ALPs on the Elbe

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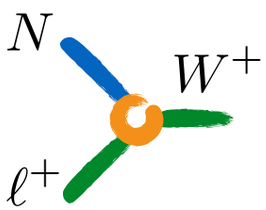
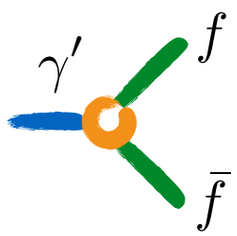
Minimalistic new physics

sterile neutrino



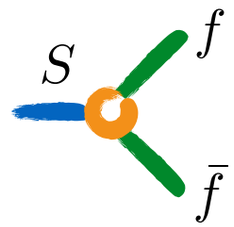
$$\mathcal{L} = y_N(\overline{L}H)N + h.c.$$

dark photon

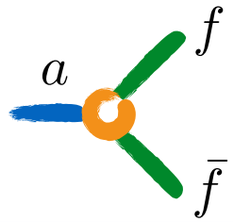


$$\mathcal{L} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$$

dark Higgs



$$\mathcal{L} = \lambda_S(H^\dagger H)S$$

axion-like particles 

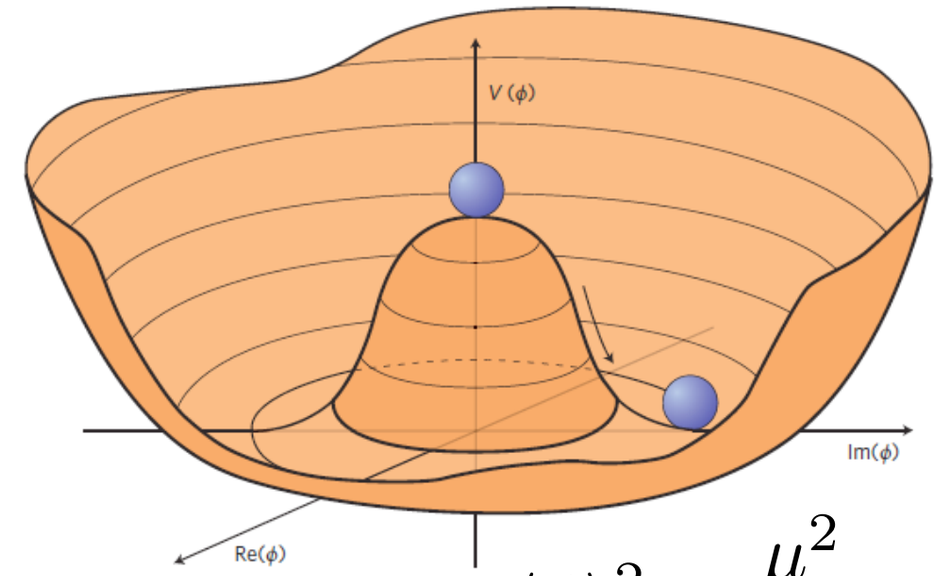
$$\mathcal{L}_{\text{eff}} = \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}(\bar{f}\gamma_\mu\gamma_5 f)$$

Pospelov, Ritz, Voloshin 2007; Georgi, Kaplan, Randall 1986

Goldstone bosons

$$V(\phi) = -\mu^2\,\phi^\dagger\phi + \frac{\lambda}{2}(\phi^\dagger\phi)^2$$

$$\phi = \big(\langle\phi\rangle + s\big)e^{i\frac{a}{f}}$$



$$\langle\phi\rangle^2 = \frac{\mu^2}{\lambda}$$

massive scalar: $m_s^2 = \mu^2$

Goldstone boson (ALP): $m_a = 0$

U(1) symmetry

$$\phi(x) \to \phi(x)e^{i\frac{c}{f}}$$

$\longleftrightarrow$

shift symmetry

$$a(x) \to a(x) + c$$

Bonnefoy et al. 2206.04182

Axion-like particles

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}(\overline{f}\gamma_\mu\gamma_5 f) + \sum_V c_{VV}\frac{a}{f_a}\frac{g^2}{(4\pi)^2}V_{\mu\nu}\widetilde{V}^{\mu\nu}$$

$a \to a + c$: ✓ ✗ ✓ anomaly

ALP mass breaks shift symmetry. $m_a \propto ?$

Axion-like particles

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}(\overline{f}\gamma_\mu\gamma_5 f) + \sum_V c_{VV}\frac{a}{f_a}\frac{g^2}{(4\pi)^2}V_{\mu\nu}\widetilde{V}^{\mu\nu}$$

$a \to a + c$: ✓ ✗ ✓ anomaly

ALP mass breaks shift symmetry. $m_a \propto ?$

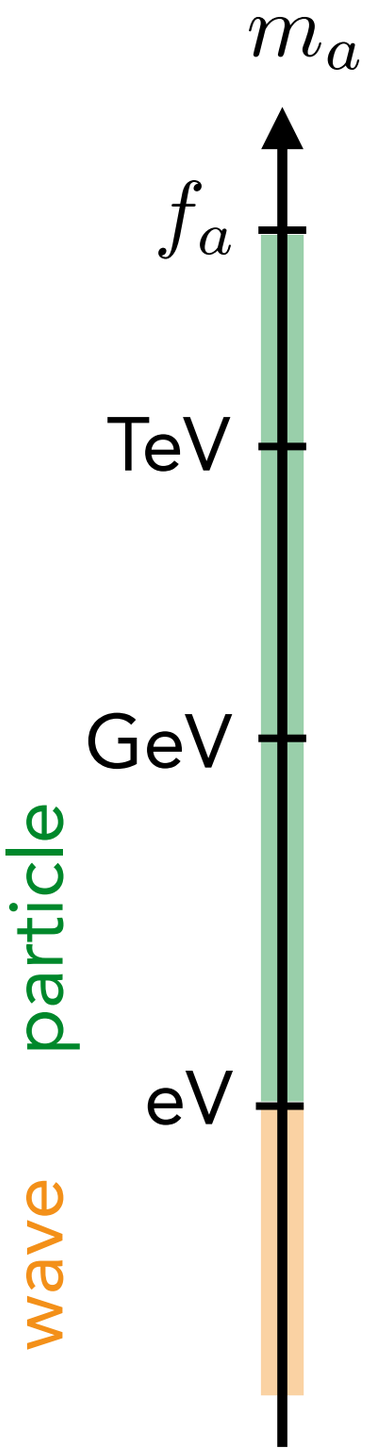
QCD axion: $U(1)_{\text{PQ}}$ spontaneously broken at $f \gg \Lambda_{\text{QCD}}$.

$$\mathcal{L} = \theta\,\frac{\alpha_s}{4\pi}\,G_{\mu\nu}\widetilde{G}^{\mu\nu} \to \left(\theta + \frac{a}{f}\right)\frac{\alpha_s}{4\pi}\,G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

Peccei, Quinn 1977

ALP mass from chiral symmetry breaking: $m_a^2 \propto \dfrac{f_\pi^2\, m_\pi^2}{f_a^2}$

ALPs across the scales

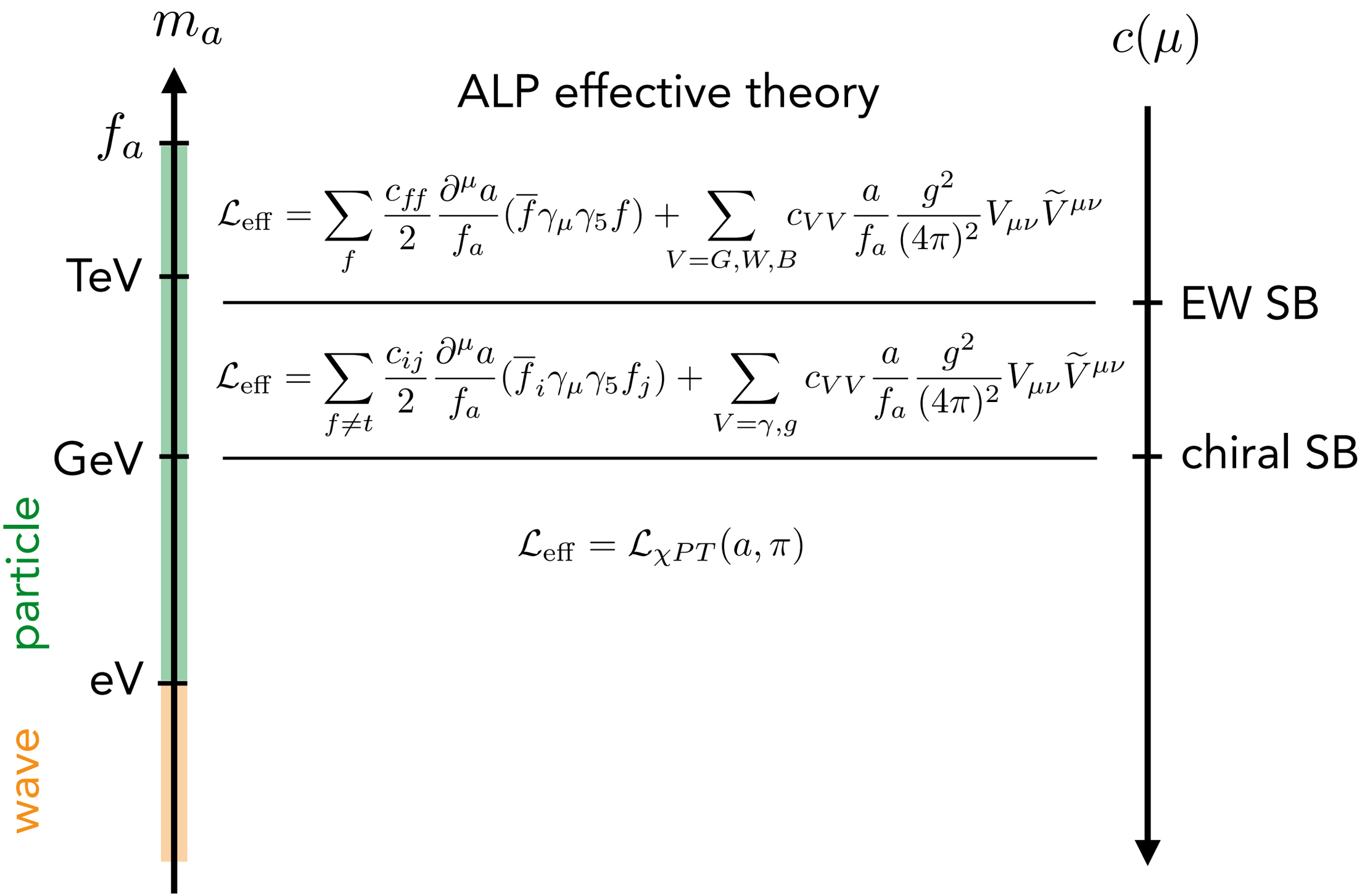


LHC: resonances, Higgs decays, …

LHC, Belle II, fixed-target

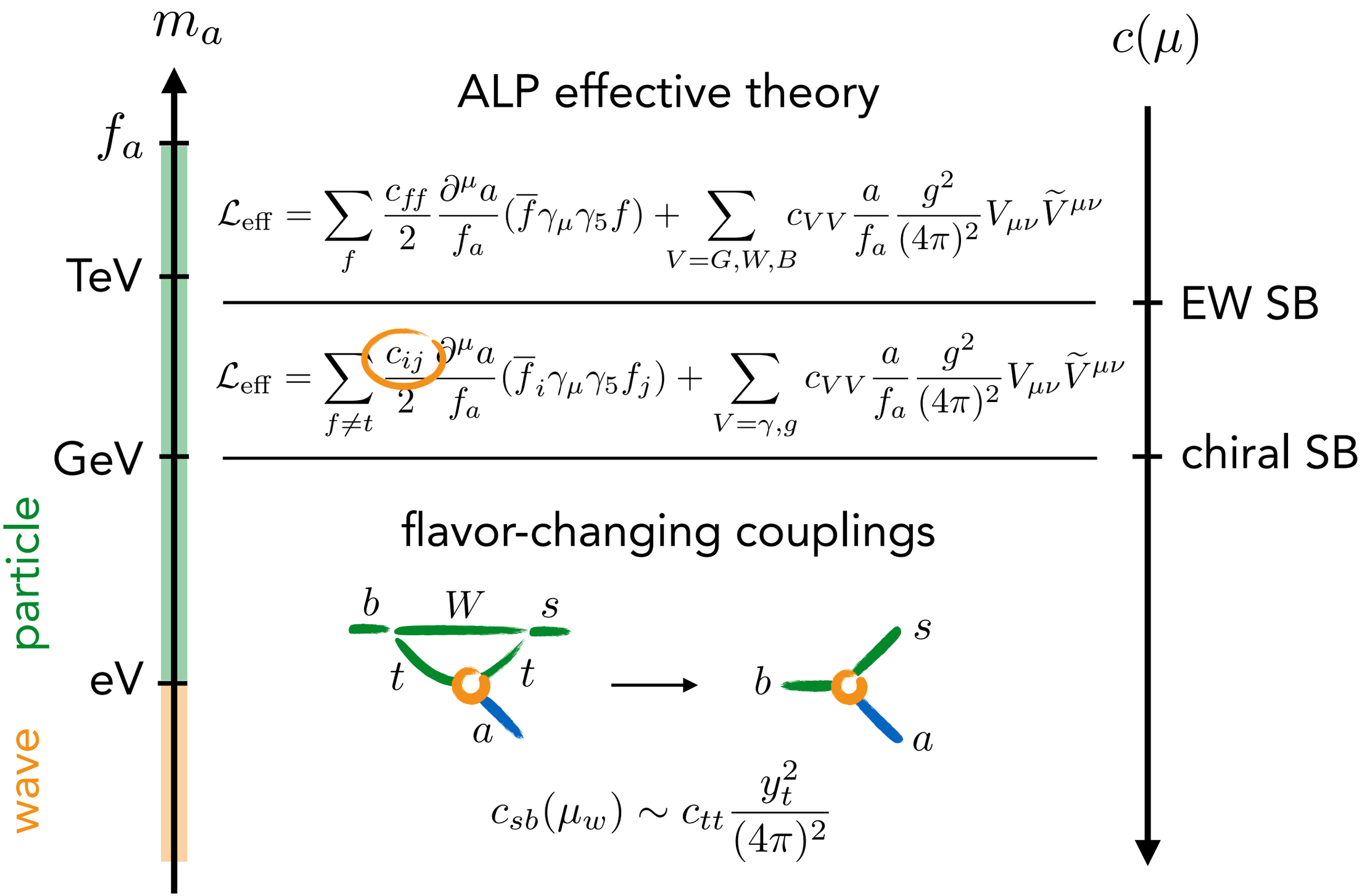
cosmology, table tops: ALPS II, …

Running couplings



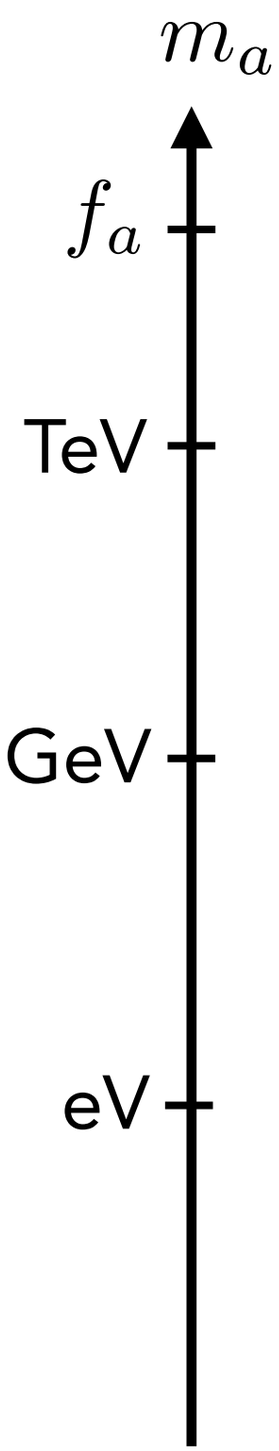
Chala et al. 2012.09017; Bauer et al. 2012.12272

Running couplings

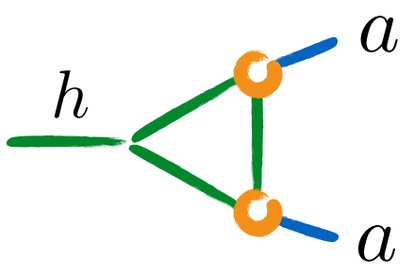


Life of an ALP

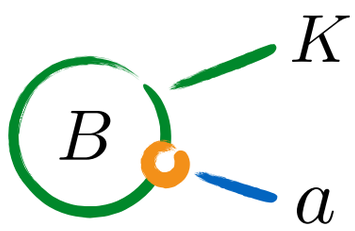
$$\mathcal{L}_{\text{eff}} = \sum_f \frac{c_{ff}}{2} \frac{\partial^\mu a}{f_a} (\overline{f} \gamma_\mu \gamma_5 f) + \sum_{V=G,W,B} c_{VV} \frac{a}{f_a} \frac{g^2}{(4\pi)^2} V_{\mu\nu} \widetilde{V}^{\mu\nu}$$



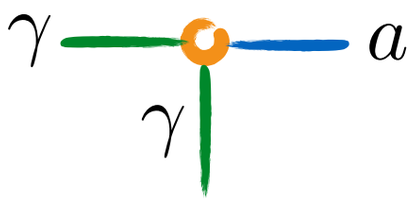
production



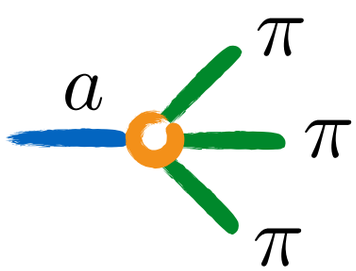
Bauer, Neubert, Thamm
1708.00443

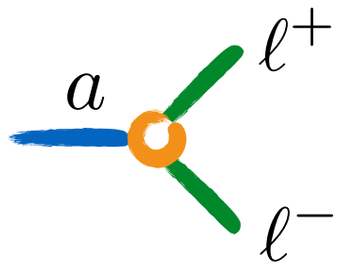


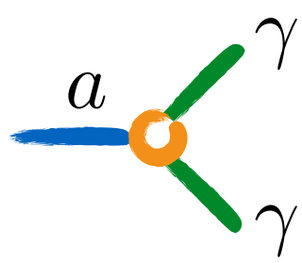
Batell, Pospelov, Ritz
0911.4938



decay

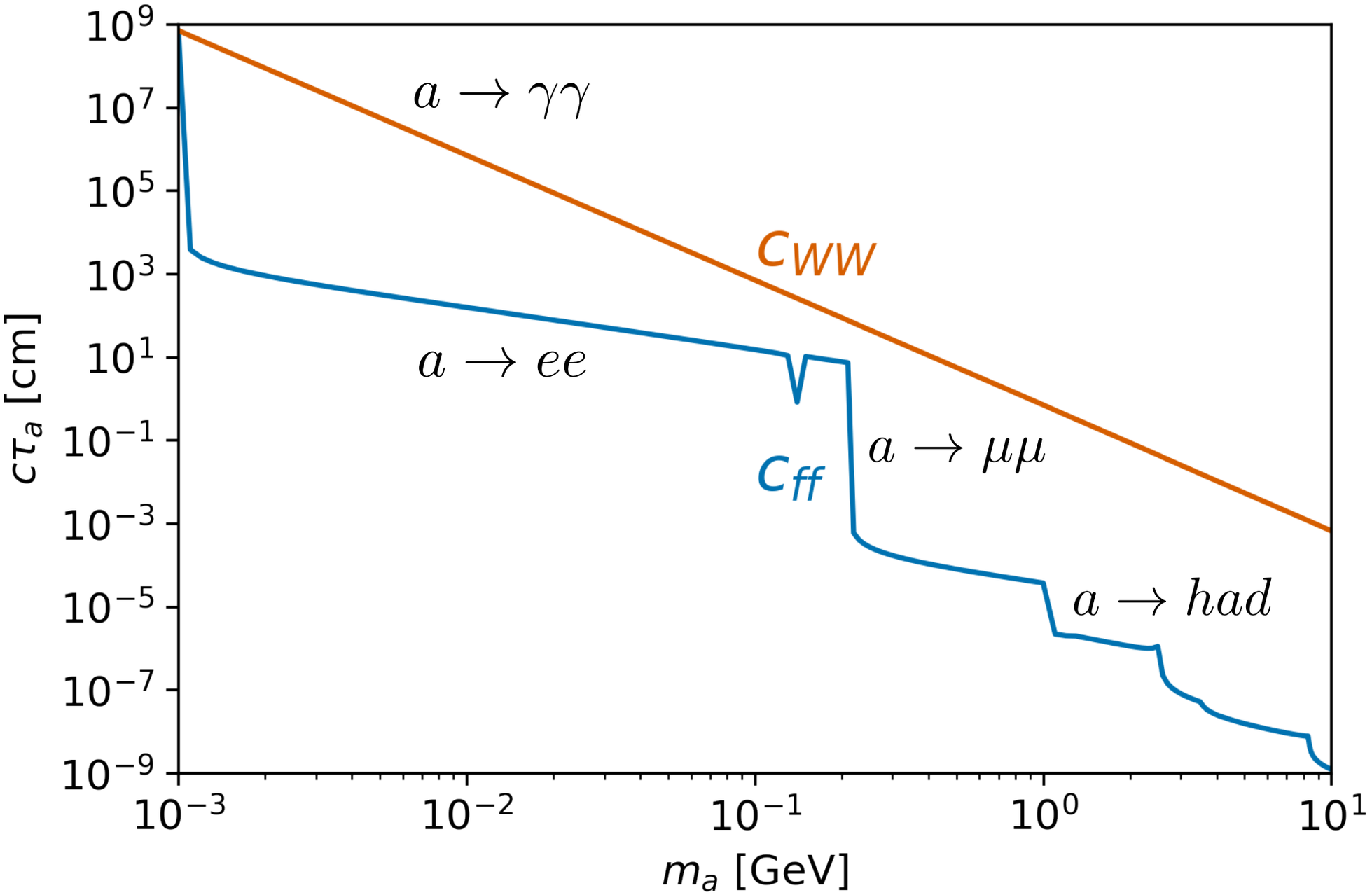




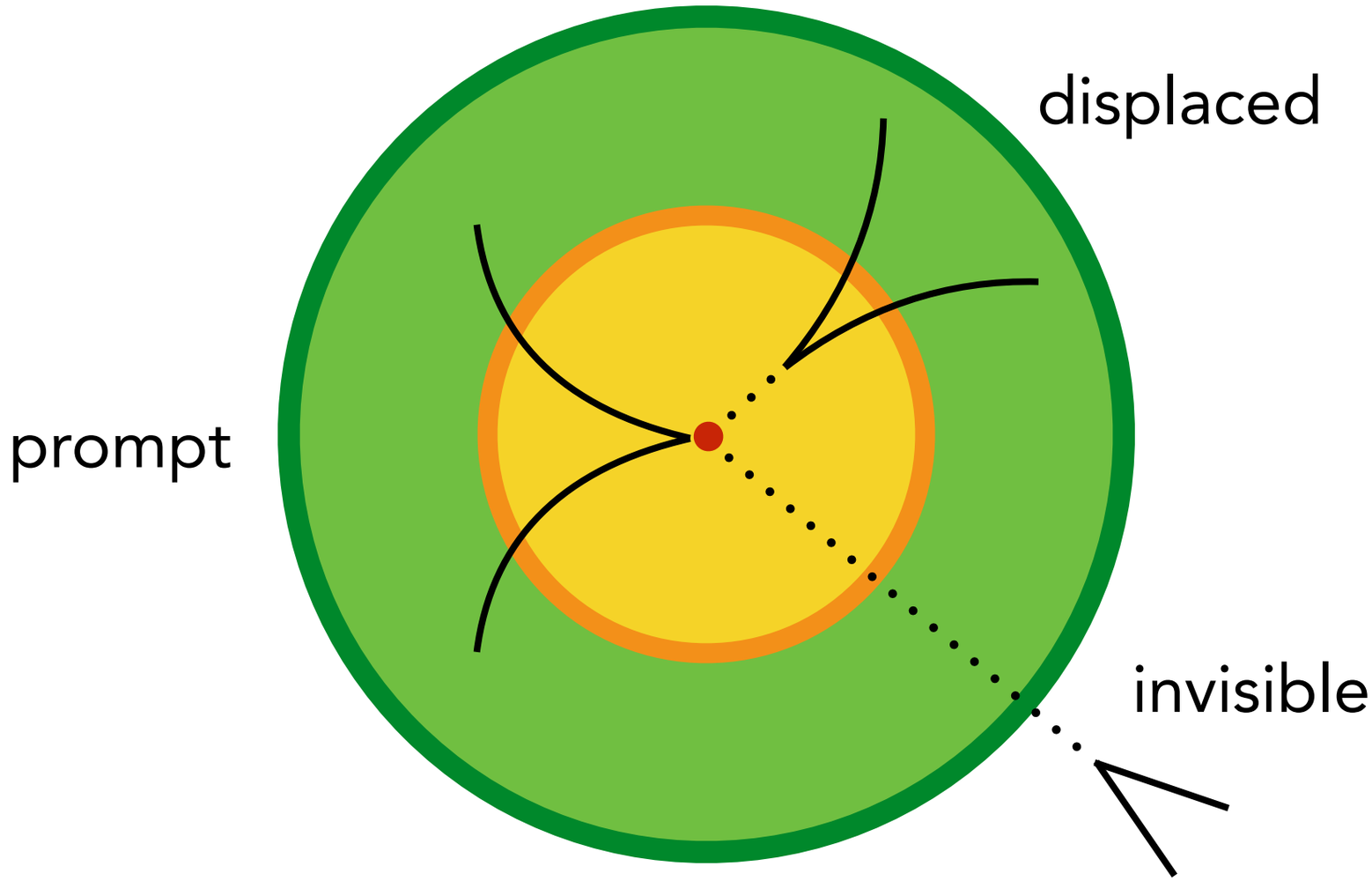


Long-lived ALPs

lifetime $\tau_a = 1/\Gamma_a$

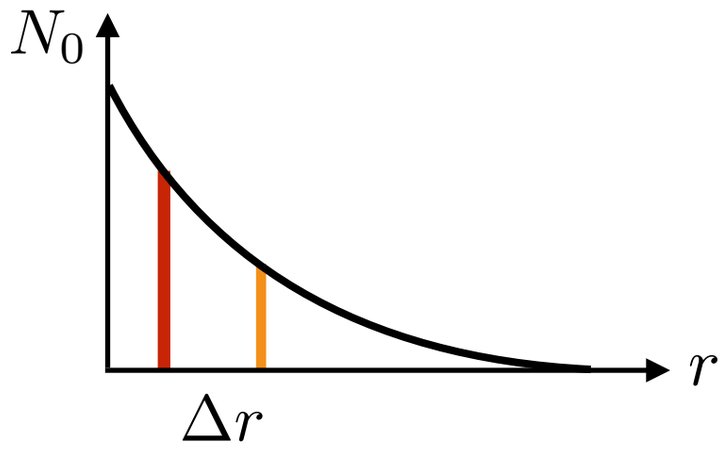


ALPs at colliders

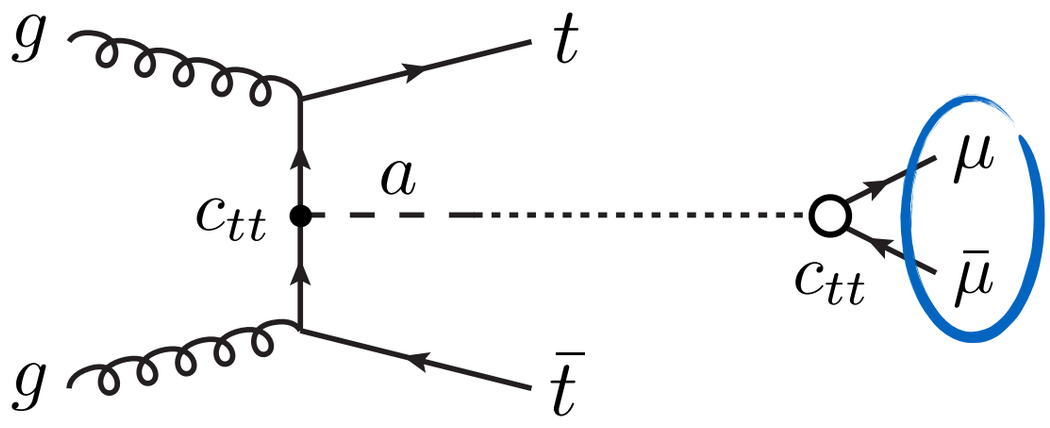


expected event rate:

$$N(\Delta V) = N_0 \frac{\Delta\Omega}{4\pi}\left[\exp\left(-\frac{r}{d}\right) - \exp\left(-\frac{r+\Delta r}{d}\right)\right]$$



LHC: ALPs in top-antitop production

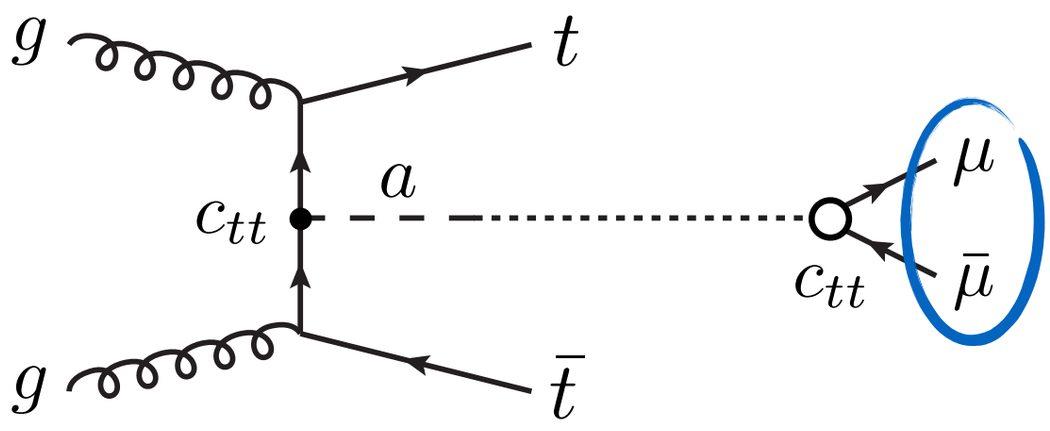


displaced vertex

Rygaard, SW et al. 2306.08686

- $pp \to t\bar{t}a,\ a \to \not{E}$: Esser et al. 2303.17634
- $pp \to t\bar{t},\ t \to ca$: Carmona et al. 2202.09371

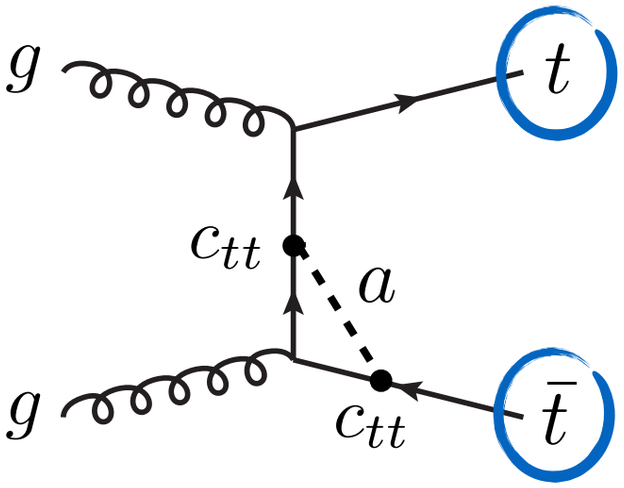
LHC: ALPs in top-antitop production



$2m_\mu < m_a \lesssim 10\,\mathrm{GeV}$

displaced vertex

Rygaard, SW et al. 2306.08686

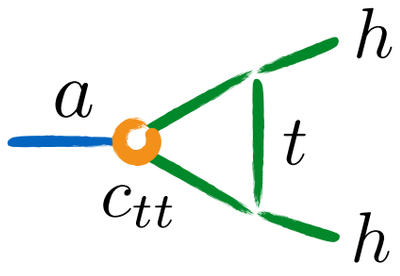


$m_a \lesssim 100\,\mathrm{GeV}$

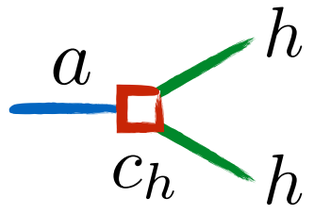
top kinematics

Phan, SW in preparation

Top-induced leptonic ALP decays



+



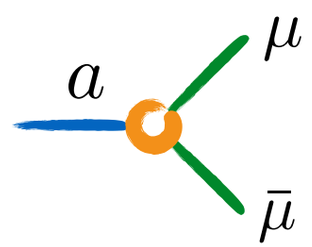
$$O_h = \frac{\partial_\mu a}{f_a}\left(H^\dagger i D^\mu H + h.c.\right)$$

- remove O_h by field redefinitions $H \to e^{ic_h a/f_a} H,\ \ f \to e^{-i\beta_f c_h a/f_a} f$

$$O_h \to \sum_f \beta_f \frac{\partial_\mu a}{f_a} \bar{f}\gamma^\mu f$$

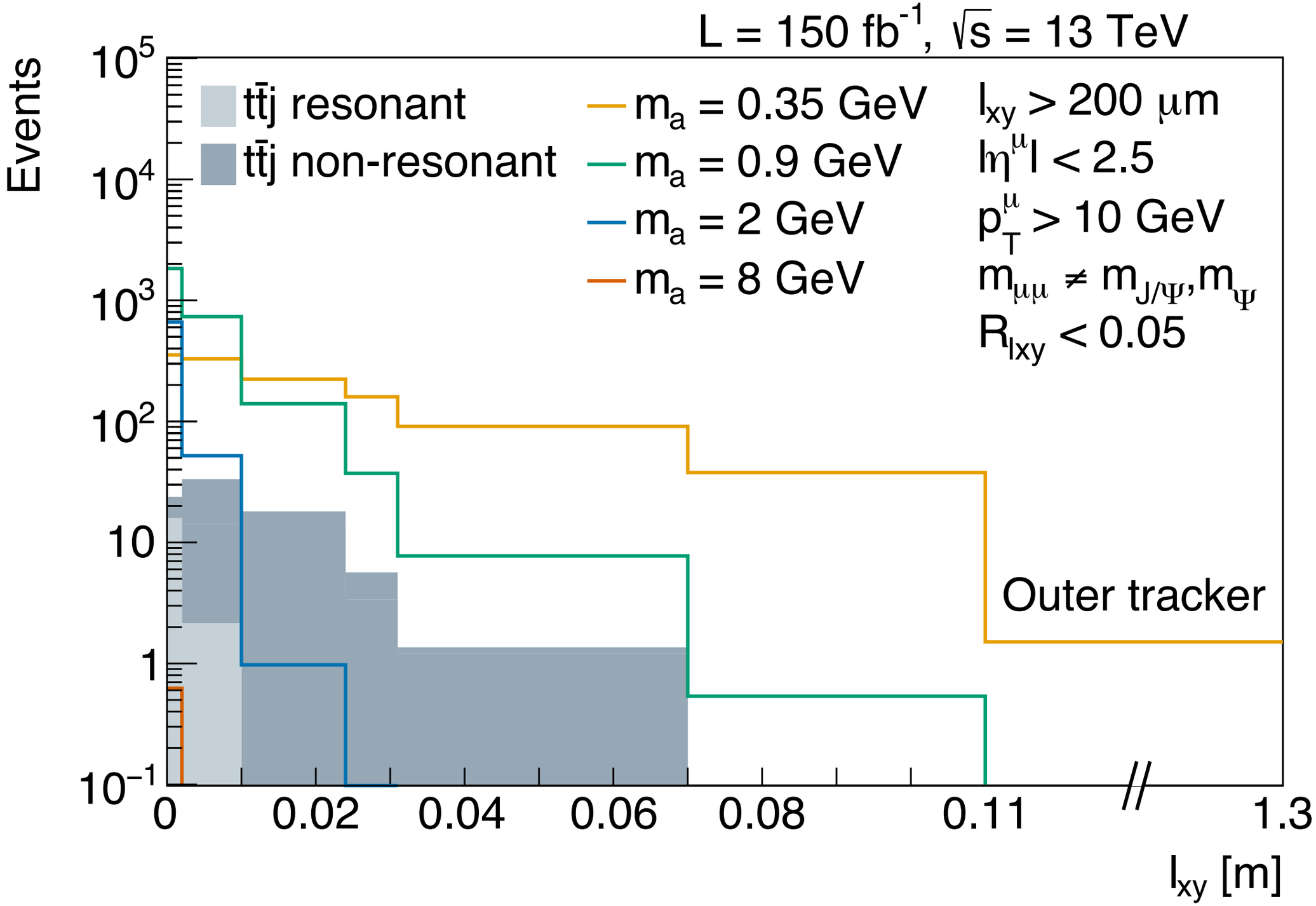
- universal top contributions to fermion couplings:

$$\frac{d}{d\ln\mu} c_{ff}(\mu) = \beta_f c_{tt} \frac{3y_t^2}{8\pi^2}$$

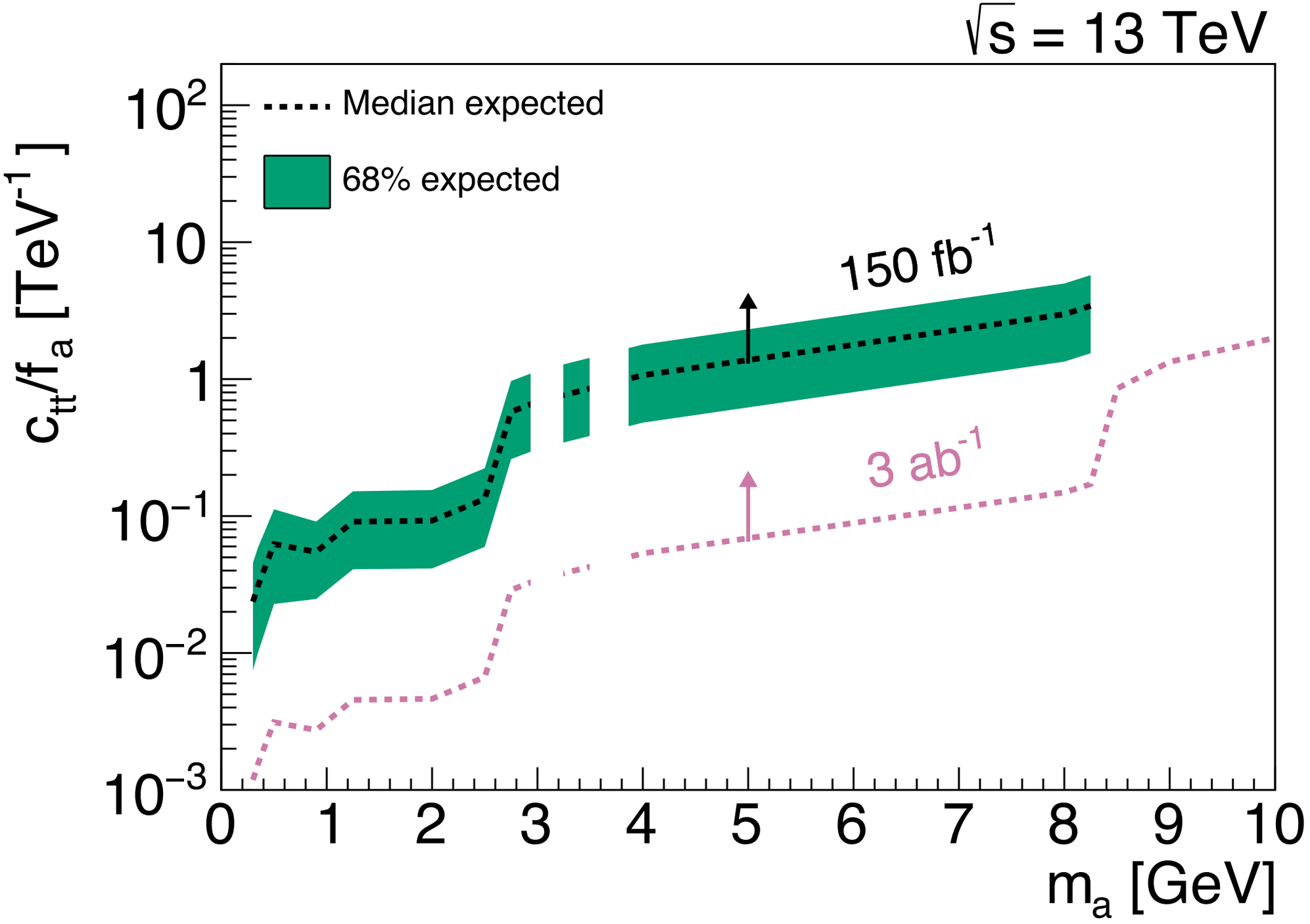


Bauer et al. 2012.12272

Transverse displacement

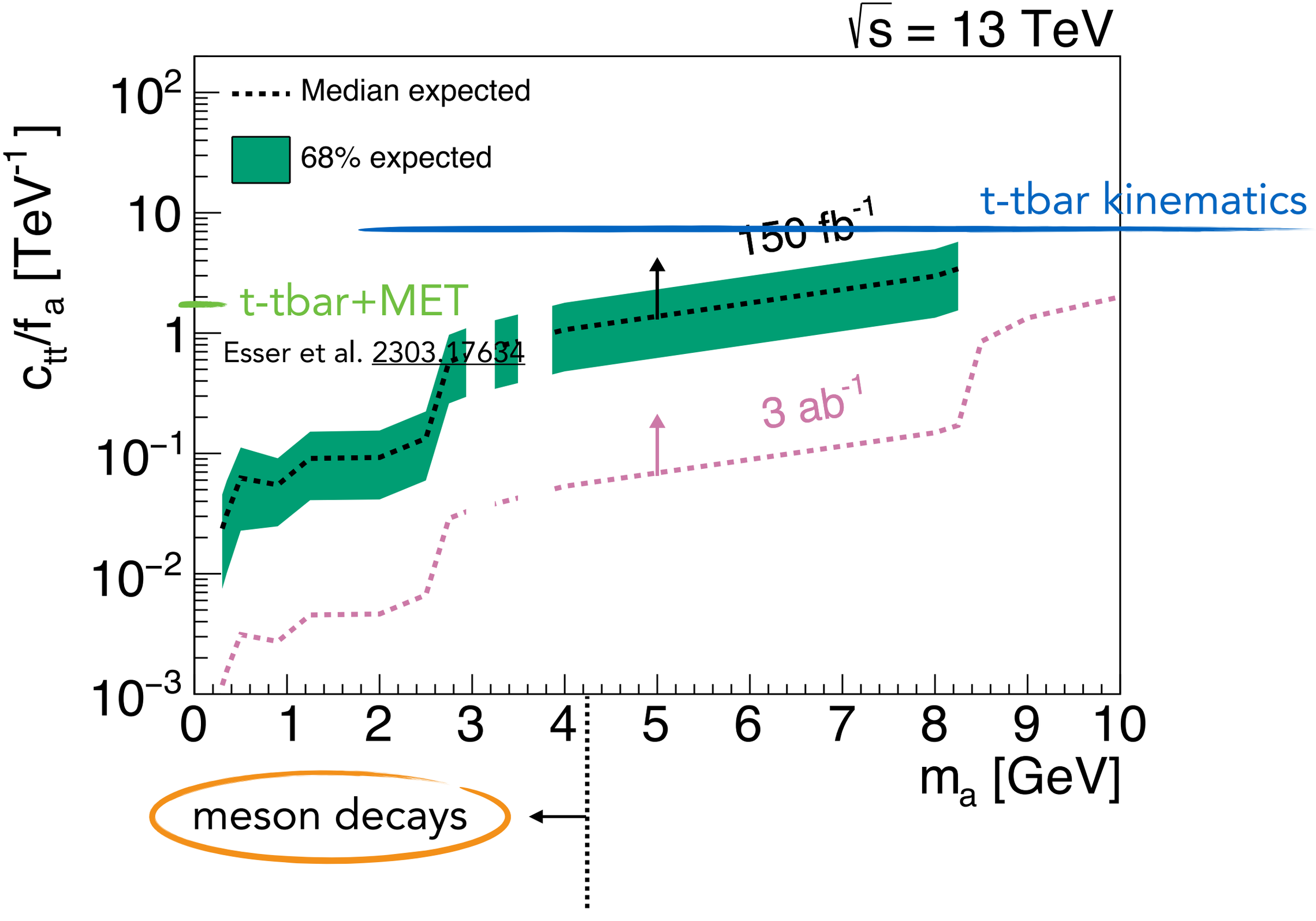


Probing the ALP-top coupling

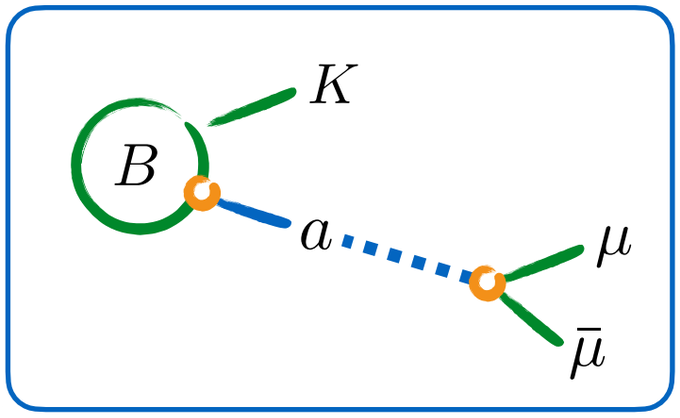


Rygaard, SW et al. 2306.08686

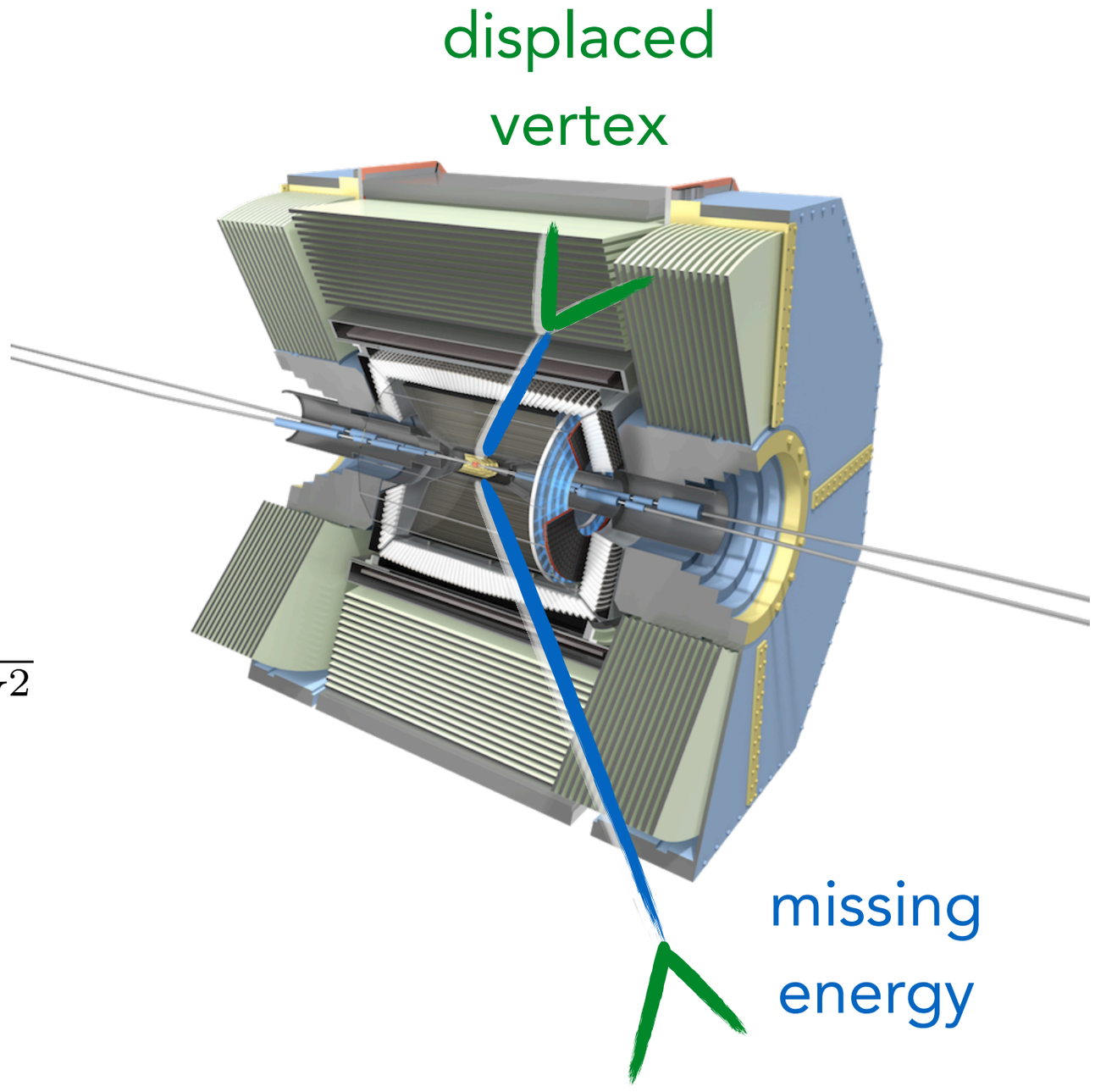
Probing the ALP-top coupling



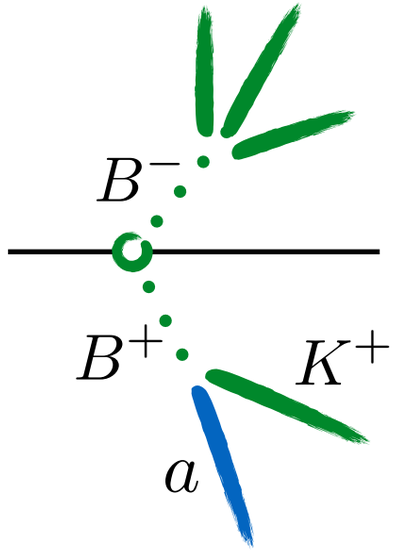
Belle II: ALPs from meson decays



$$\mathcal{B}(B^+ \to K^+ a) = 0.03 \, \frac{c_{tt}^2}{\mathrm{TeV}^2}$$

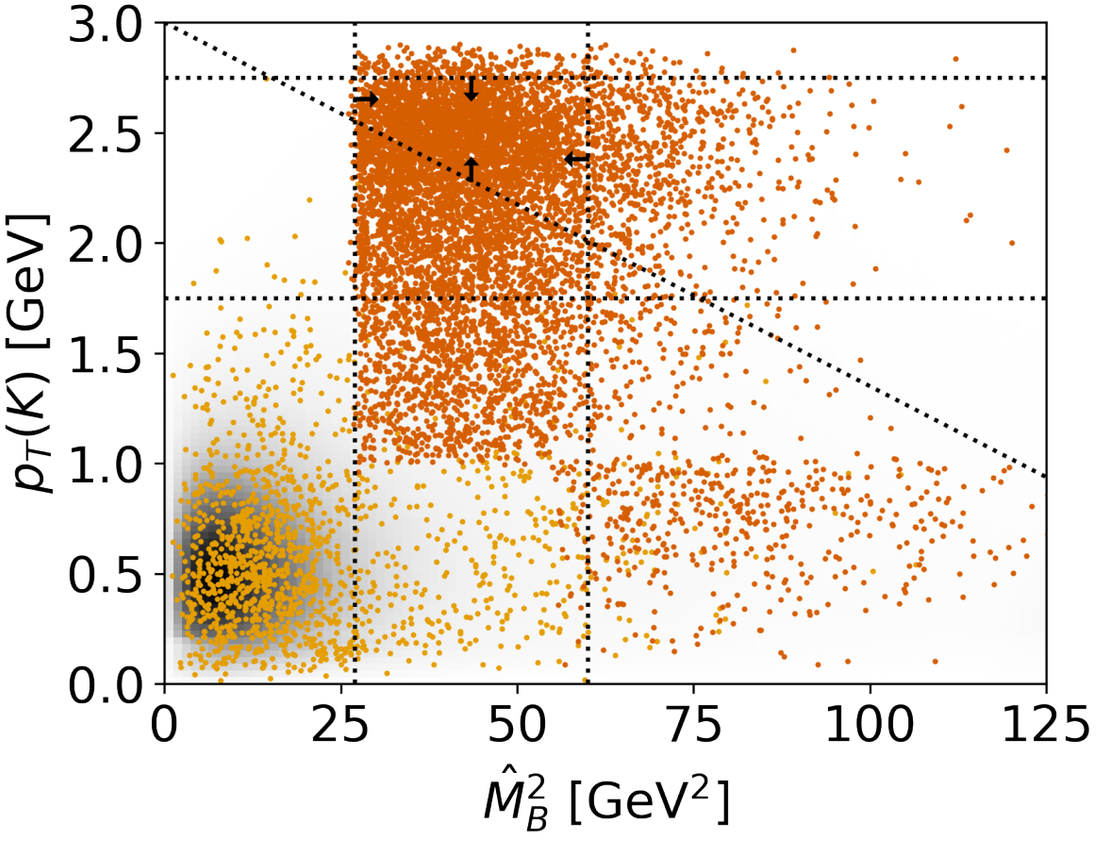


Selecting an ALP

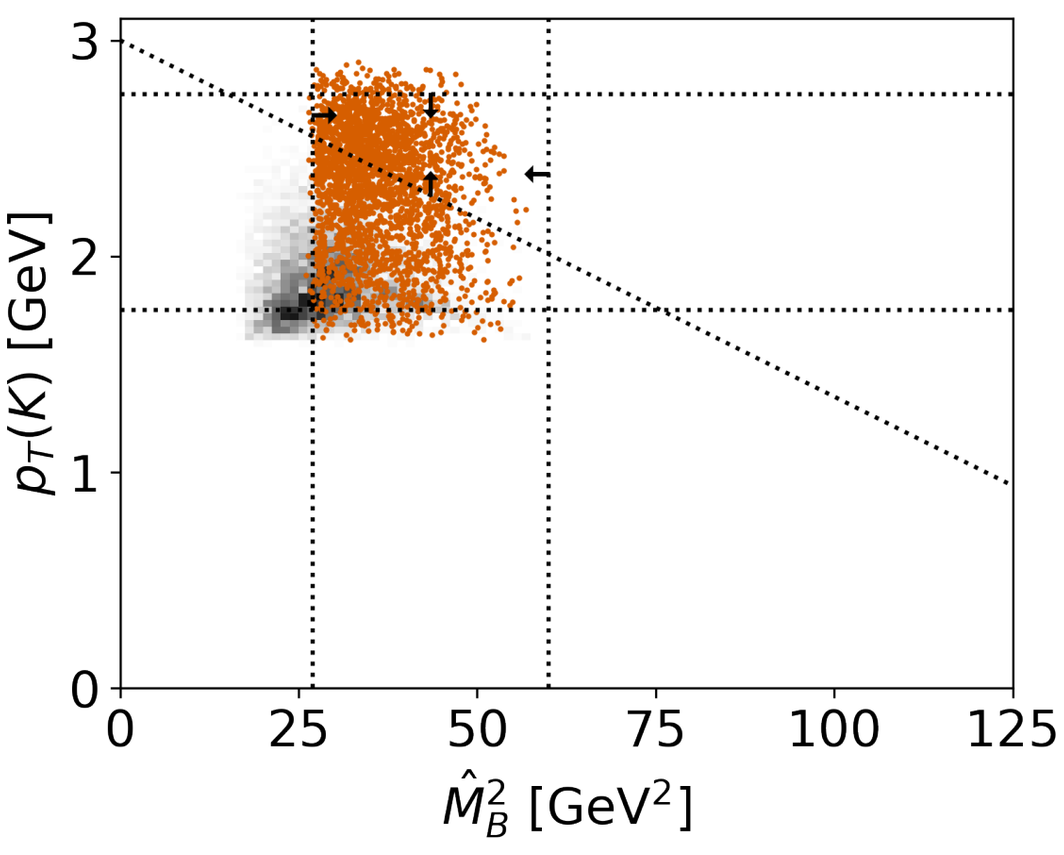


- ALP signal
- misrec. ALP-K pair
- background

before

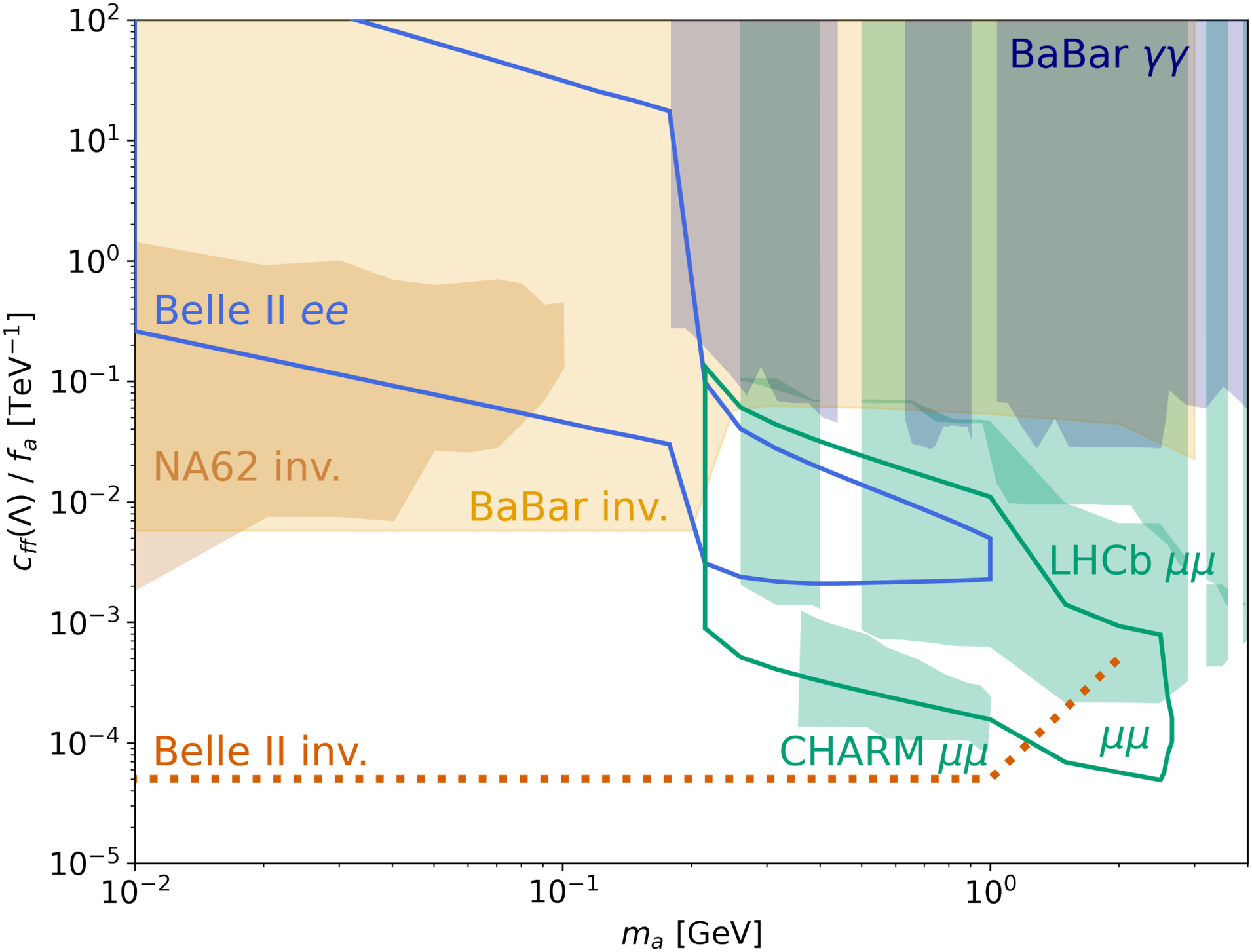


after



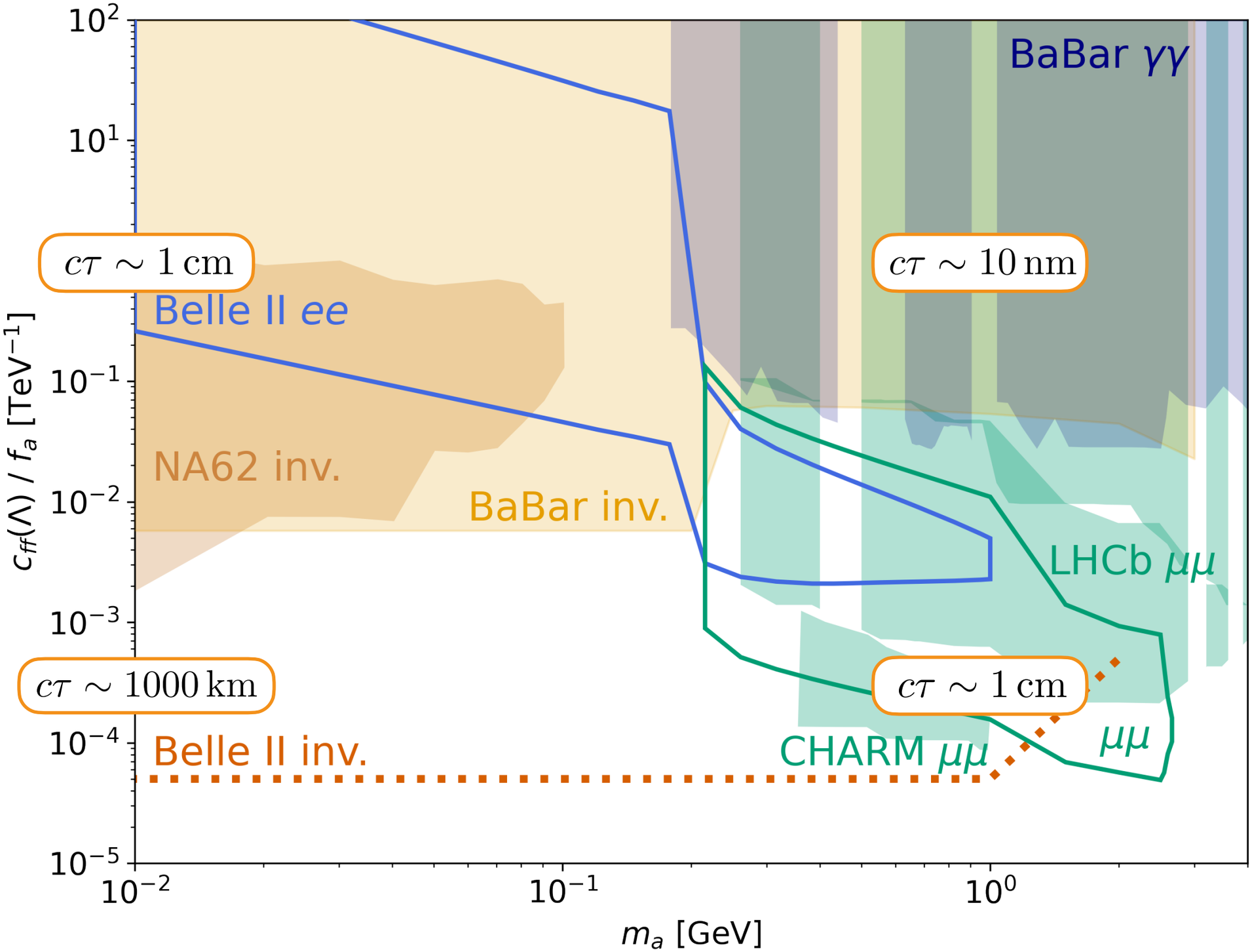
Ferber, Filimonova, Schaefer, SW 2201.06580

Displaced versus invisible



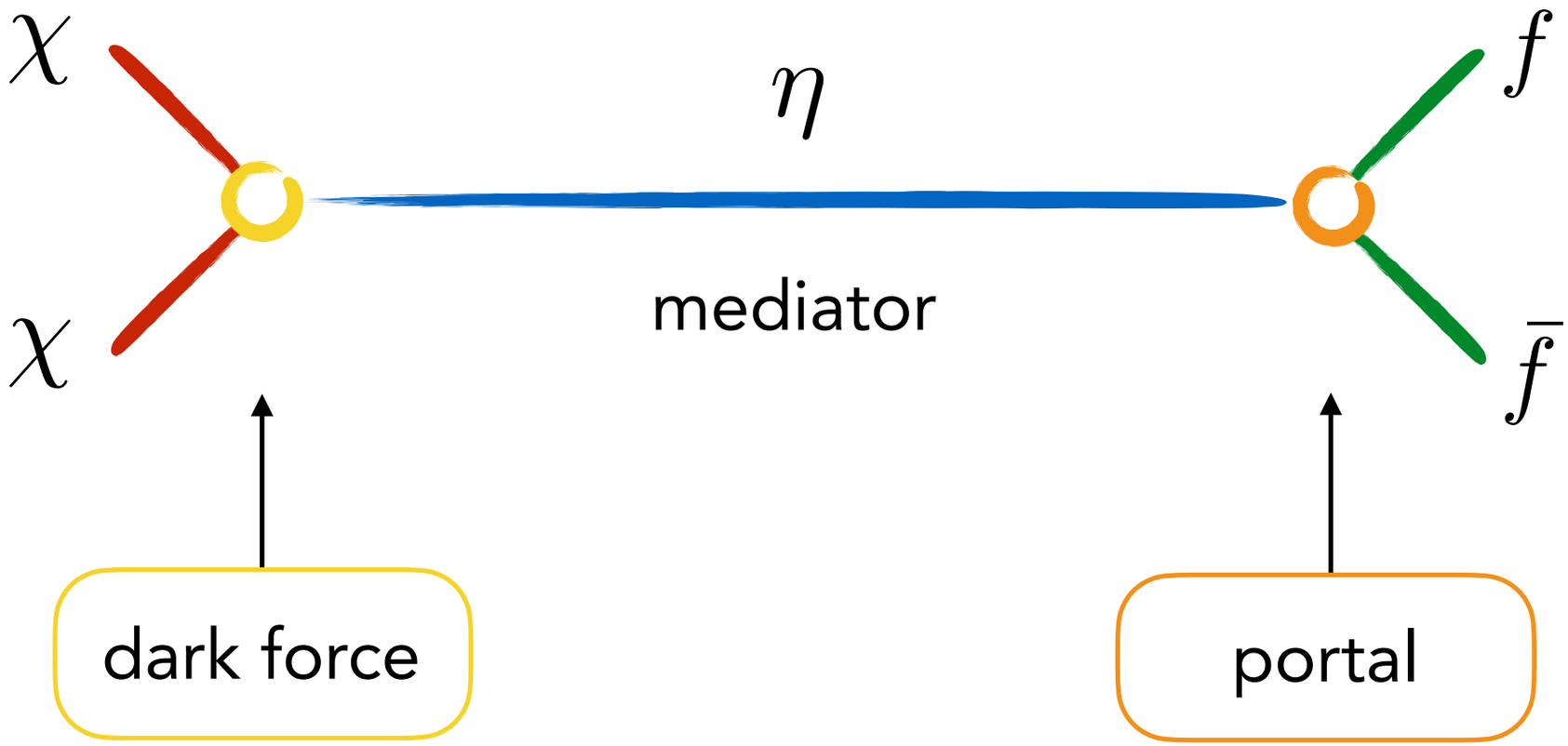
Ferber, Filimonova, Schaefer, SW 2201.06580

Displaced versus invisible



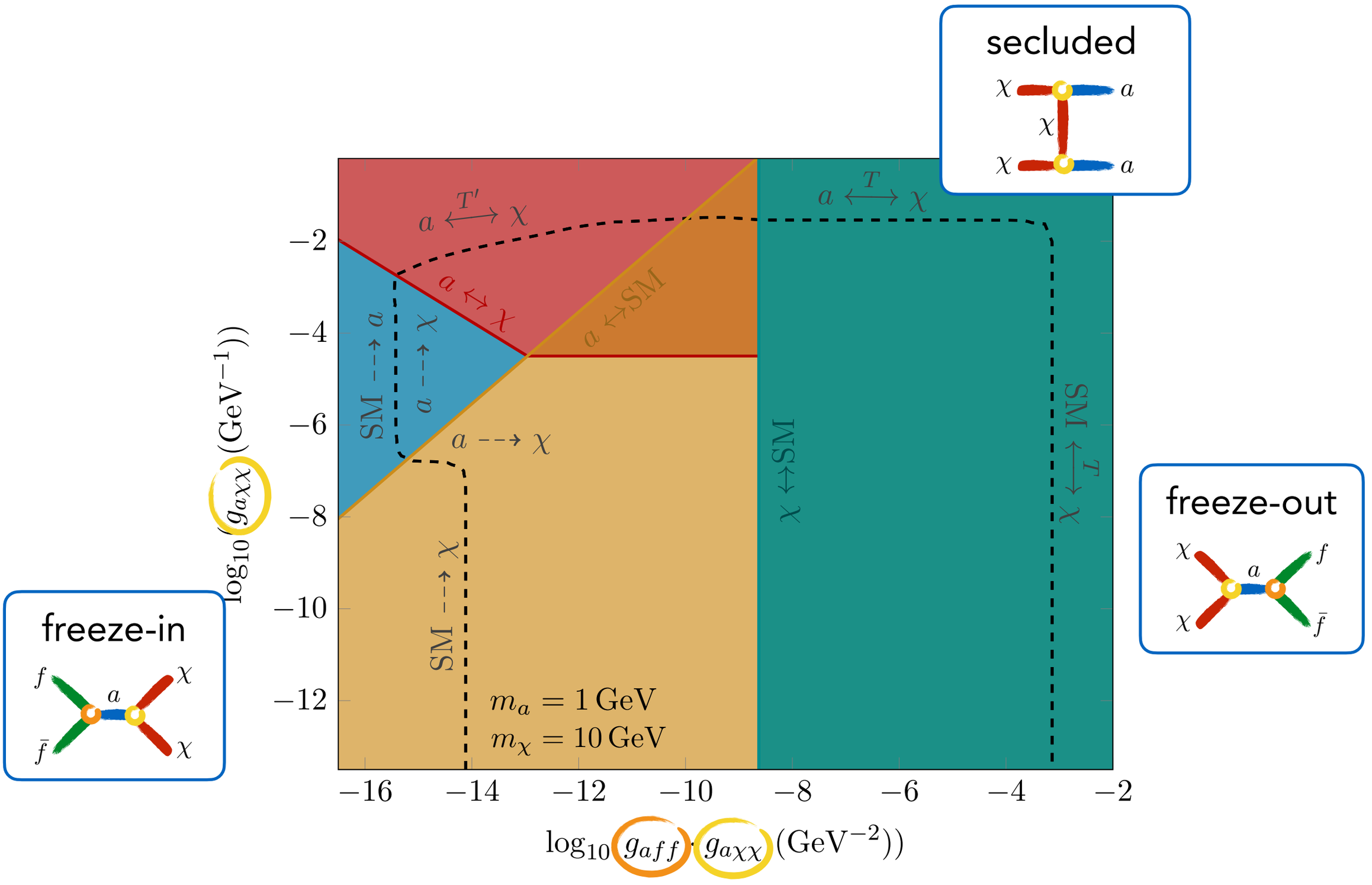
Ferber, Filimonova, Schaefer, SW 2201.06580

ALPs and dark matter



Pospelov, Ritz, Voloshin 2007

Dark matter abundance

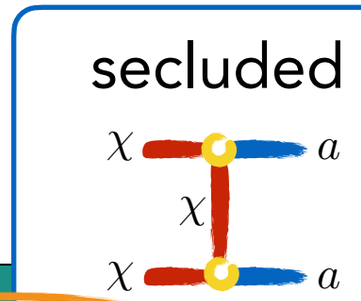


Chu, Hambye, Tytgat 1112.0493; Bharucha et al. 2209.03932

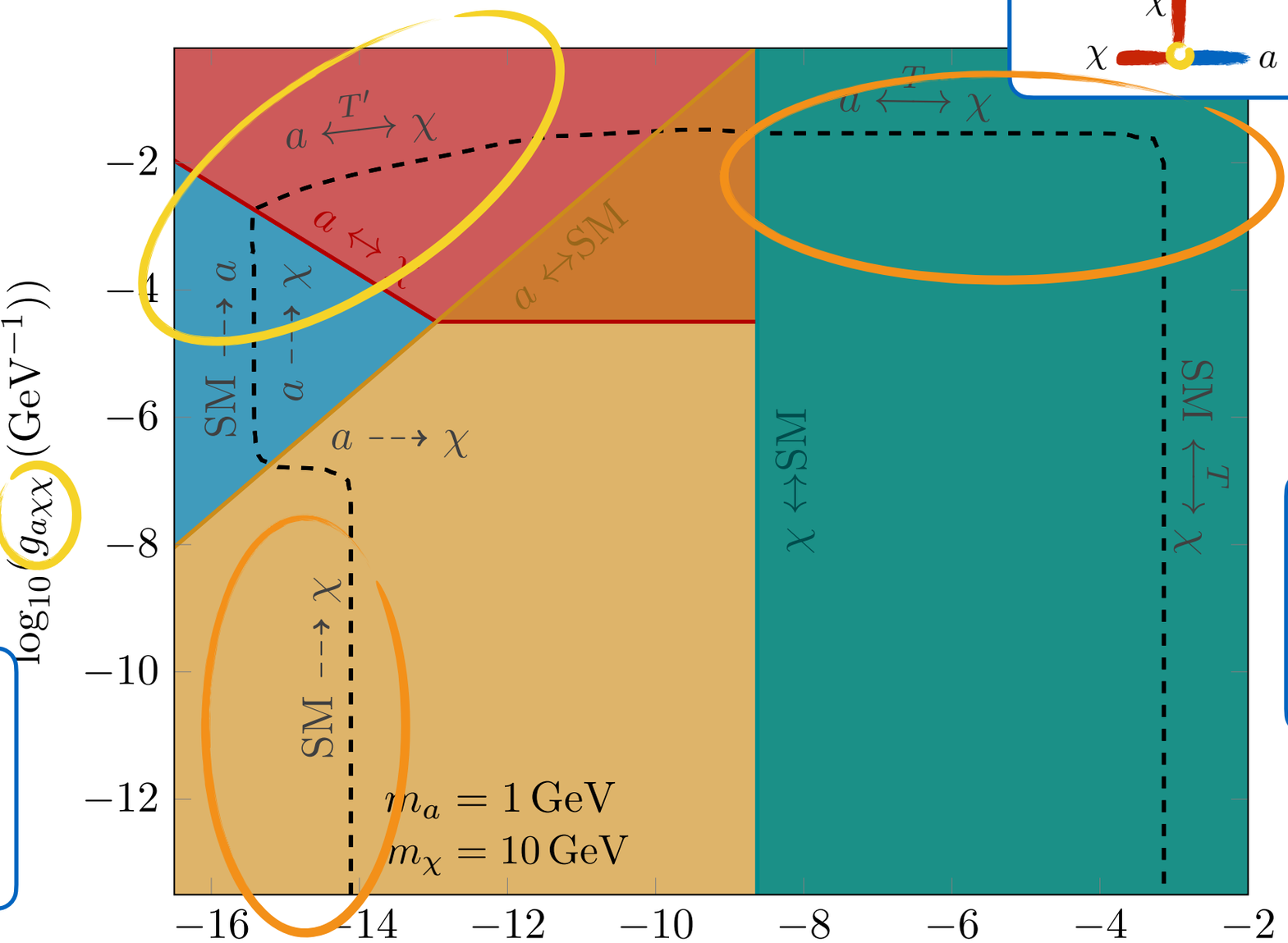
Dark matter abundance

missing energy

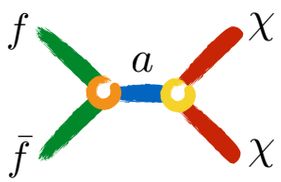
secluded



long-lived ALPs

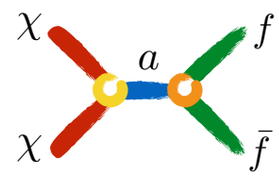


freeze-in



long-lived ALPs

freeze-out



Summary

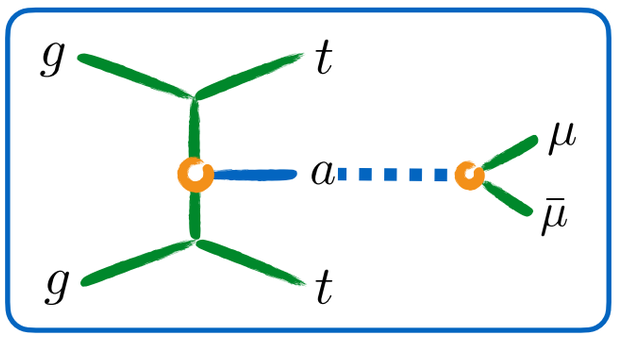
ALPs

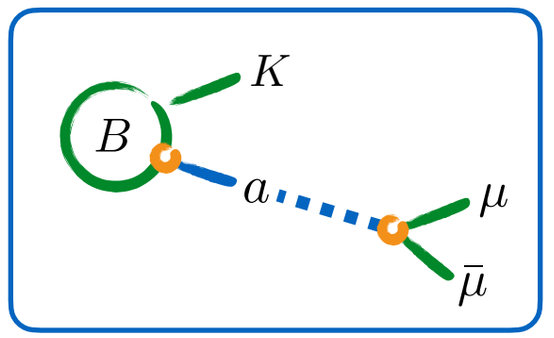
- Goldstone bosons; shift symmetry
- ALP couplings: effective theory

Probing feebly interacting ALPs

- at colliders:

  displaced or invisible

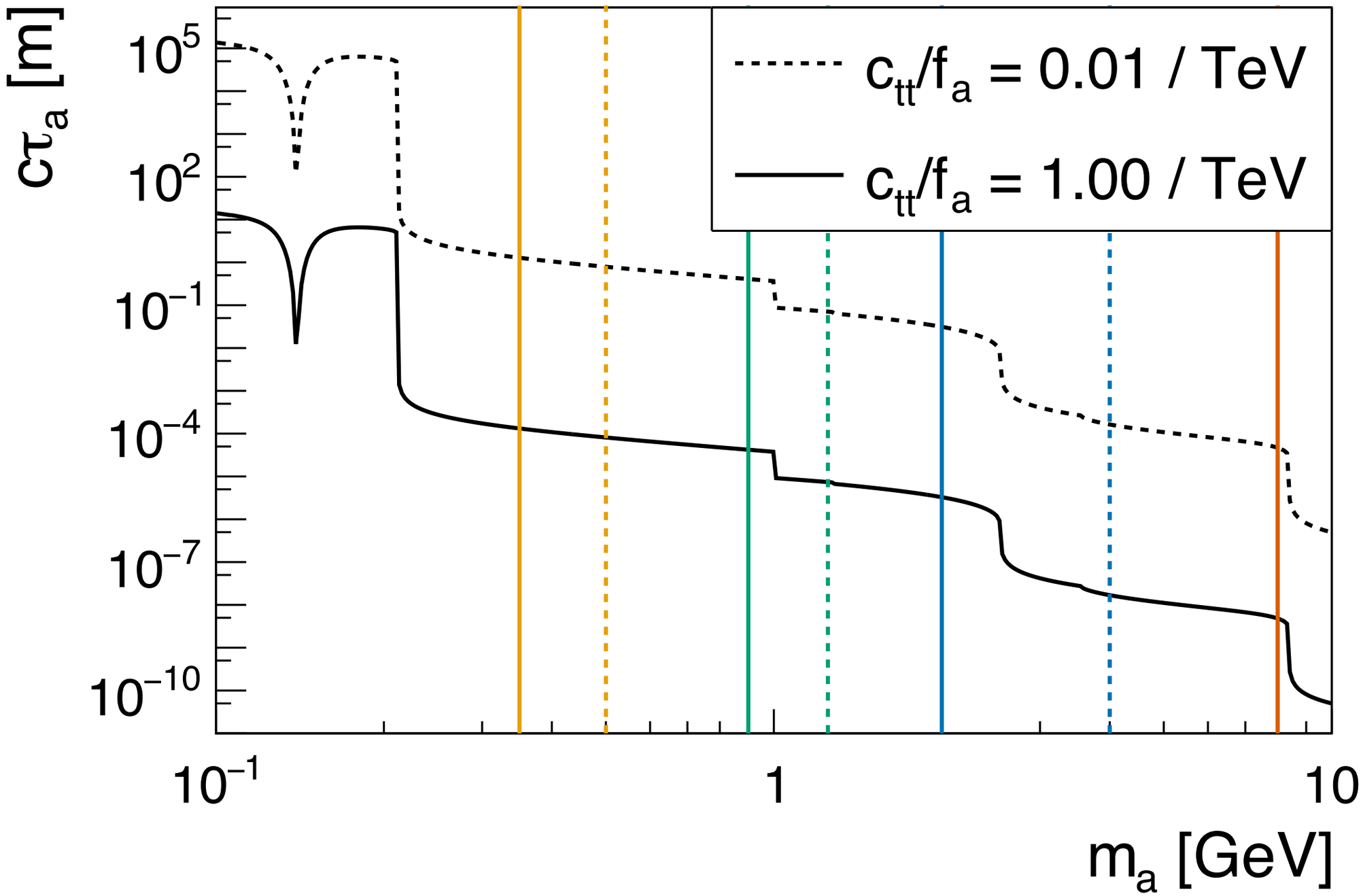




- beyond colliders: FASER, fixed-target, astrophysics, …

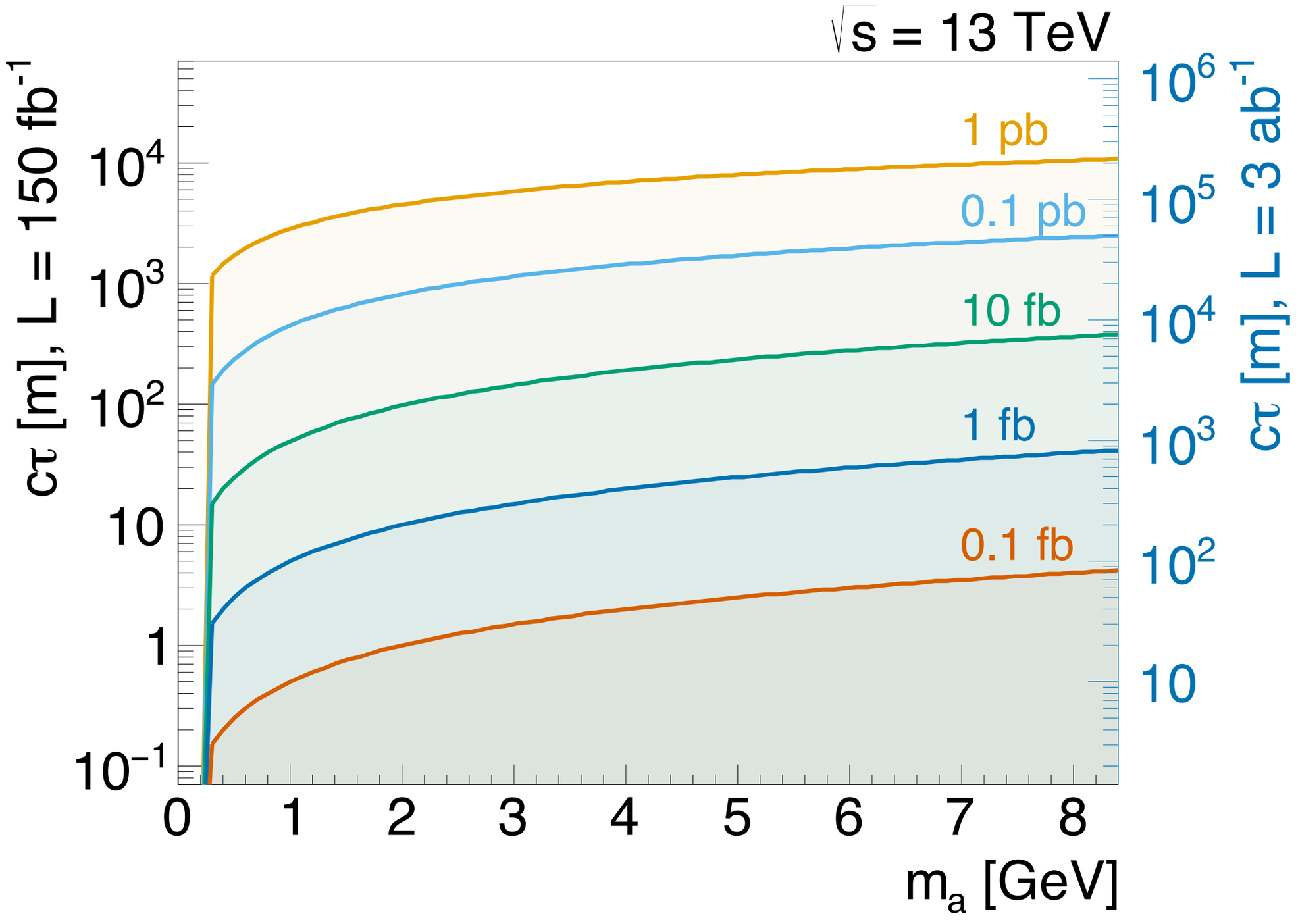
BACKUP

ALP lifetime in top scenario



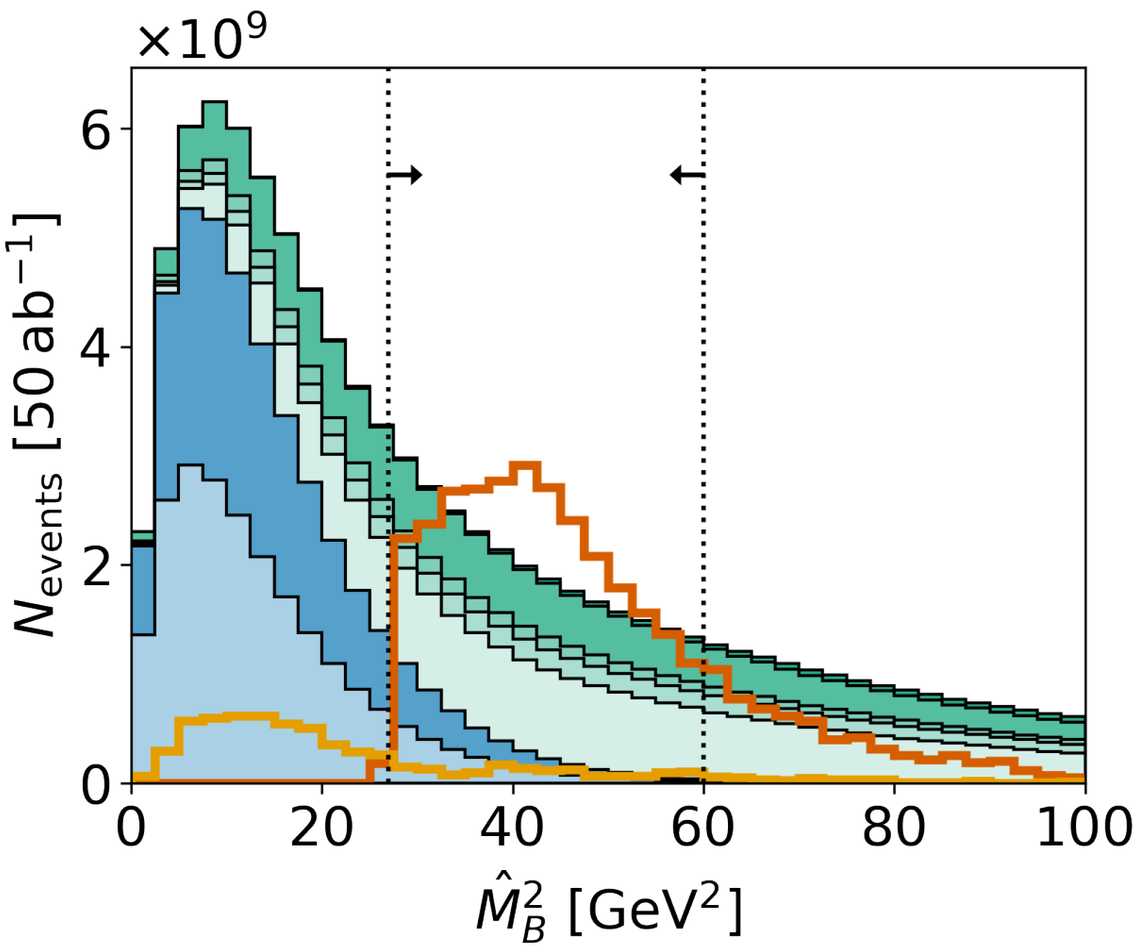
Rygaard, SW et al. 2306.08686

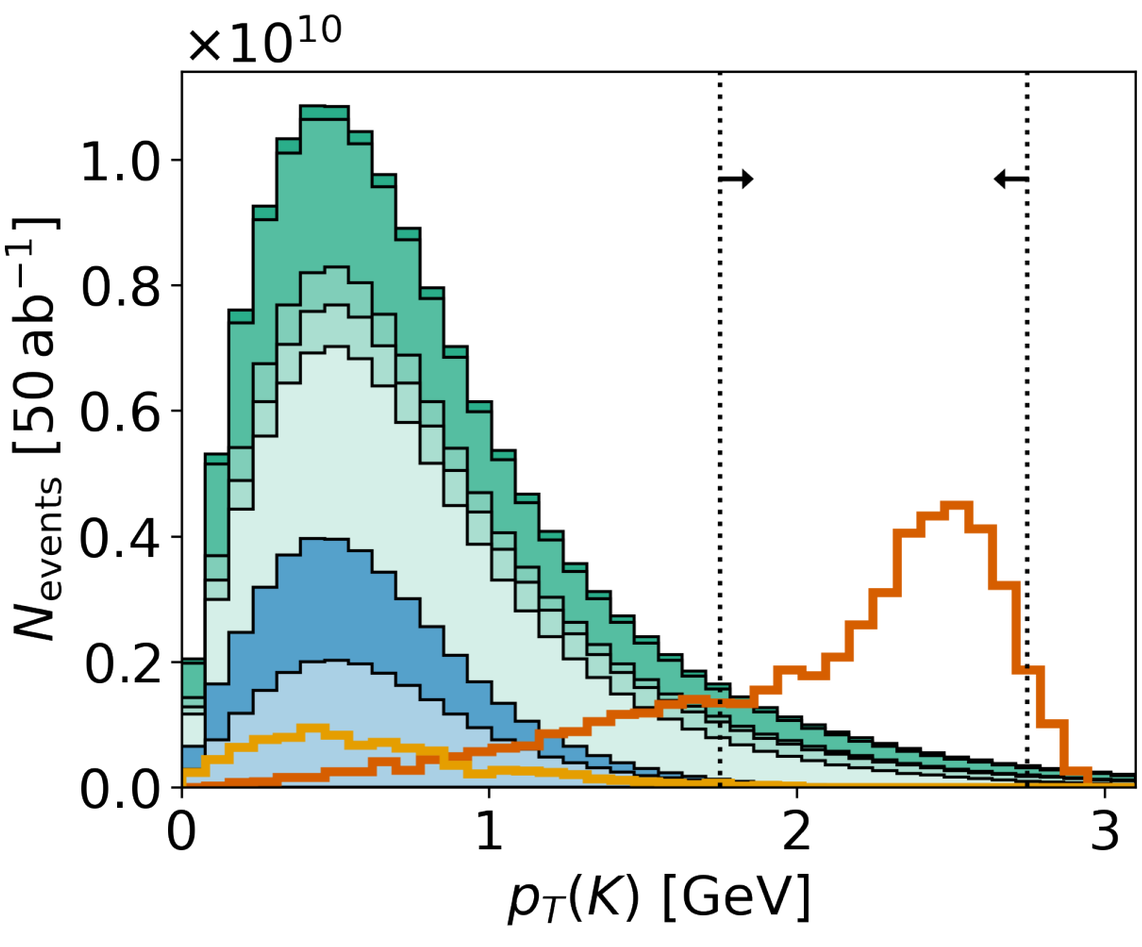
Displaced ALPs in top production

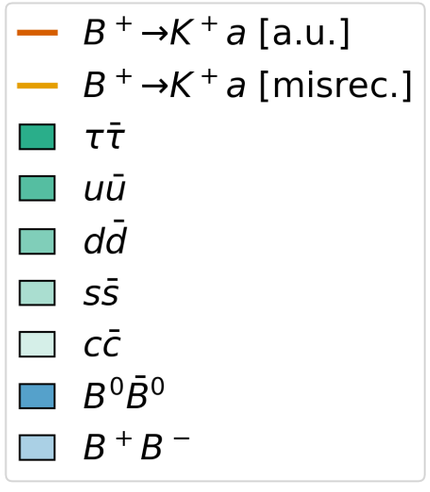


Rygaard, SW et al. 2306.08686

Invisible ALPs from B decays

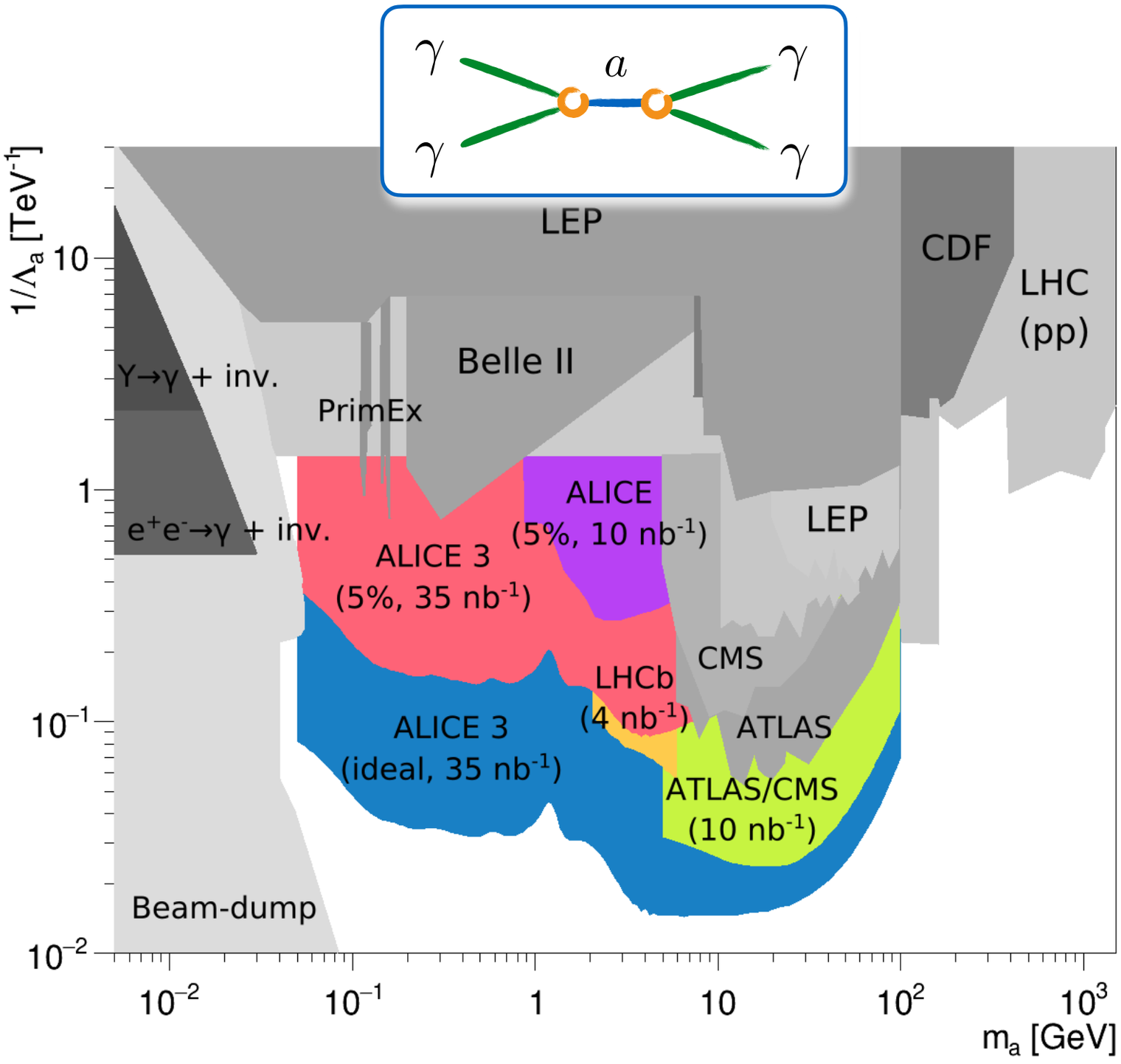






Ferber, Filimonova, Schaefer, SW 2201.06580

ALPs from photon fusion



d'Enterria et al. 2203.05939