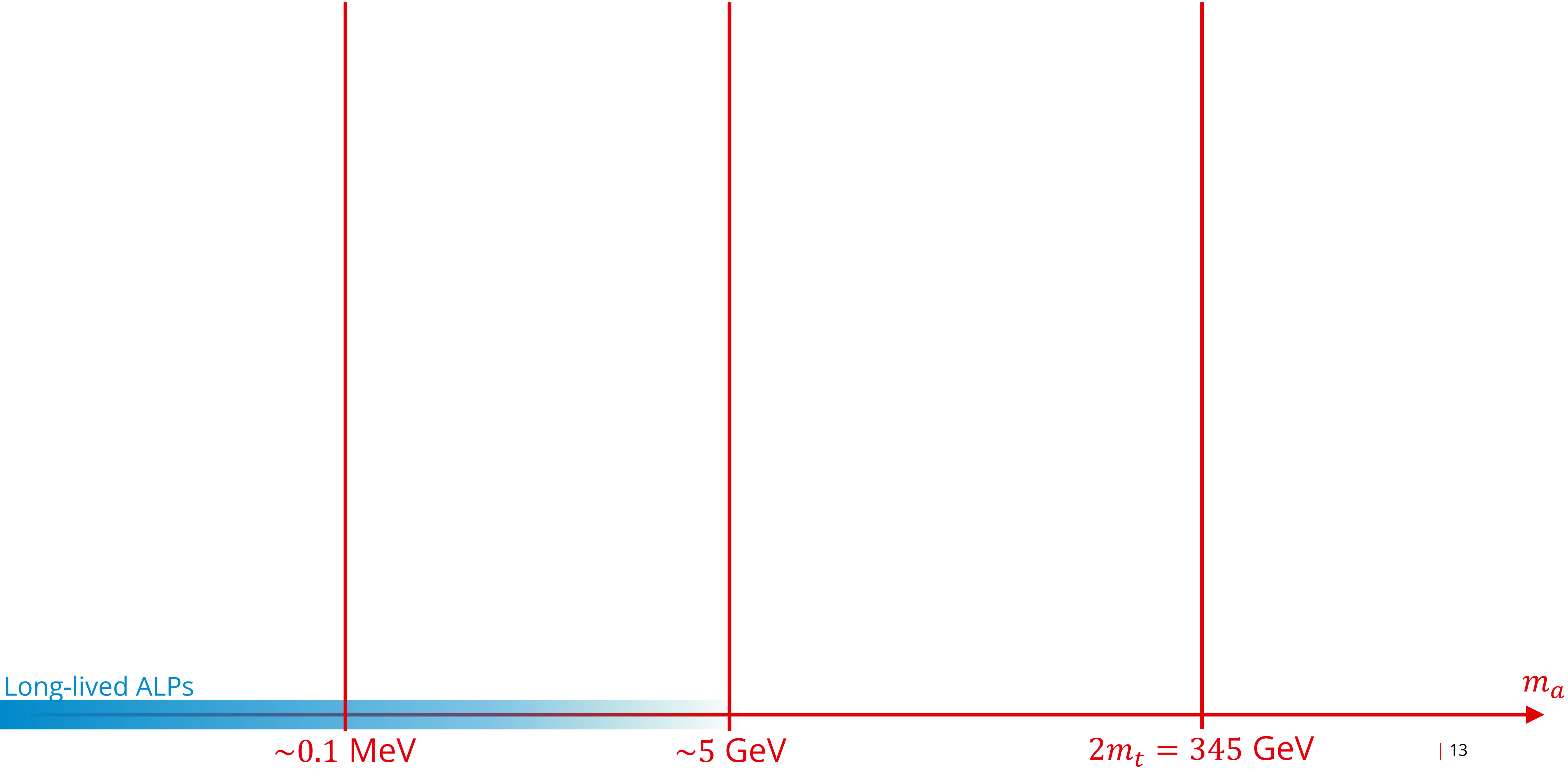


Long-lived ALPs

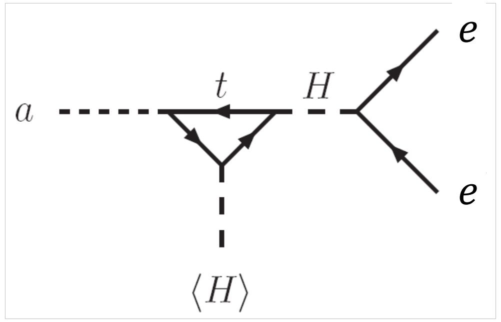
HOW TO PROBE ALP-TOP INTERACTION?



HOW TO PROBE ALP-TOP INTERACTION?

Astrophysics

ALP-electron



Bonilla et al. (2021) [2107.11392]

Long-lived ALPs

m_a

~0.1 MeV

~5 GeV

$2m_t = 345$ GeV

STELLAR ALPS

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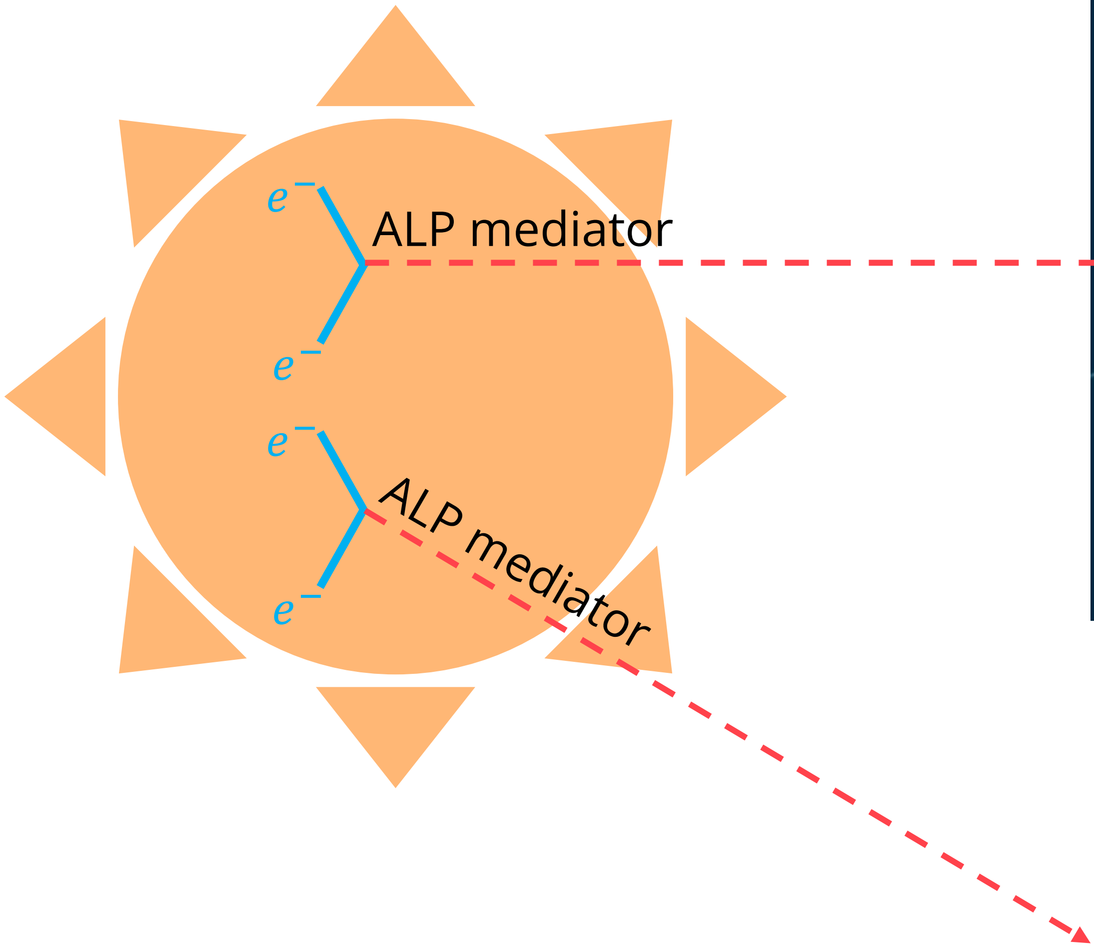
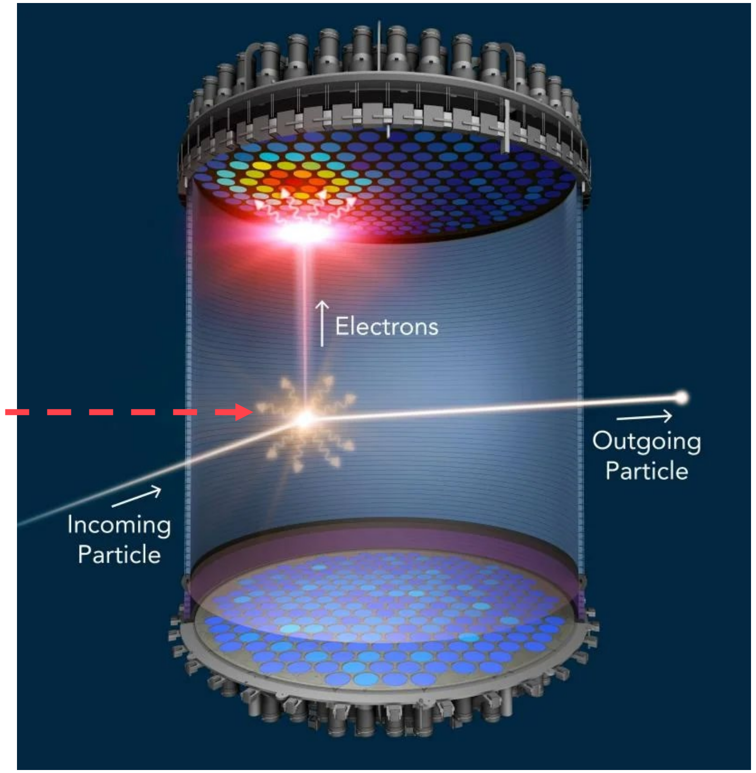


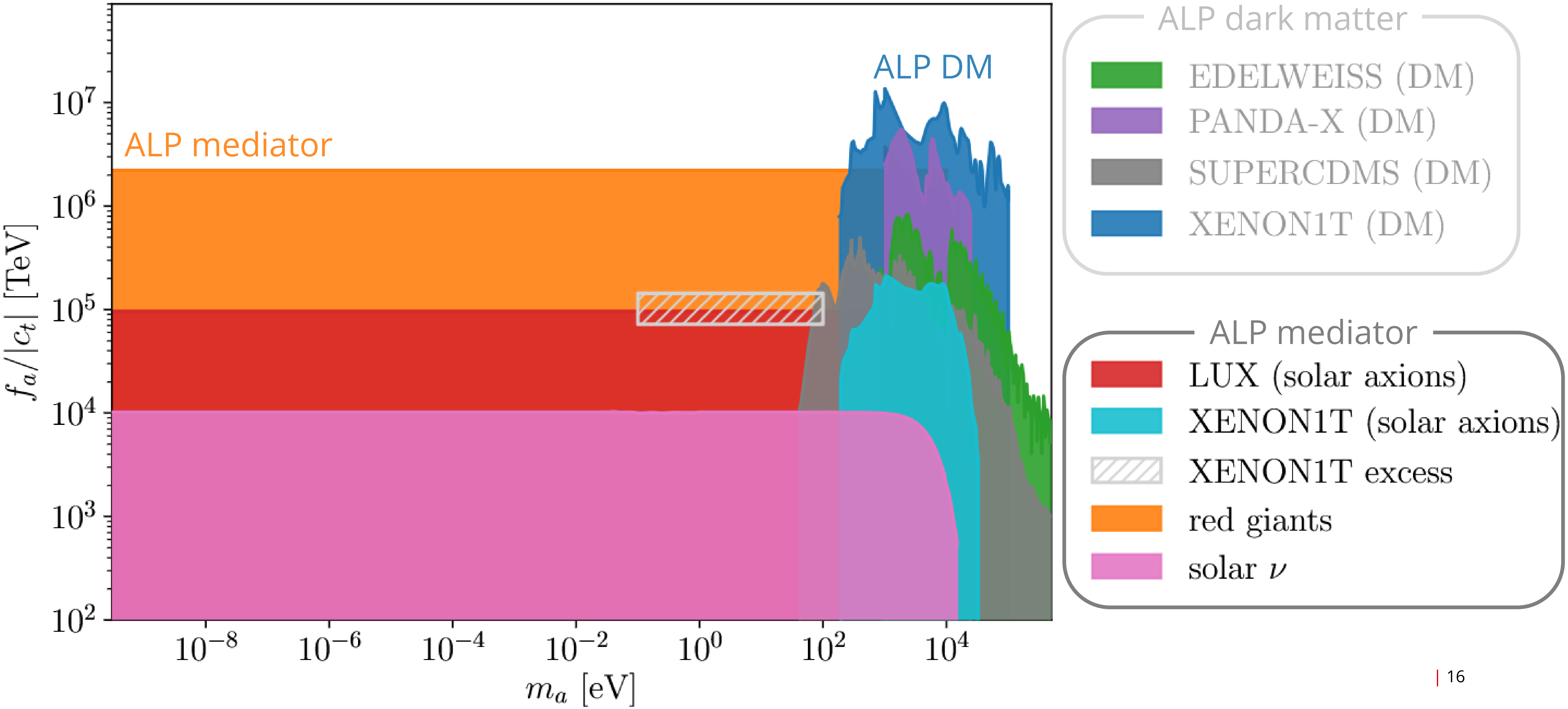
LZ experiment



Change solar luminosity

STELLAR ALPS

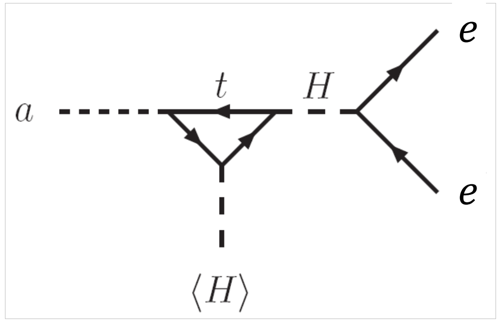
Bonilla et al. (2021) [2107.11392]



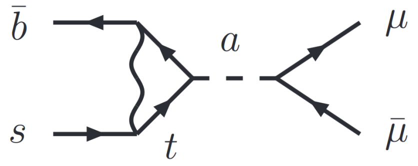
HOW TO PROBE ALP-TOP INTERACTION?

Astrophysics | **In meson decays**

ALP-electron



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



$K \to \pi + \mathrm{inv}$
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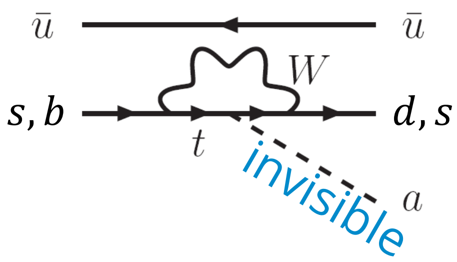

Bonilla et al. (2021) [2107.11392]

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

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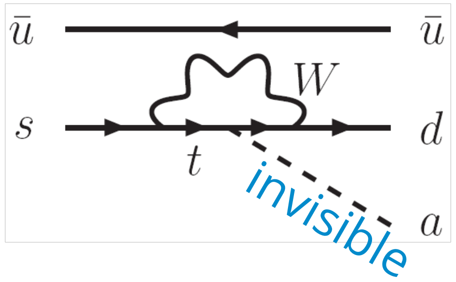
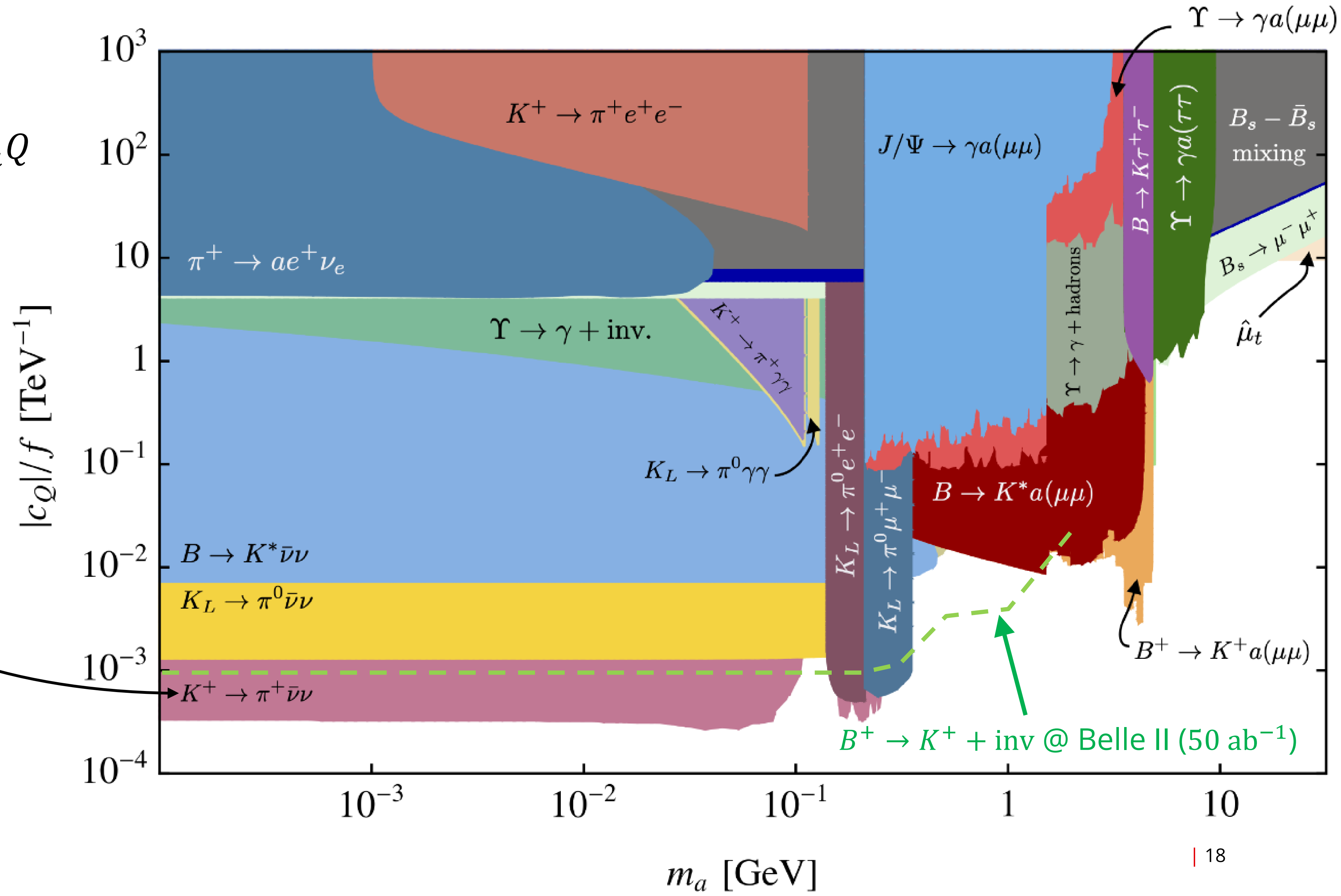
ALPS IN MESON DECAYS

Bauer et al. (2021) [2110.10698]
Ferber et al. (2023) [2201.06580]

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

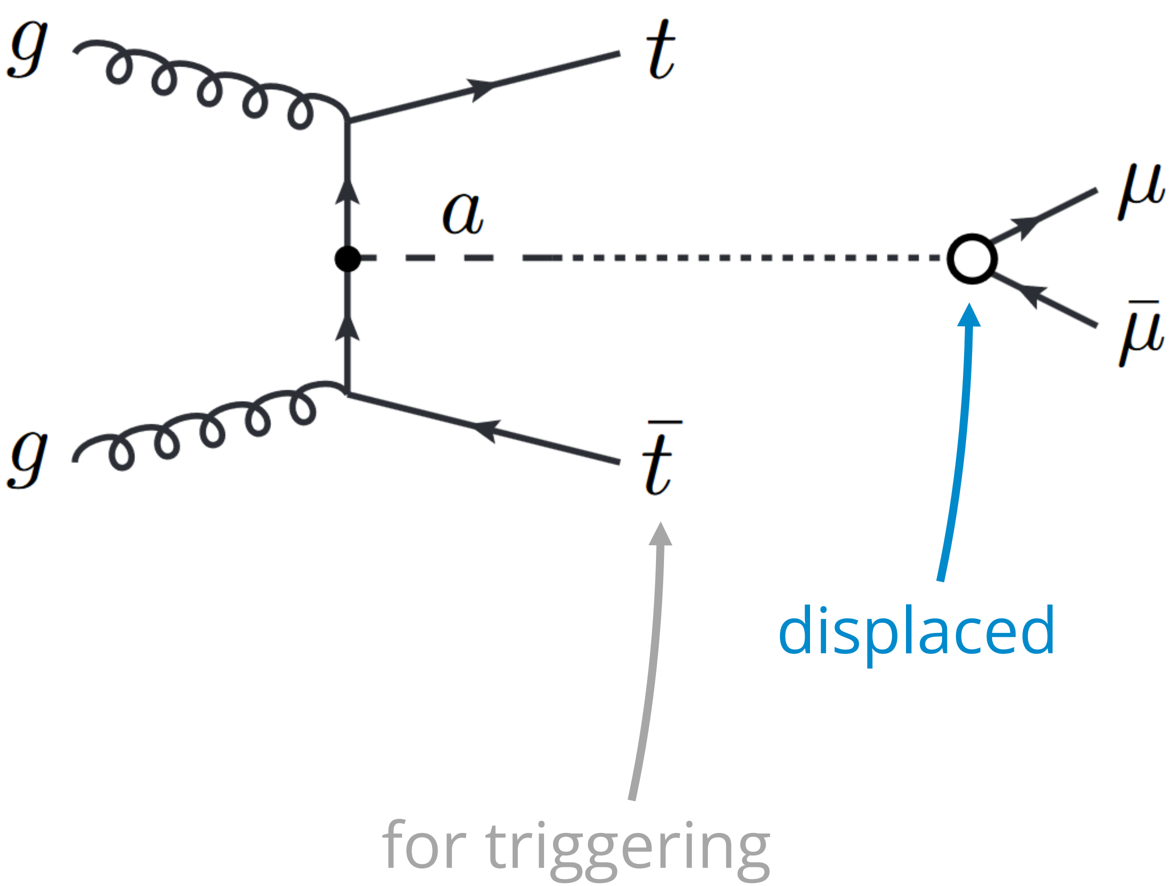




ALP's flavor changing couplings are turned off

DISPLACED ALPS AT THE LHC

Rygaard et al. (2023) [2306.08686]



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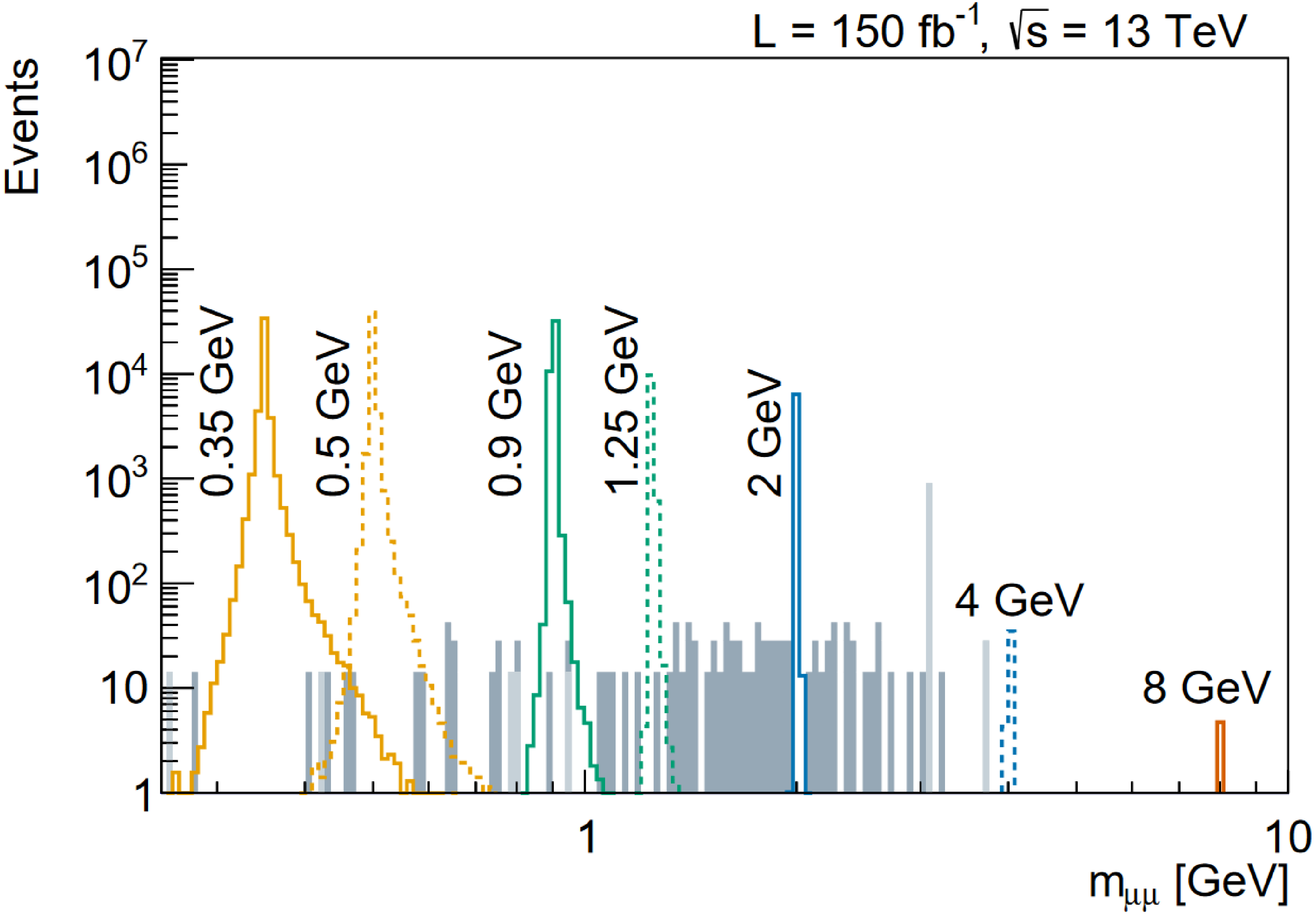

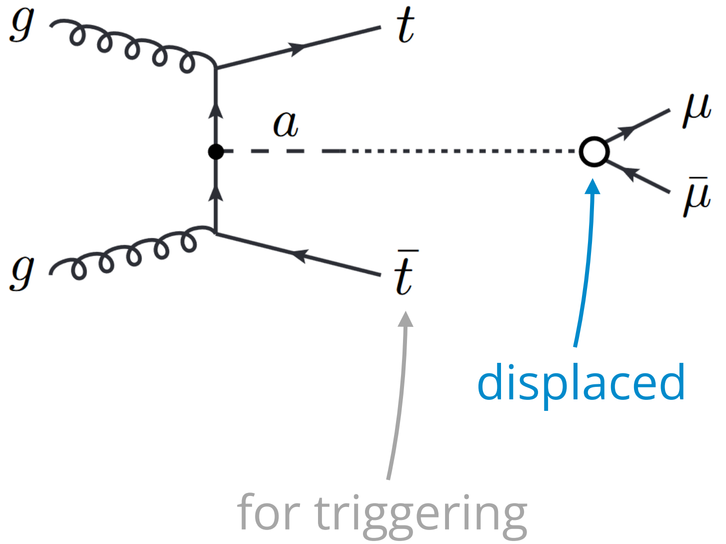

$$\frac{c_{tt}(\Lambda)}{f_a} = \frac{1}{\text{TeV}}, \; c_{\mu\mu}(\Lambda) = 0$$

DISPLACED ALPS AT THE LHC

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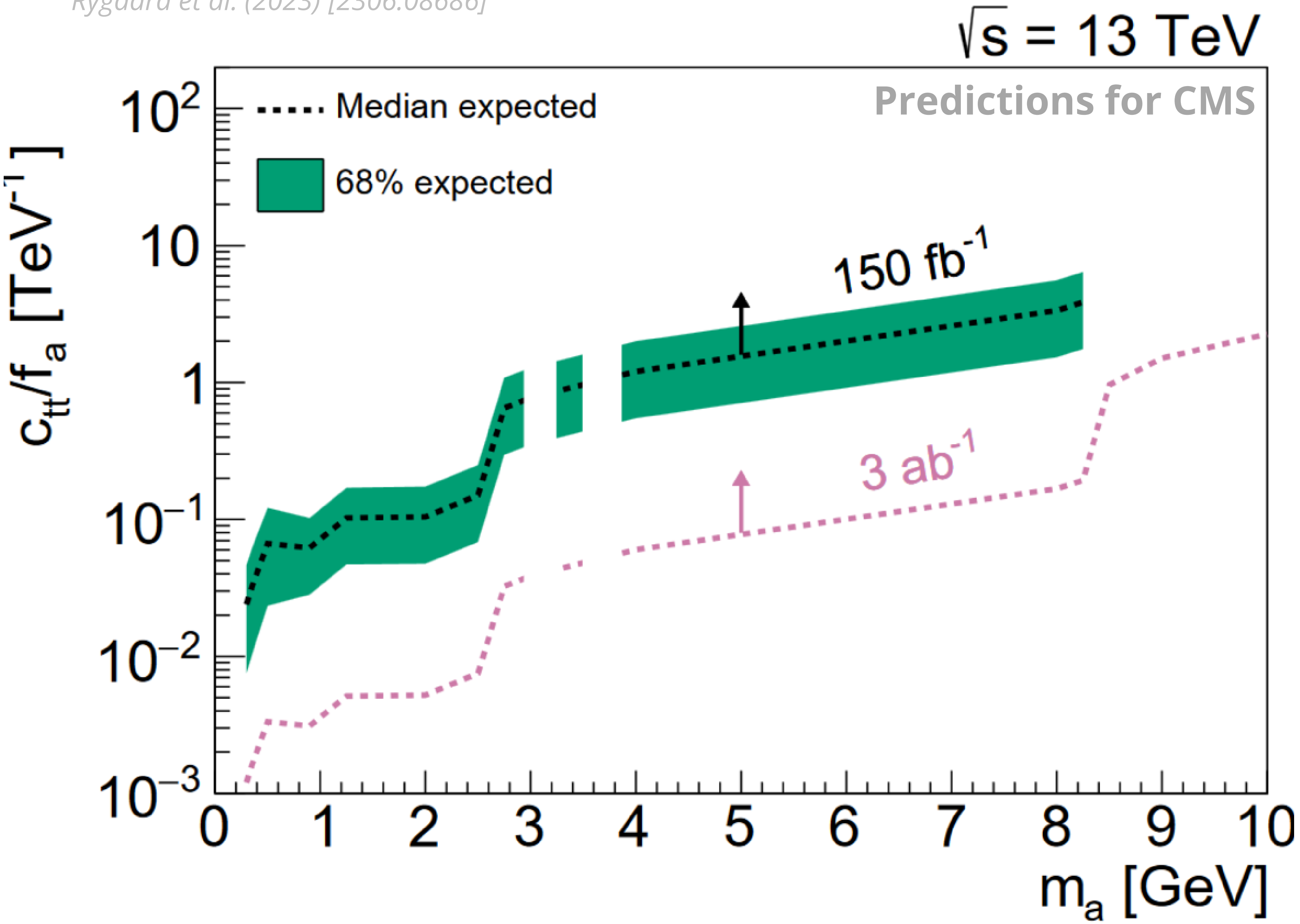

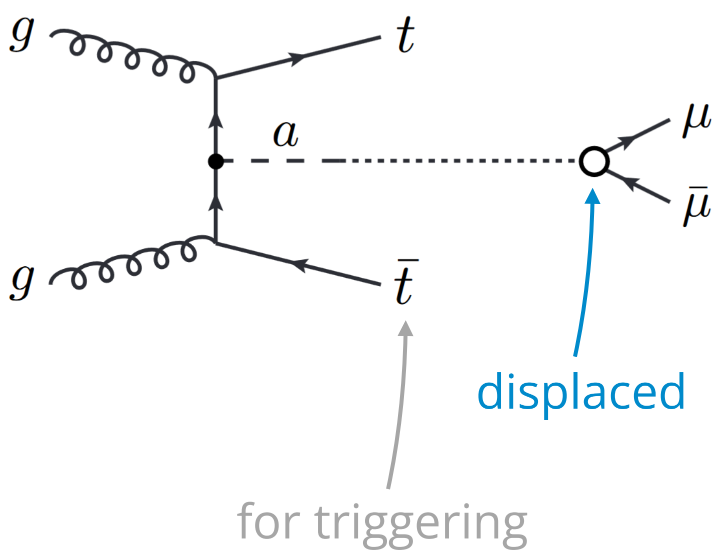

MESON DECAYS VERSUS TOP-ASSOCIATED ALPS

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

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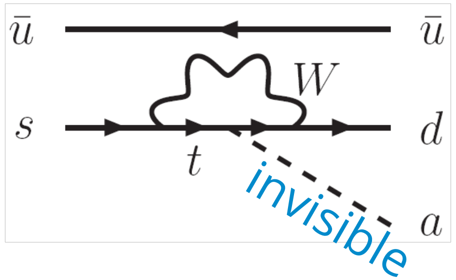

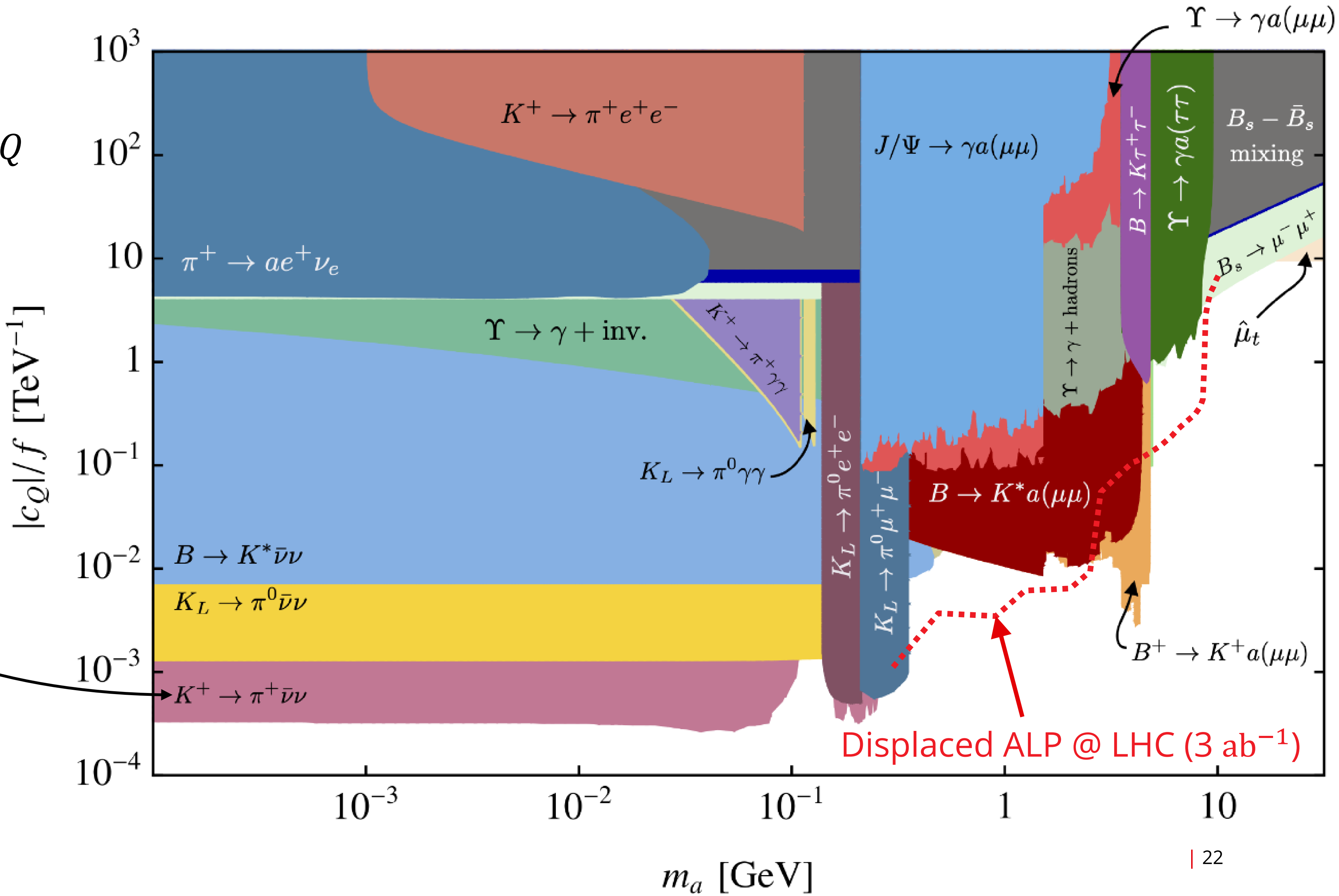

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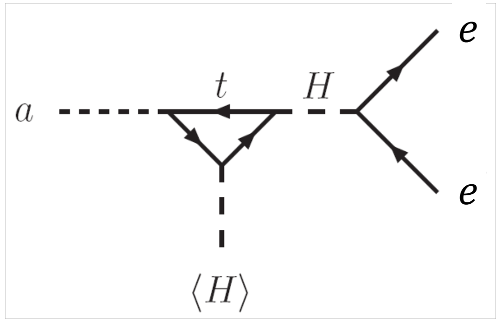
HOW TO PROBE ALP-TOP INTERACTION?

Astrophysics

ALP-electron



Bonilla et al. (2021) [2107.11392]

In meson decays

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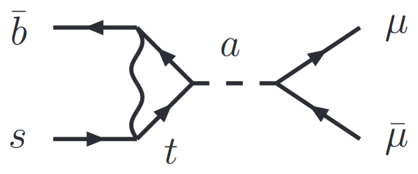

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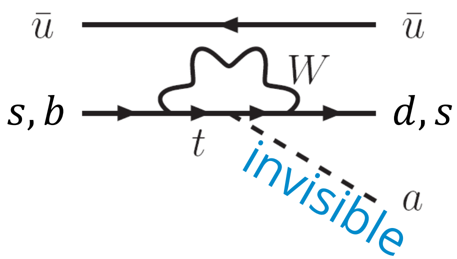

Bauer et al. (2021) [2110.10698]
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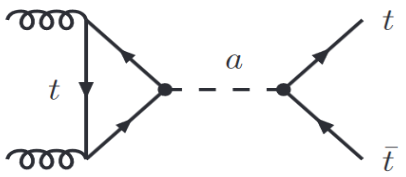
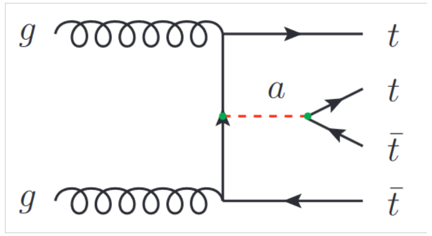
In top observables

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]

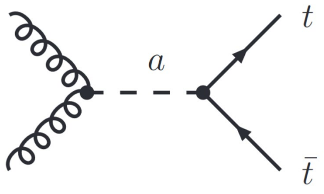
Long-lived ALPs

m_a

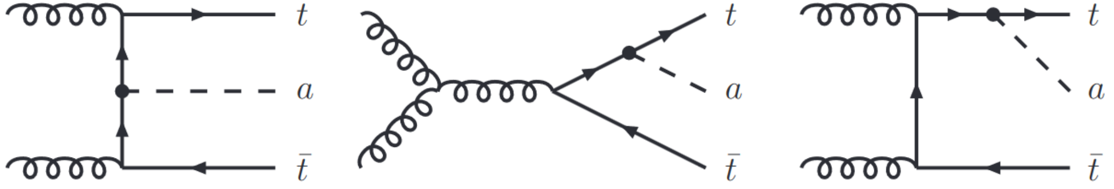
~0.1 MeV   ~5 GeV $2m_t = 345$ GeV

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

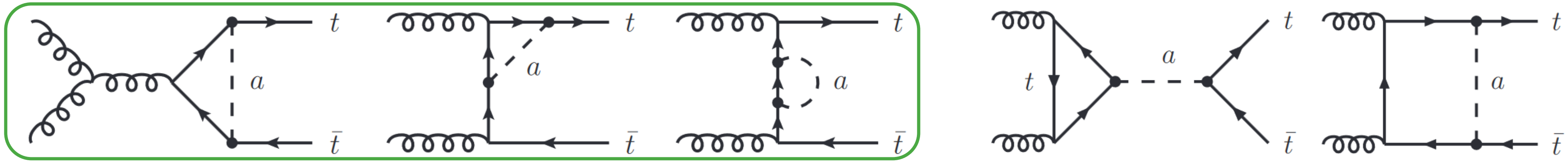
Tree-level



Real ALP radiation



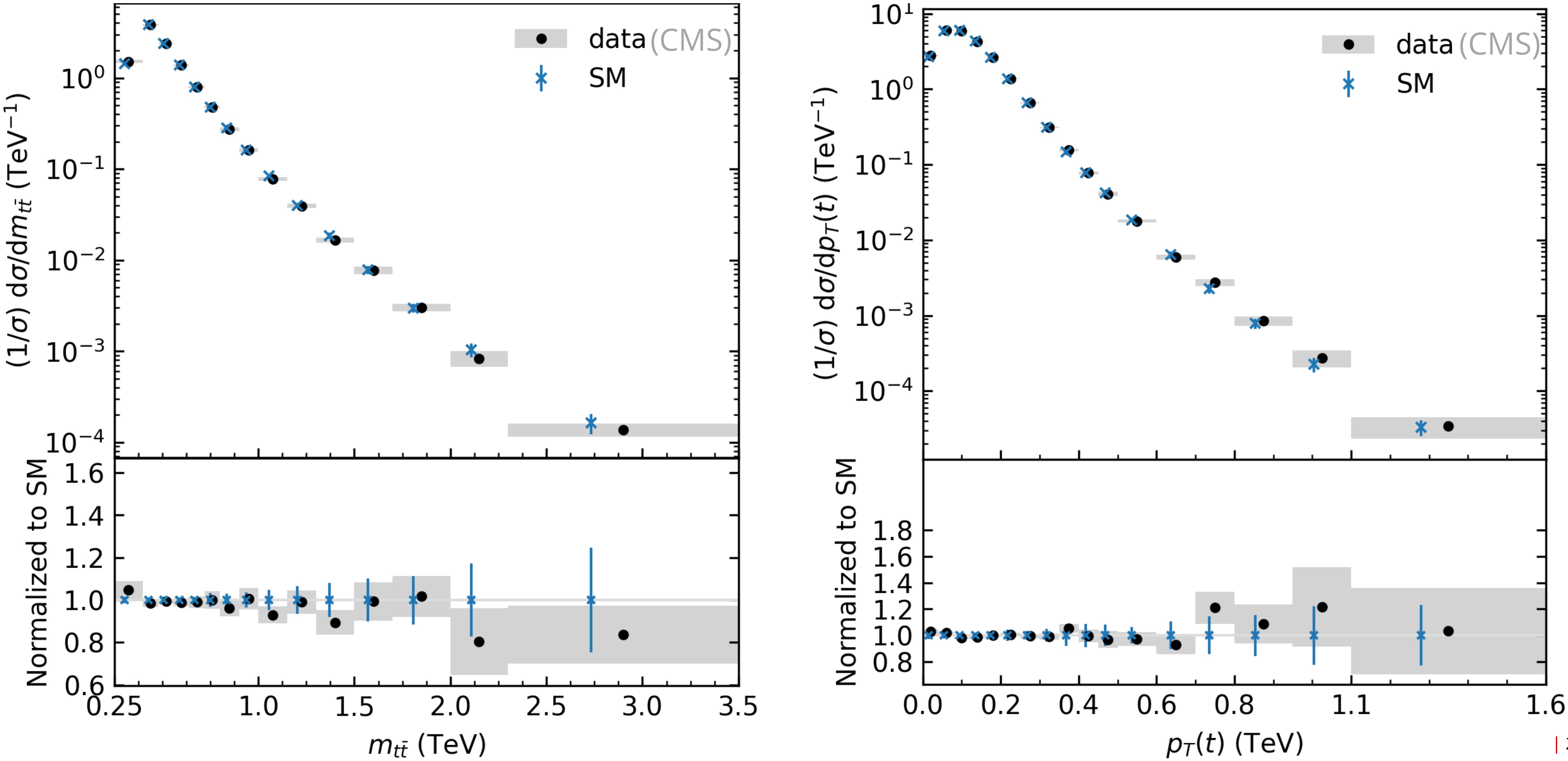
Virtual corrections



Needs renormalization

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

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



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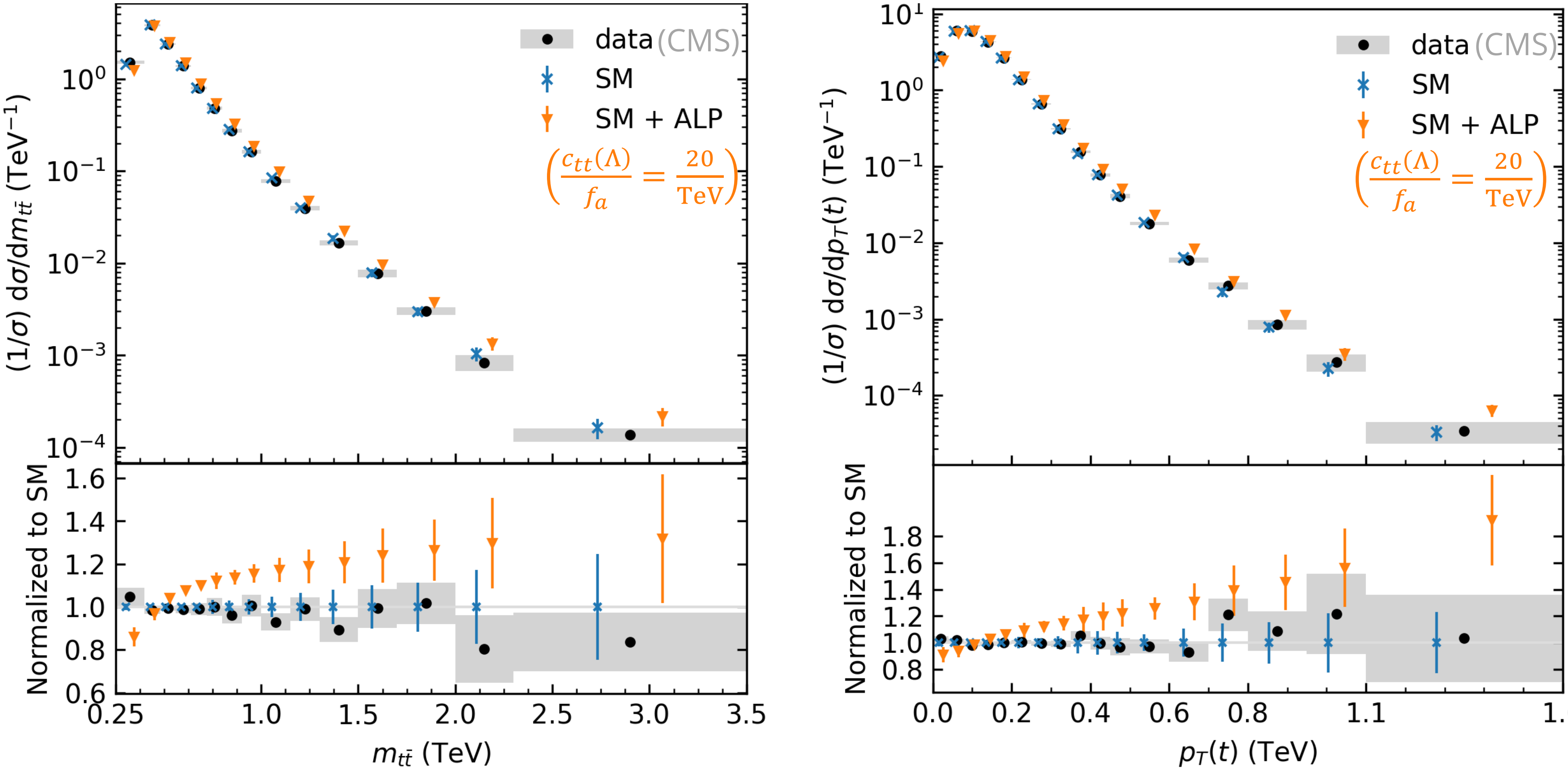

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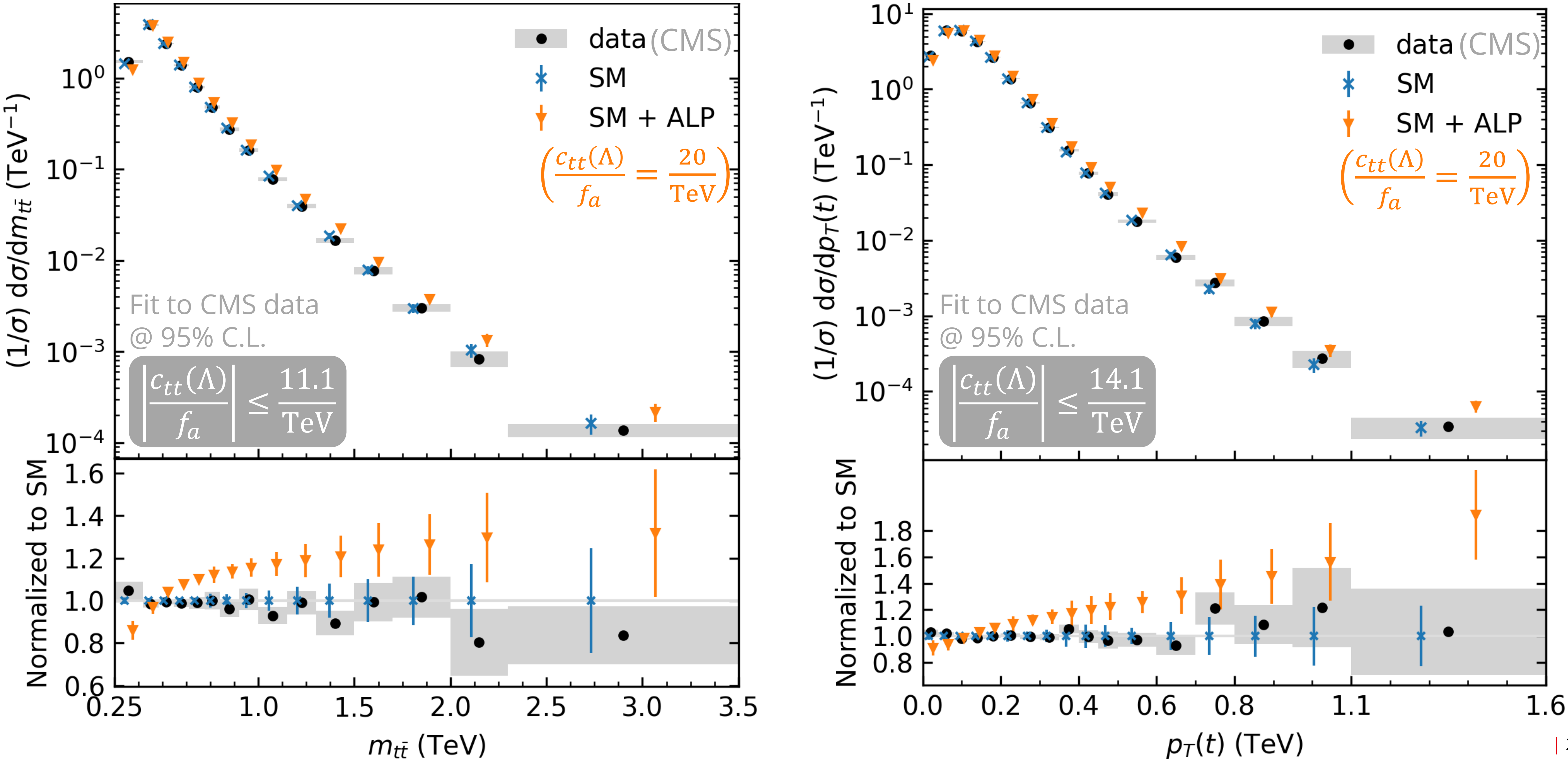
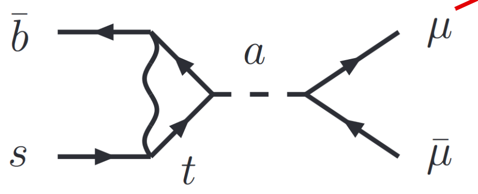
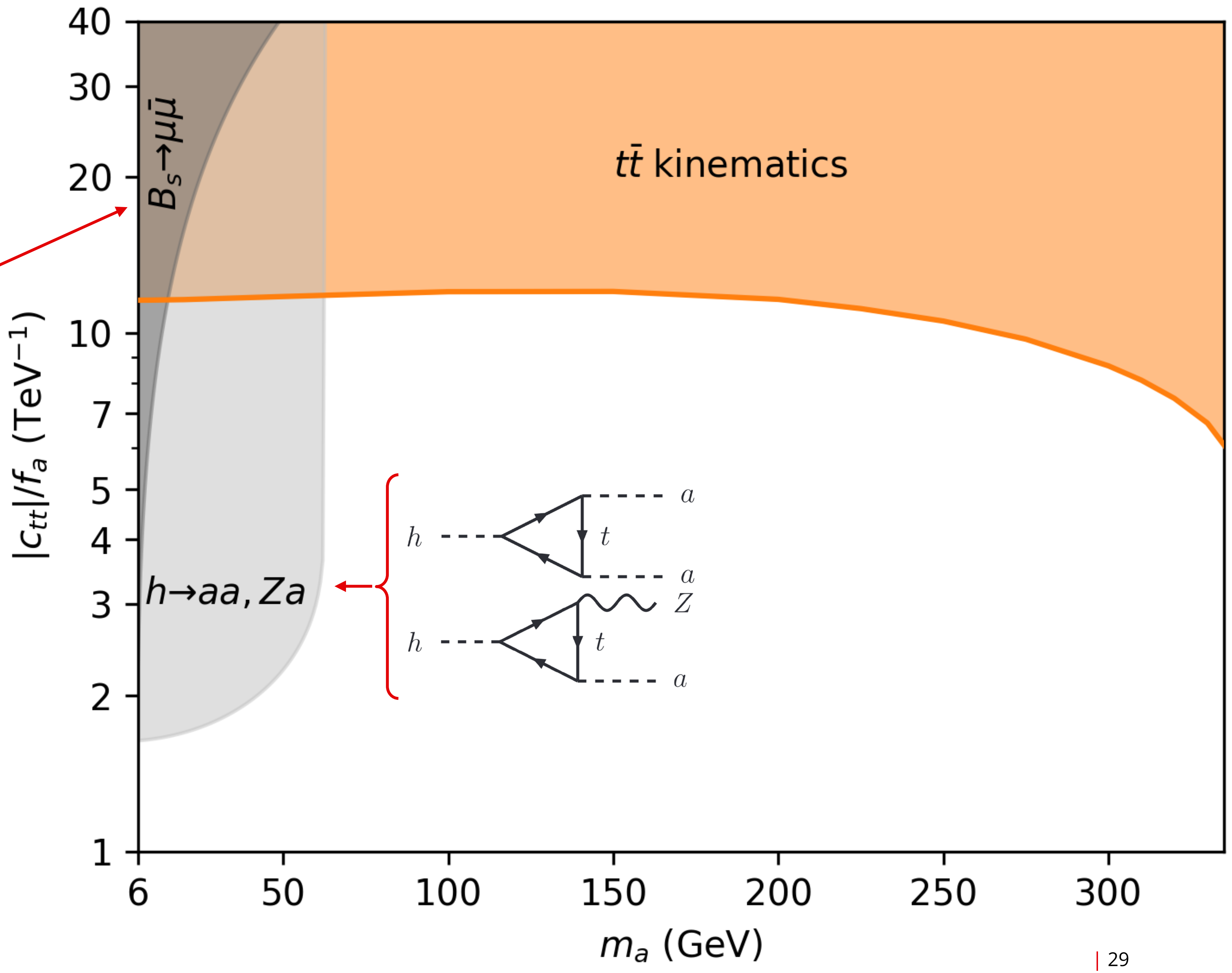


BOUNDS ON c_{tt} FROM VIRTUAL TOP

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





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].

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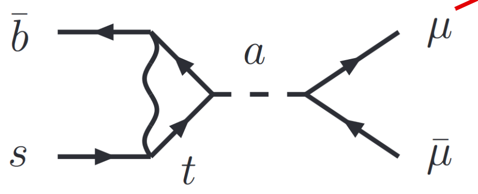

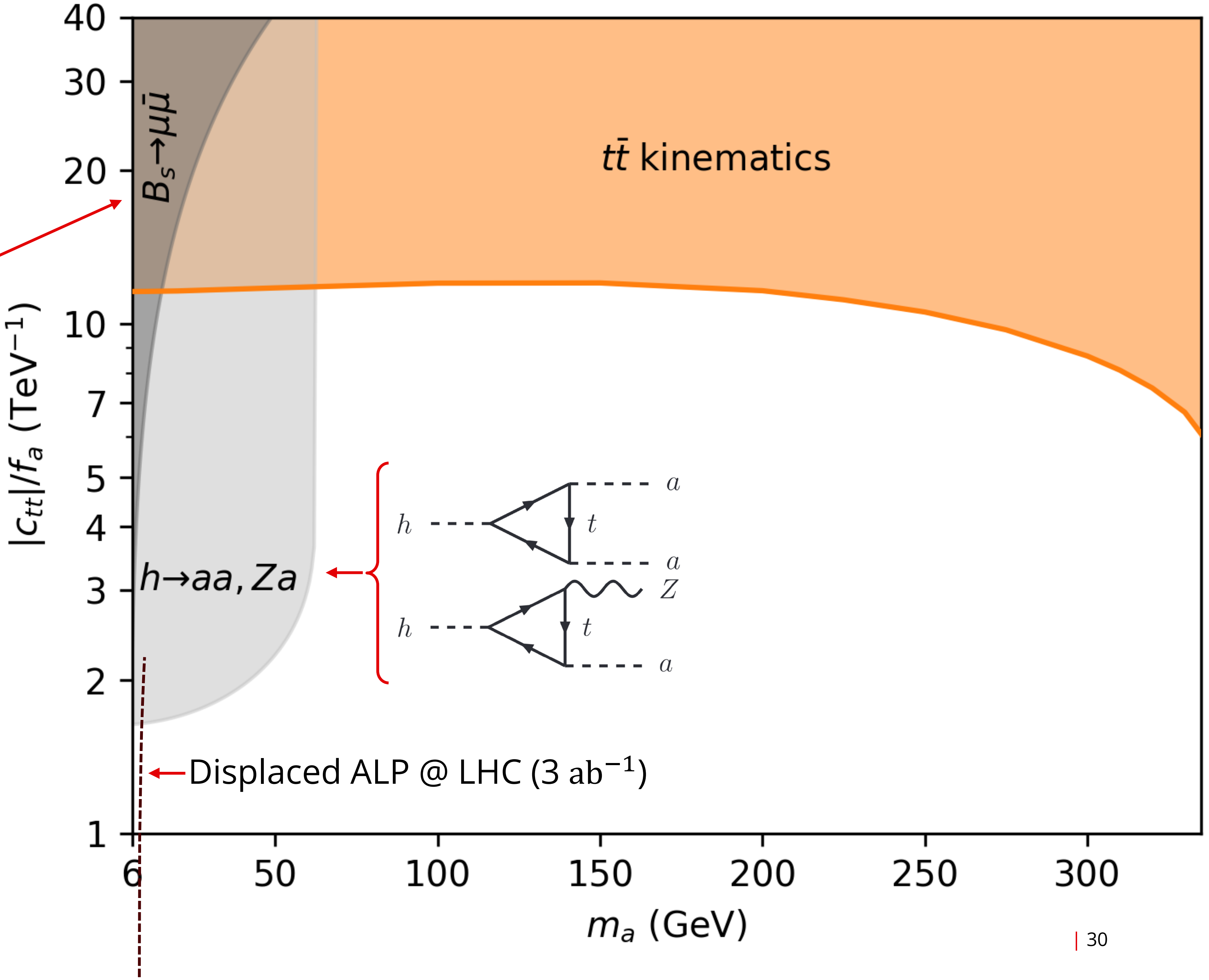

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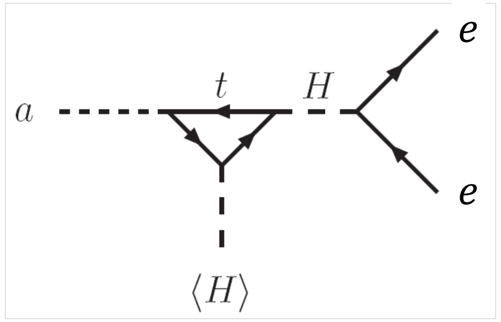
HOW TO PROBE ALP-TOP INTERACTION?

Astrophysics | **In meson decays** | **In top observables**

Astrophysics

ALP-electron



Bonilla et al. (2021) [2107.11392]

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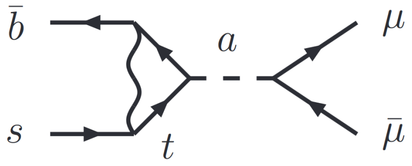

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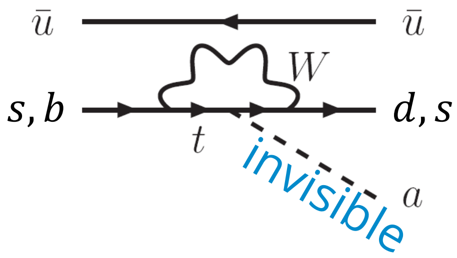

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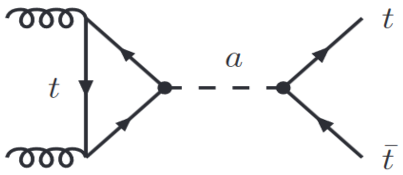
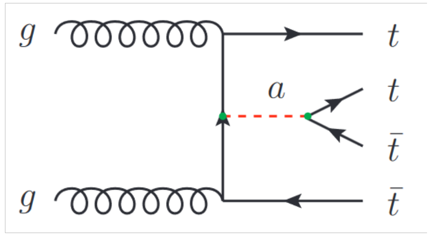
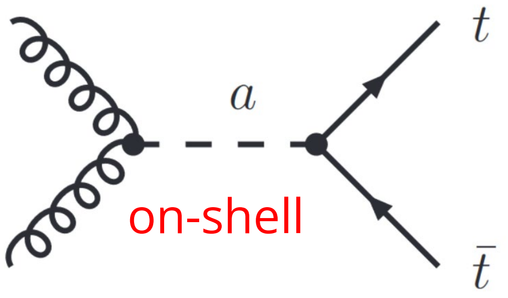


$pp \to t\bar{t}t\bar{t}$



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]

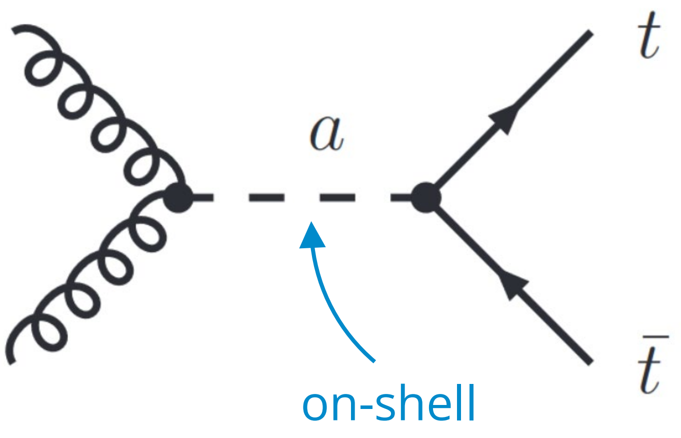
Long-lived ALPs

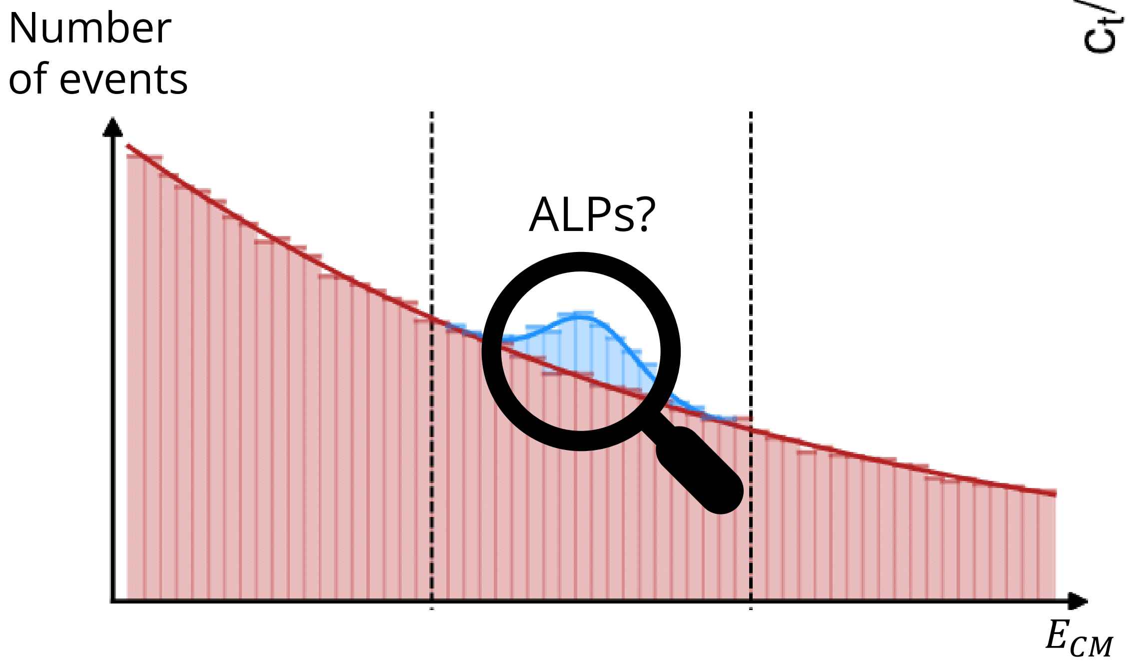
m_a

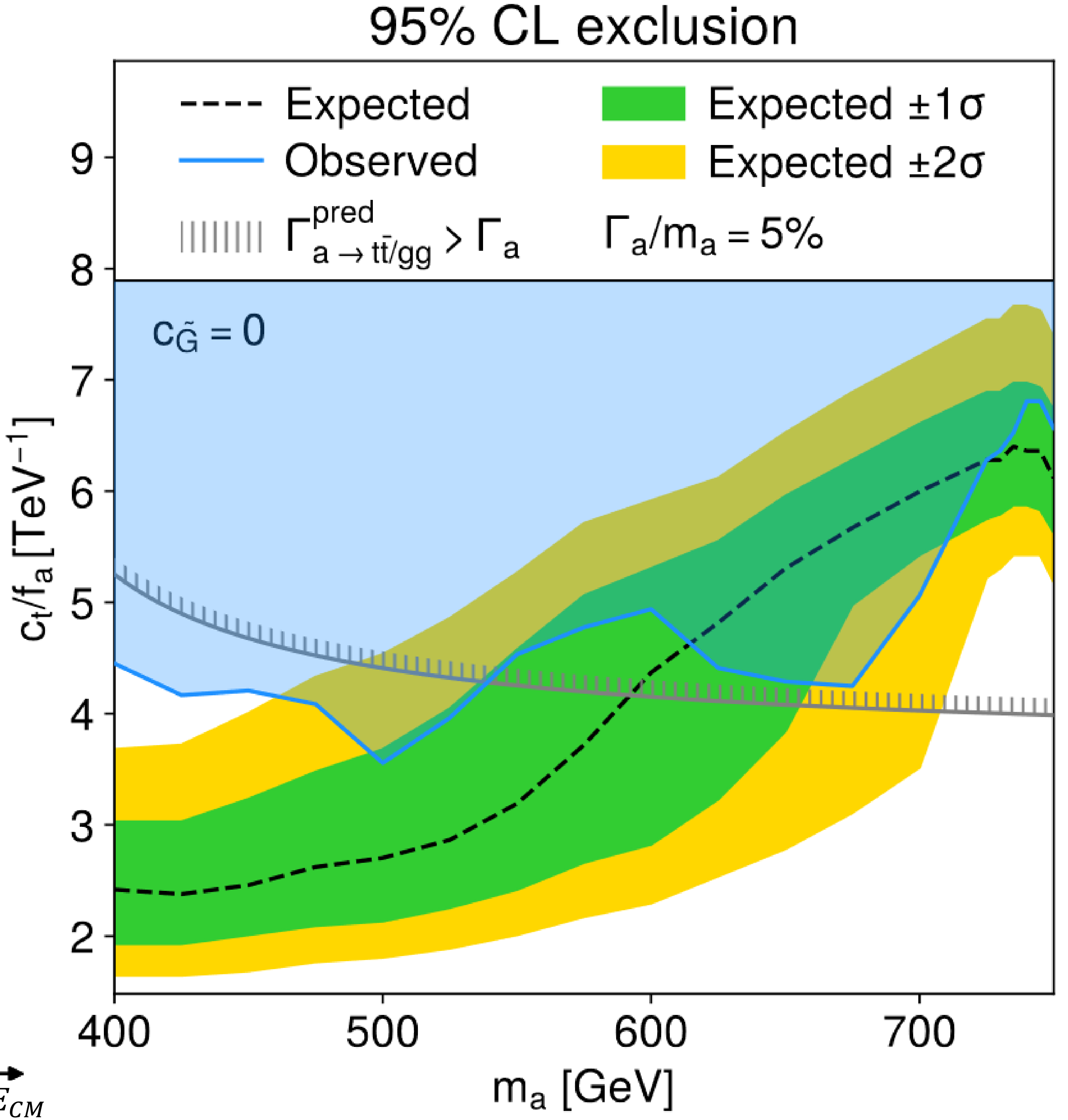
~ 0.1 MeV | ~ 5 GeV | $2m_t = 345$ GeV

RESONANCE SEARCHES

Anuar et al. (2024) [2404.19014]

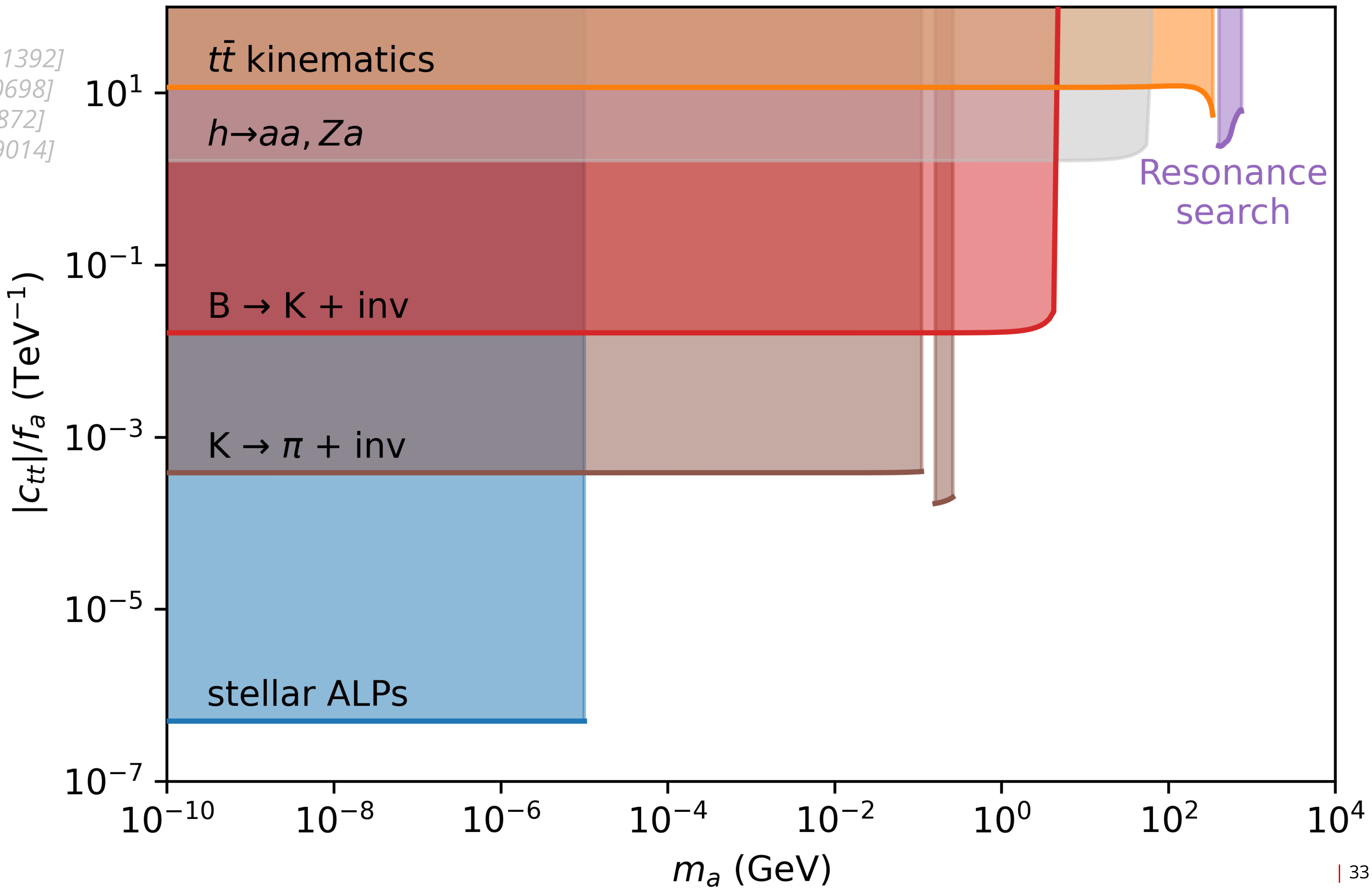






SUMMARY

Bonilla et al. (2021) [2107.11392]
Bauer et al. (2021) [2110.10698]
Phan et al. (2023) [2312.00872]
Anuar et al. (2024) [2404.19014]



Conclusions

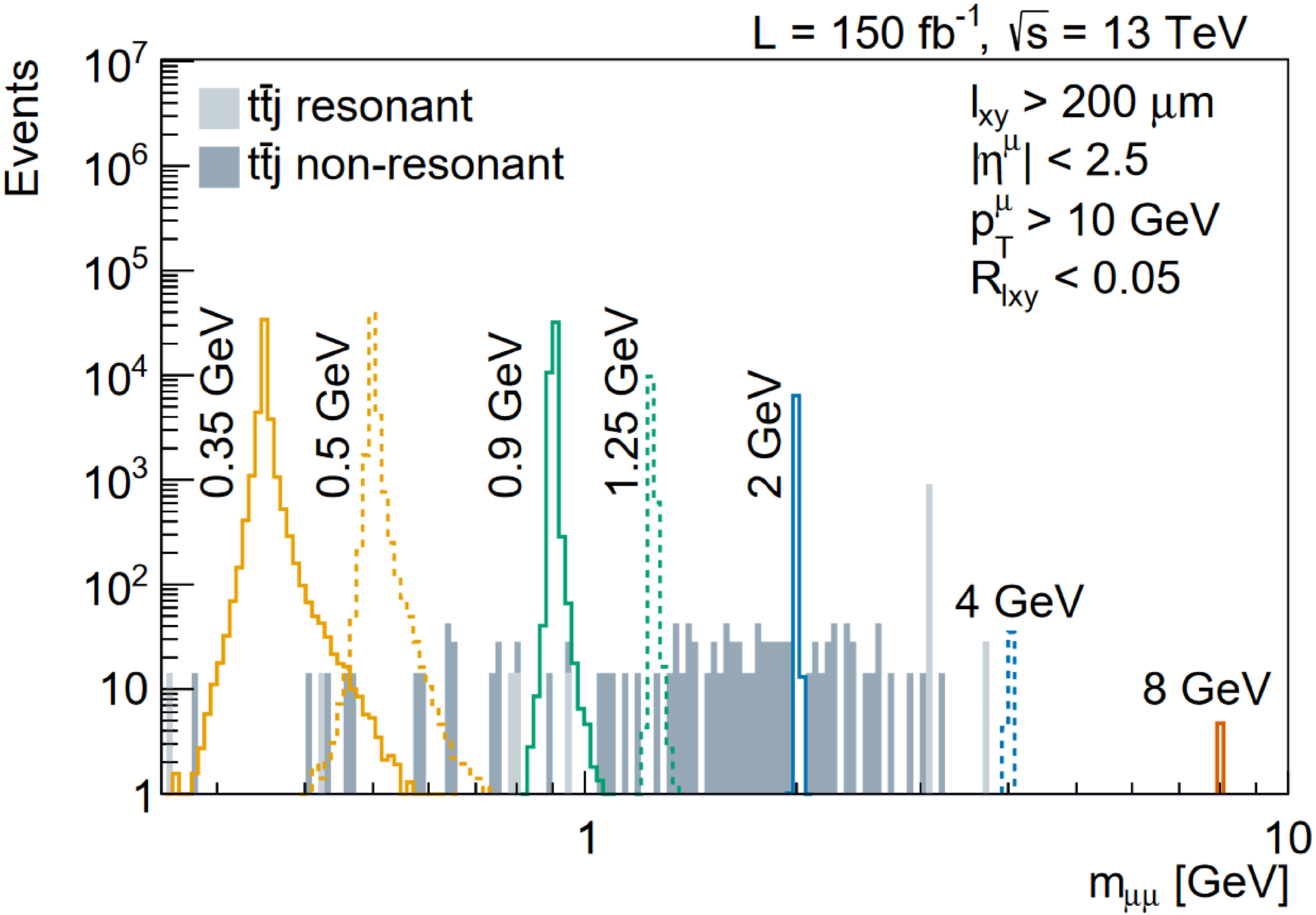
- Among the SM fermions, **top is most sensitive to ALPs**.
- Top **induces all other ALP couplings** ⇒ rich phenomenology.
- Collider probes of the ALP-top coupling apply for any ALP mediator with $m_a < 2m_{\mathrm{DM}}$.

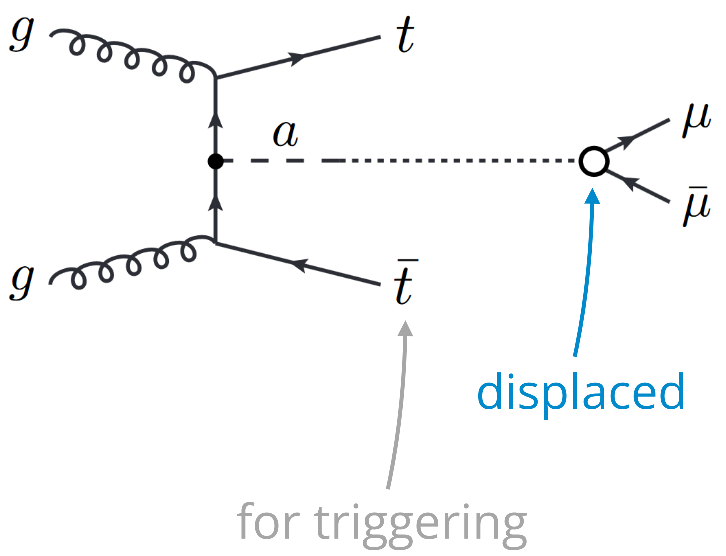
Thank you for listening!

BACKUP SLIDES

DISPLACED ALPS AT THE LHC

Rygaard et al. (2023) [2306.08686]



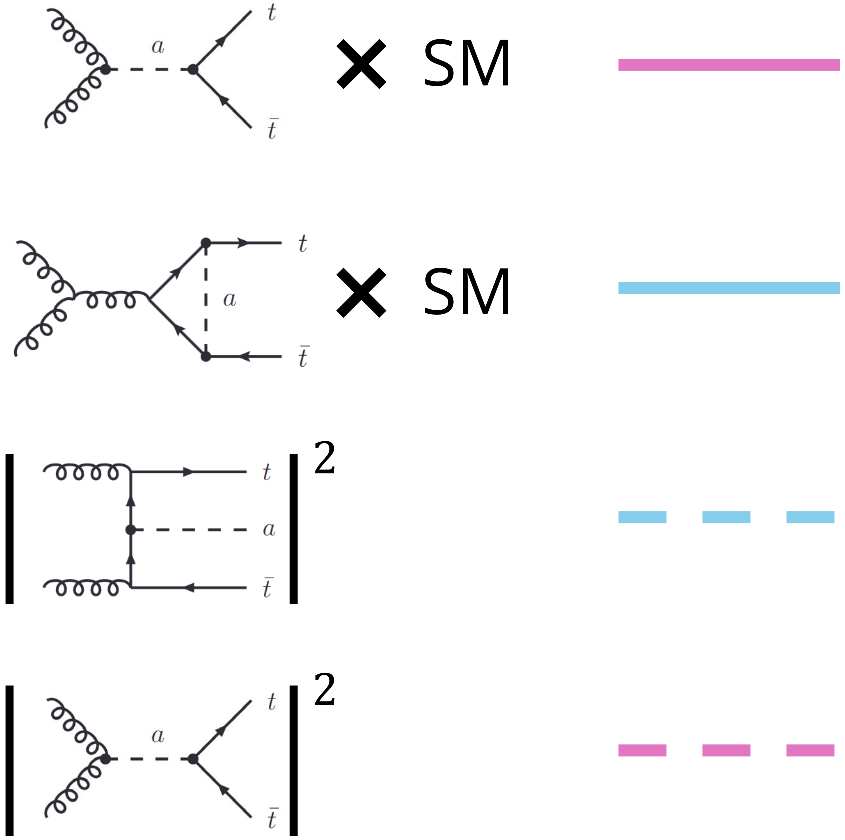


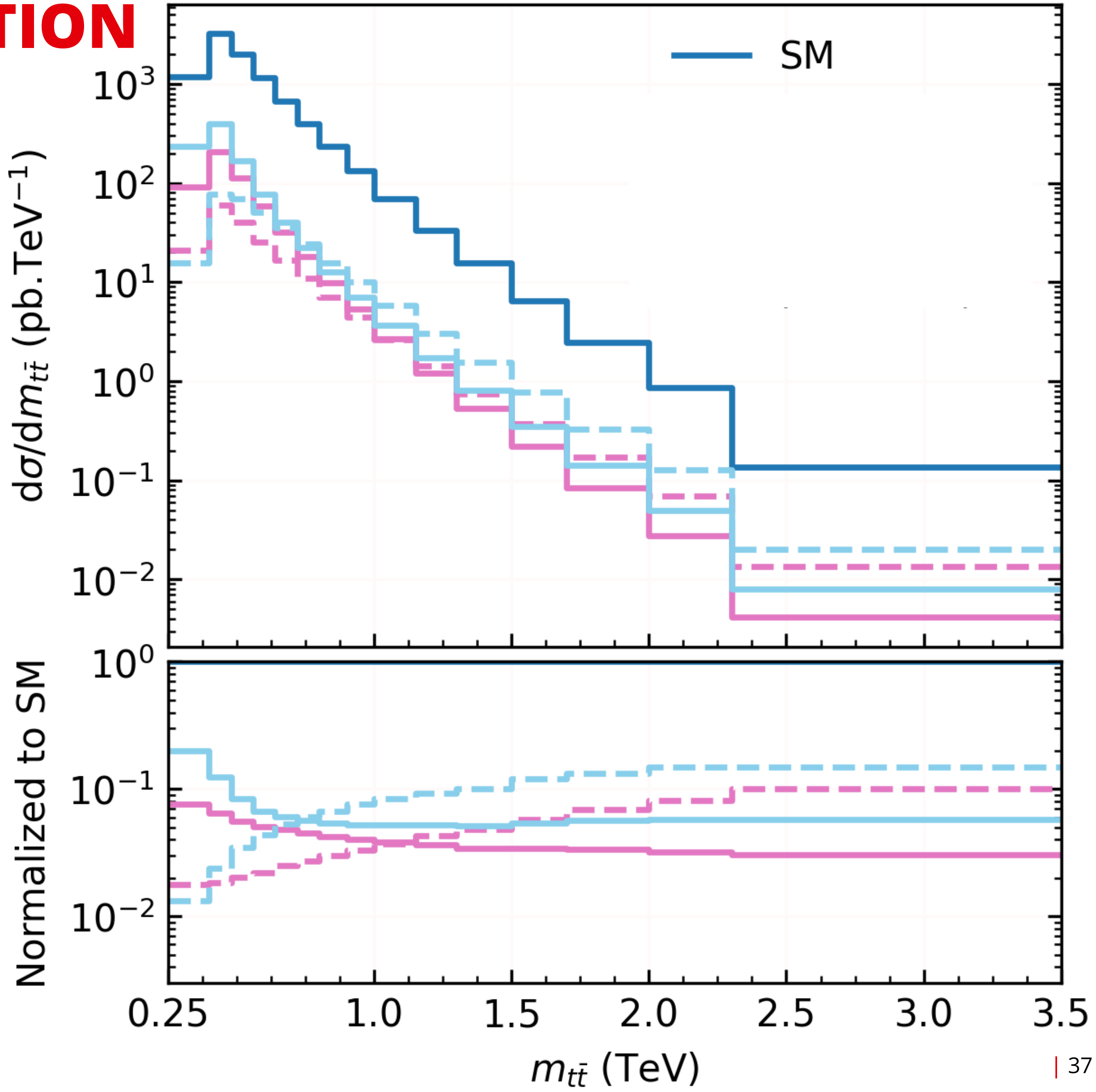
$$\frac{c_{tt}(\Lambda)}{f_a} = \frac{1}{\text{TeV}}\,,\; c_{\mu\mu}(\Lambda) = 0$$

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

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

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

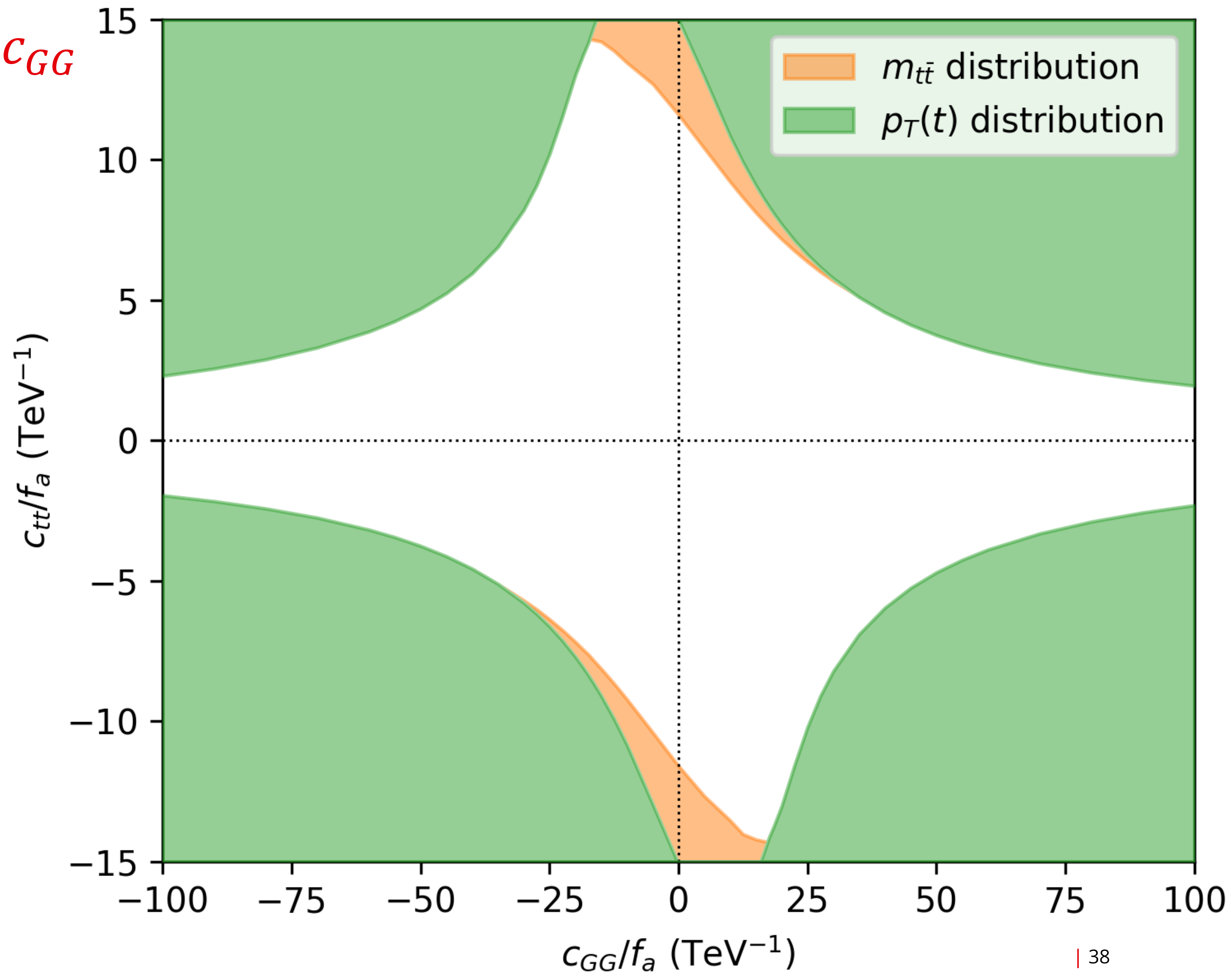




BOUNDS ON c_{tt} AND c_{GG}

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

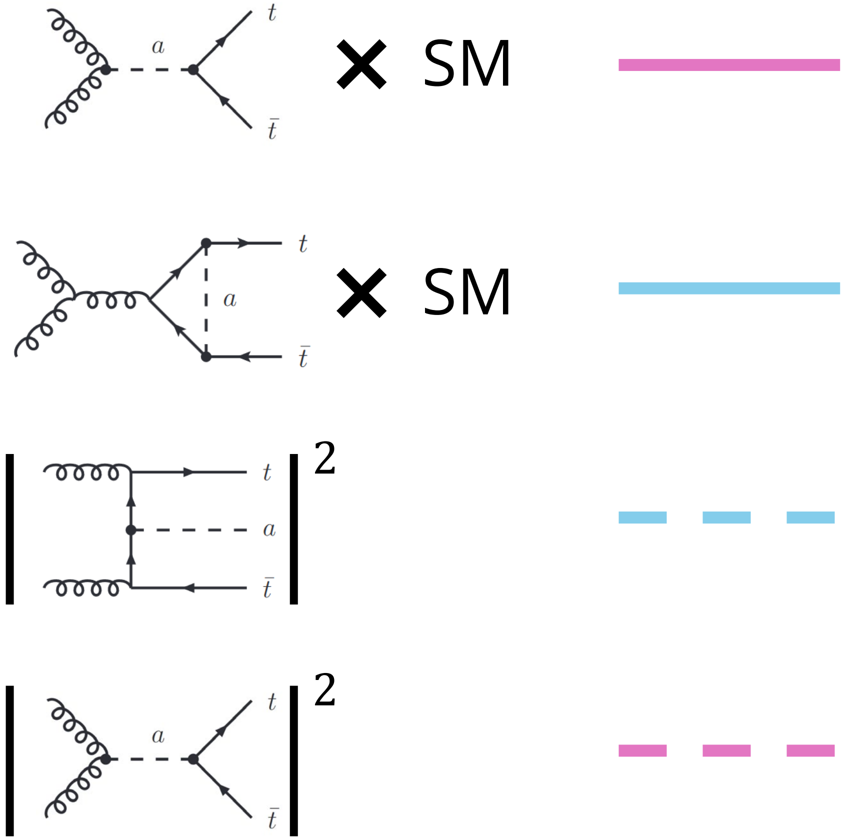
$m_a = 10$ GeV,
c_{GG}, c_{tt} vary

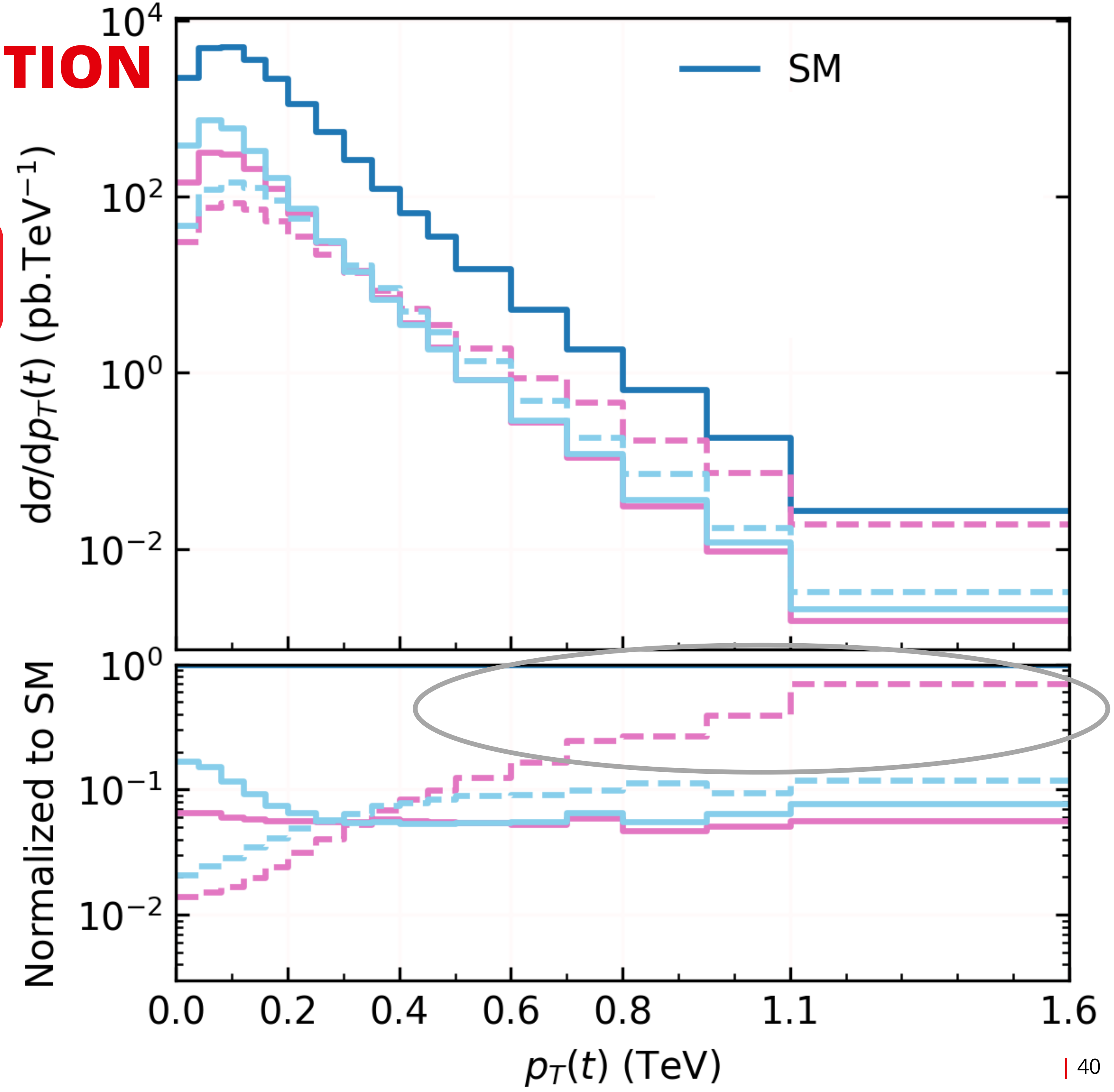


ALP EFFECTS IN p_T DISTRIBUTION

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

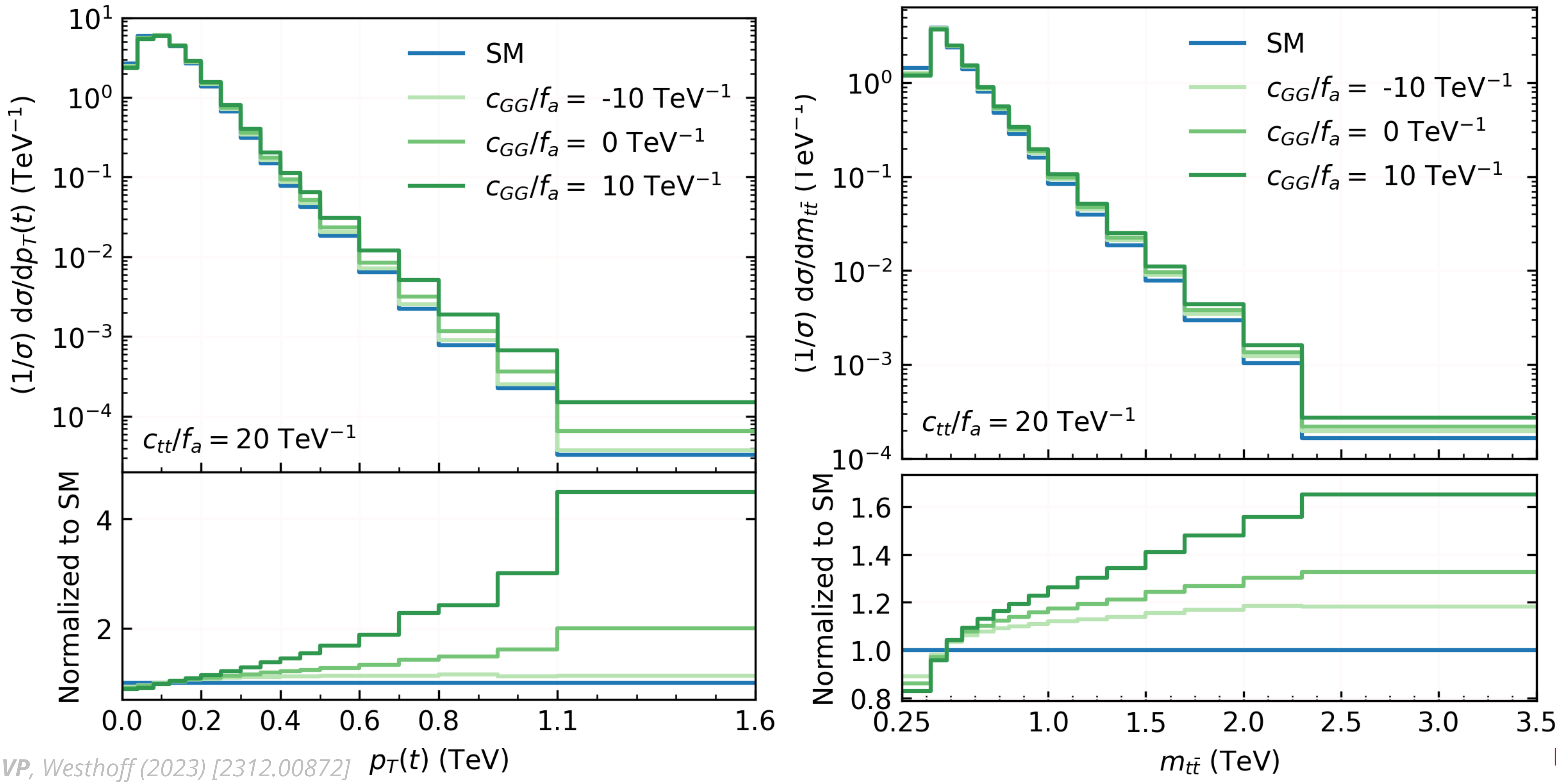
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$





$c_{GG}(\Lambda)$ DEPENDENCE

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



AVP, Westhoff (2023) [2312.00872]

RESULTS

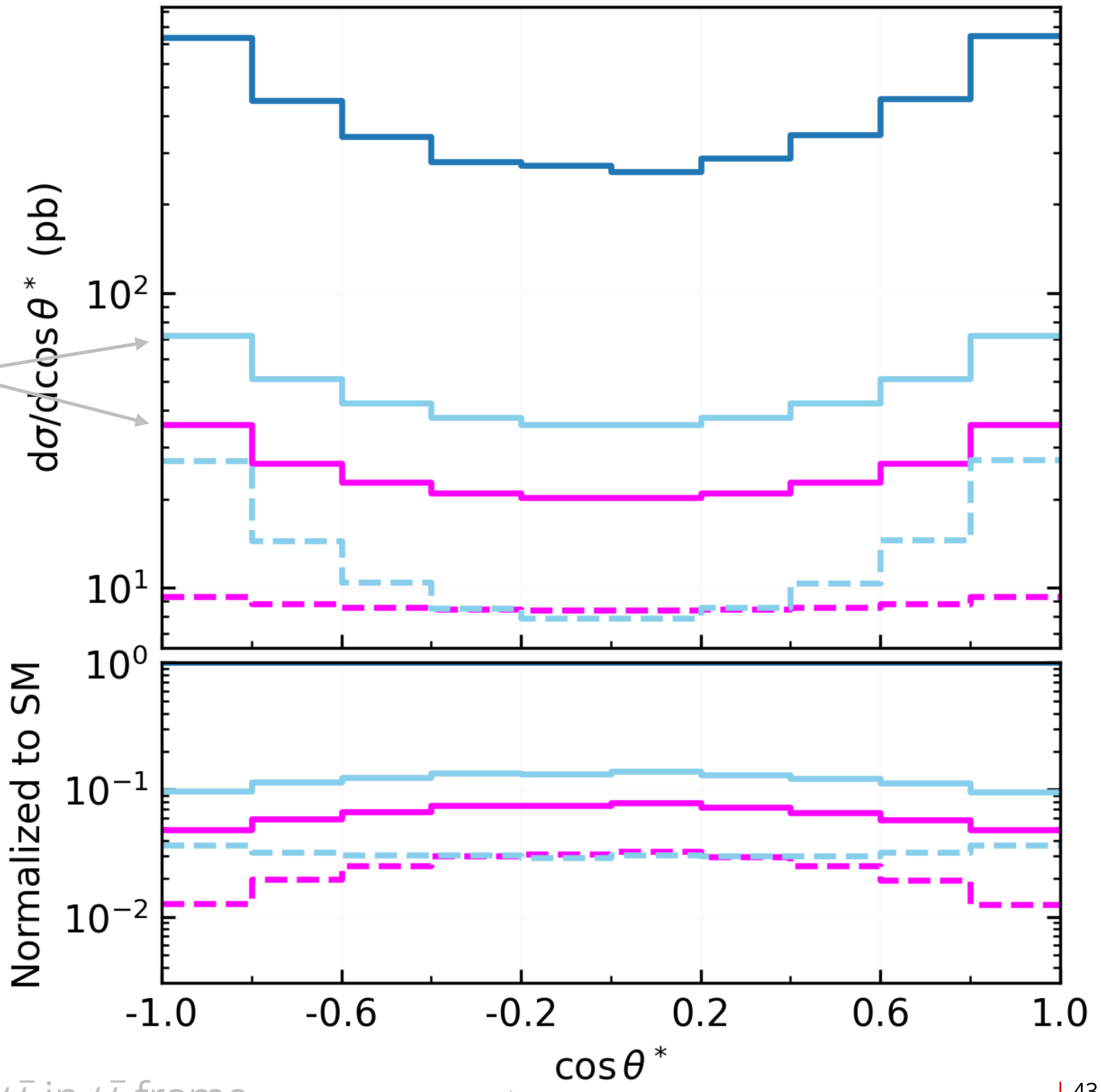
INDIVIDUAL CONTRIBUTIONS

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

RESULTS

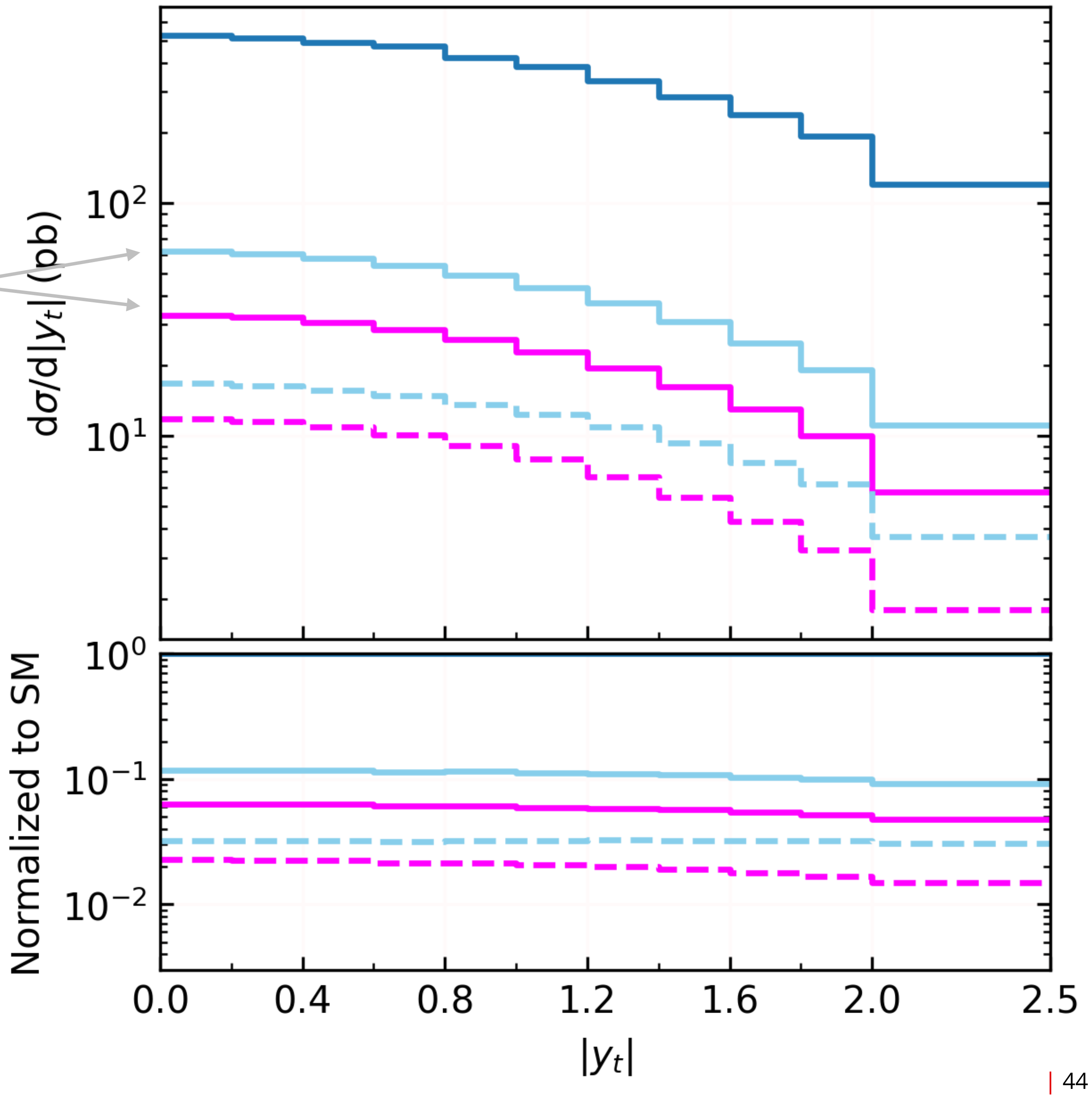
INDIVIDUAL CONTRIBUTIONS

SM: PRD 104 (2021) 092013

Virtual ALP and tree-level interferences with SM are negative

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

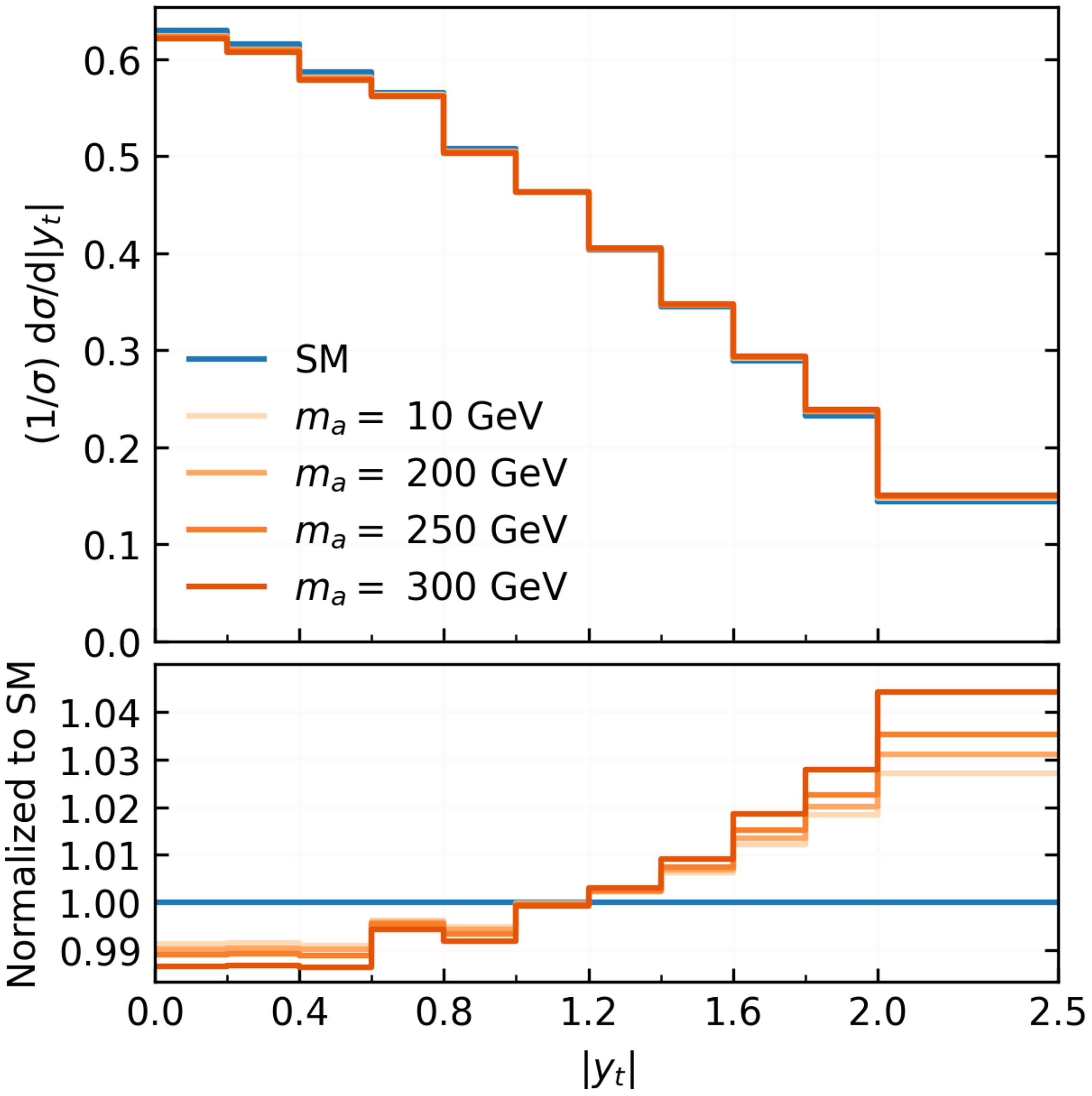
New Physics scale $\Lambda = 4\pi f_a$

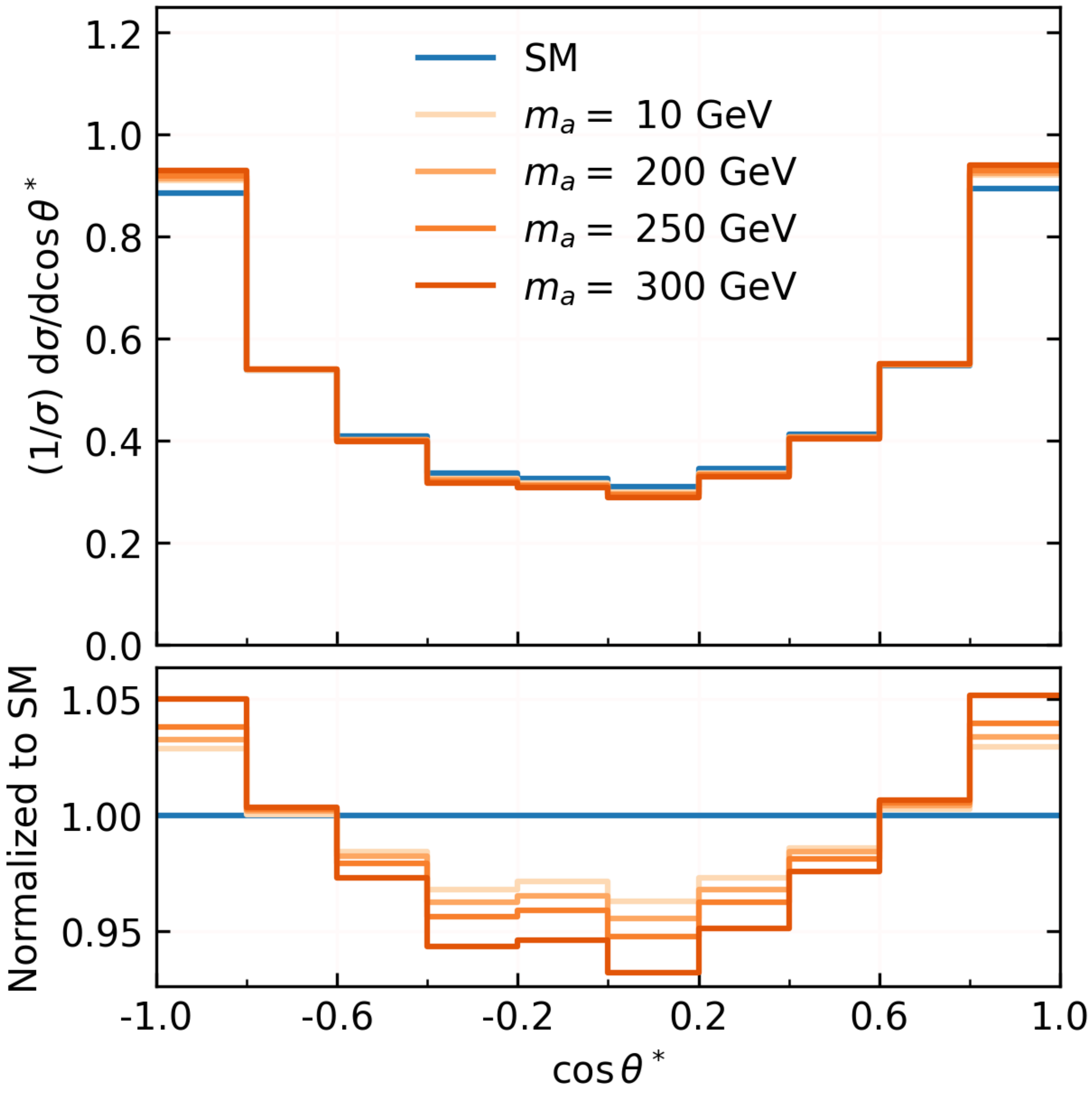


RESULTS

ALP MASS DEPENDENCE

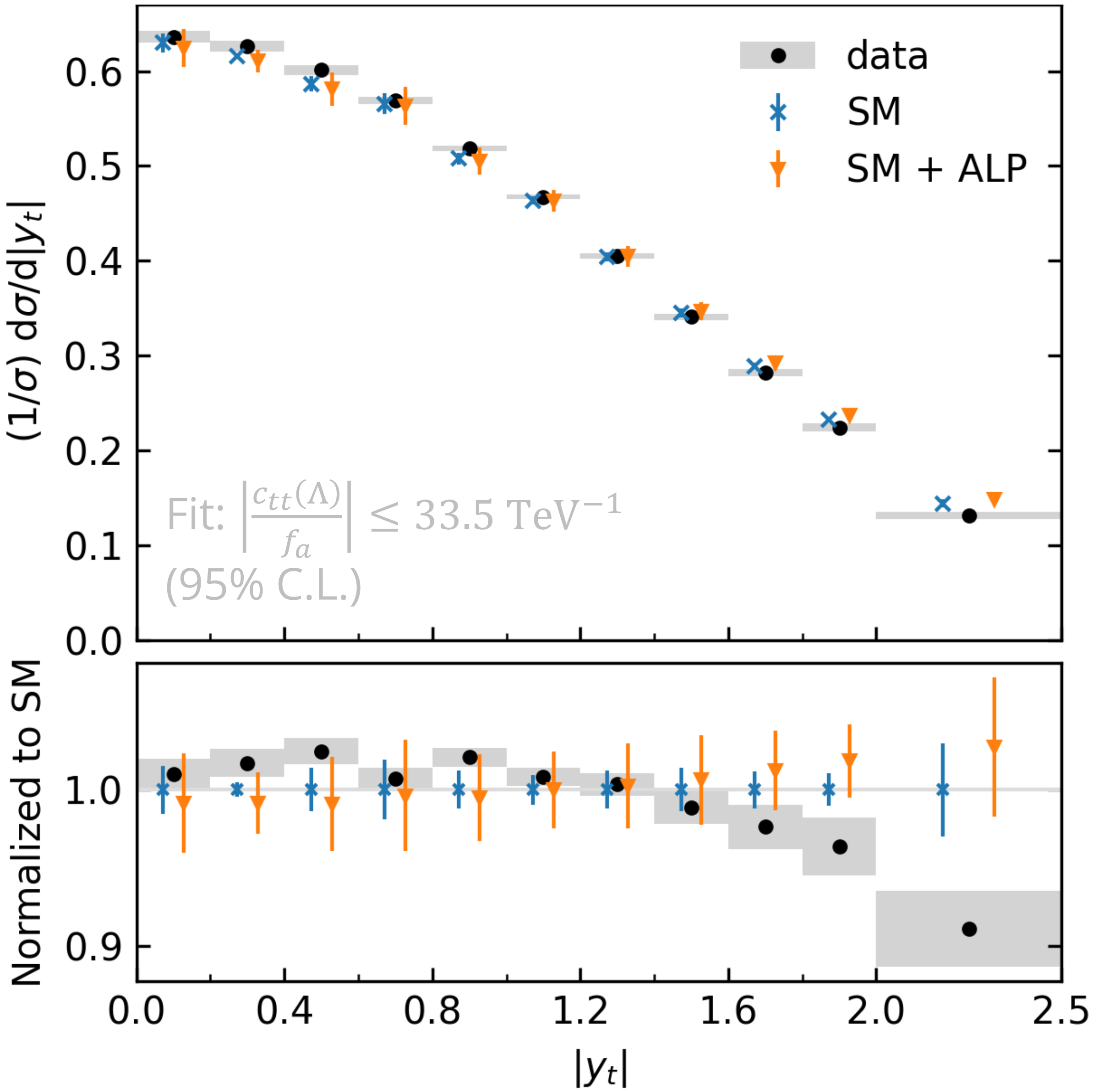
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\ ;\ c_{GG}(\Lambda) = 0$$

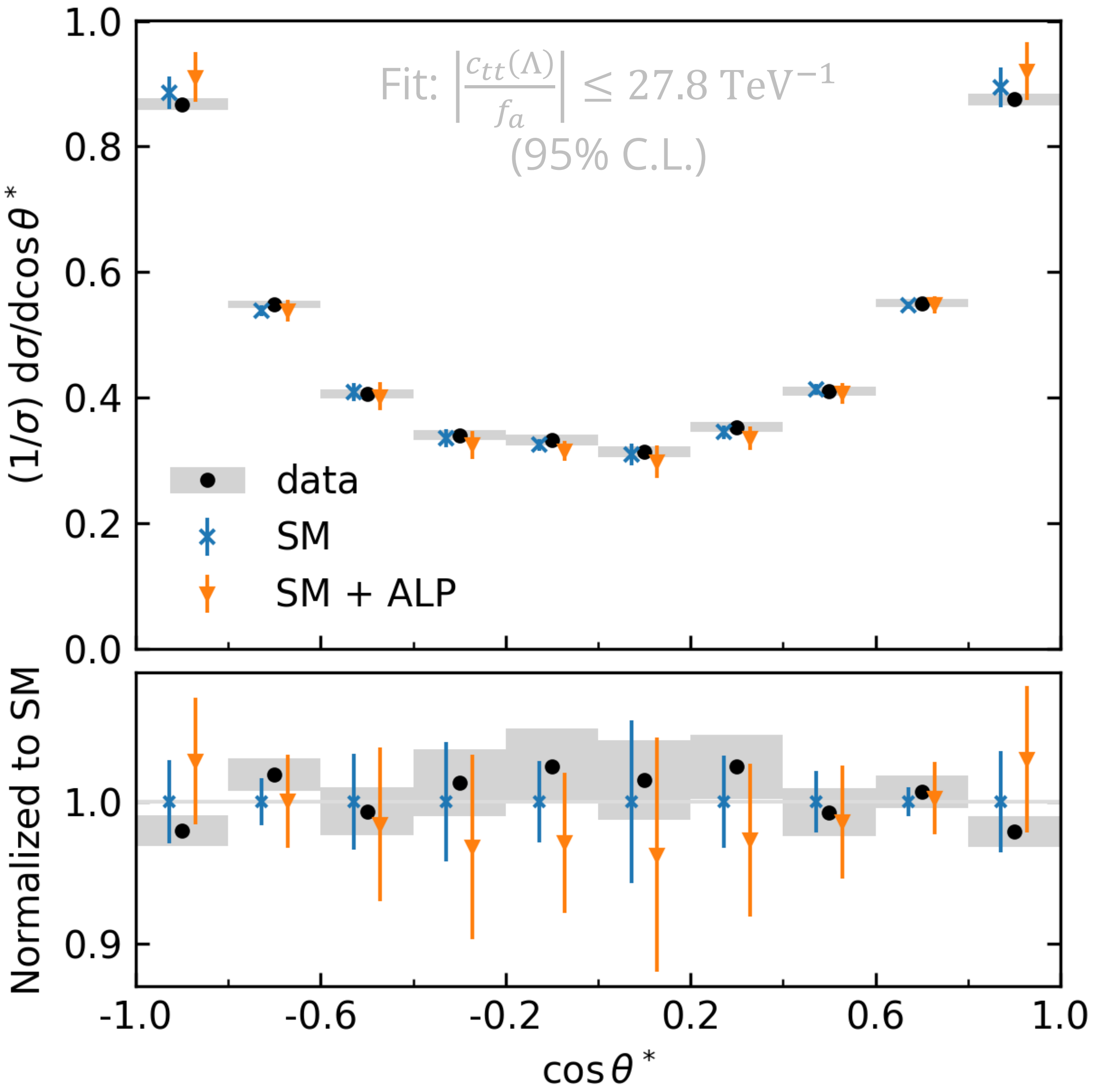




Data: PRD 104 (2021) 092013
ALP uncertainty: 10%

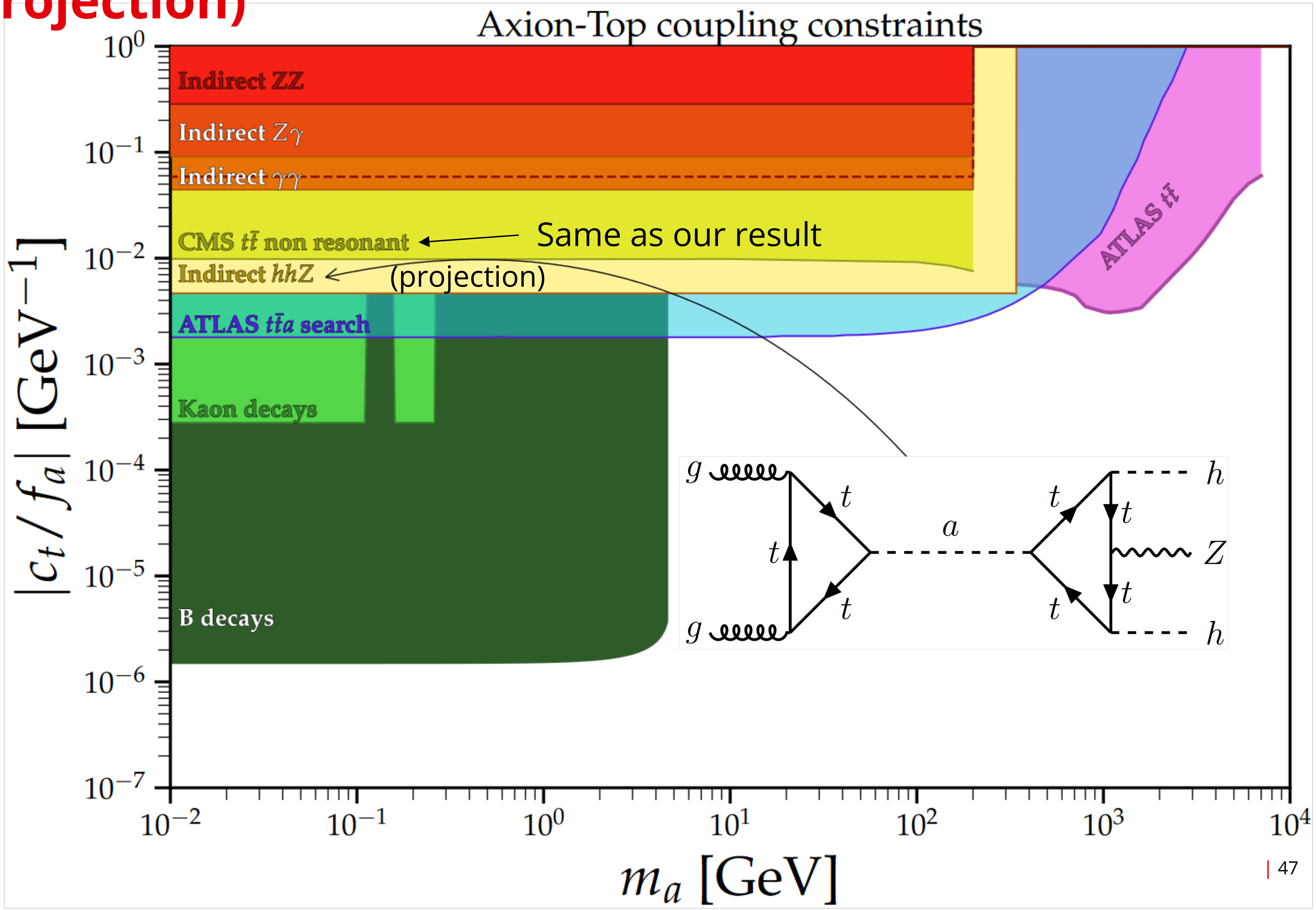
$$\frac{c_{tt}(\Lambda)}{f_a} = 20\ \mathrm{TeV}^{-1}\,;\, c_{GG}(\Lambda) = 0\,;\, m_a = 10\ \mathrm{GeV}$$





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]