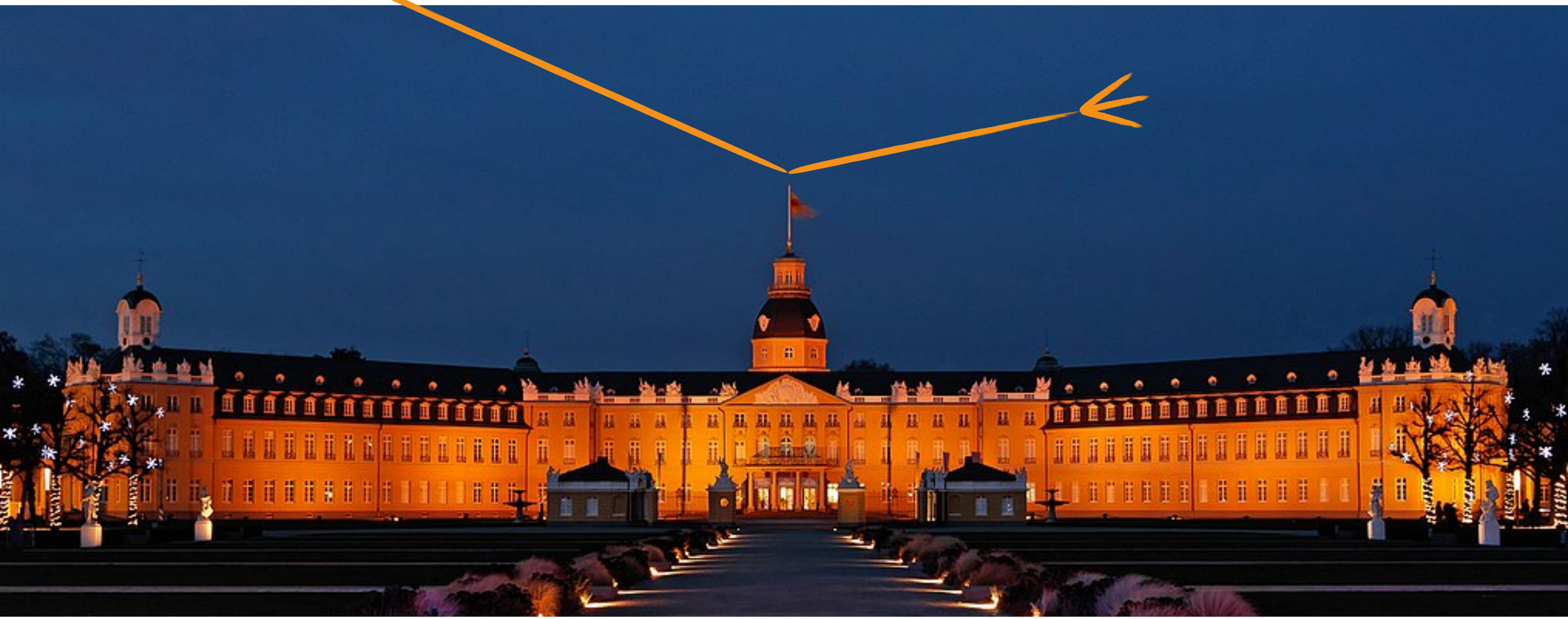
Light Dark ALPs



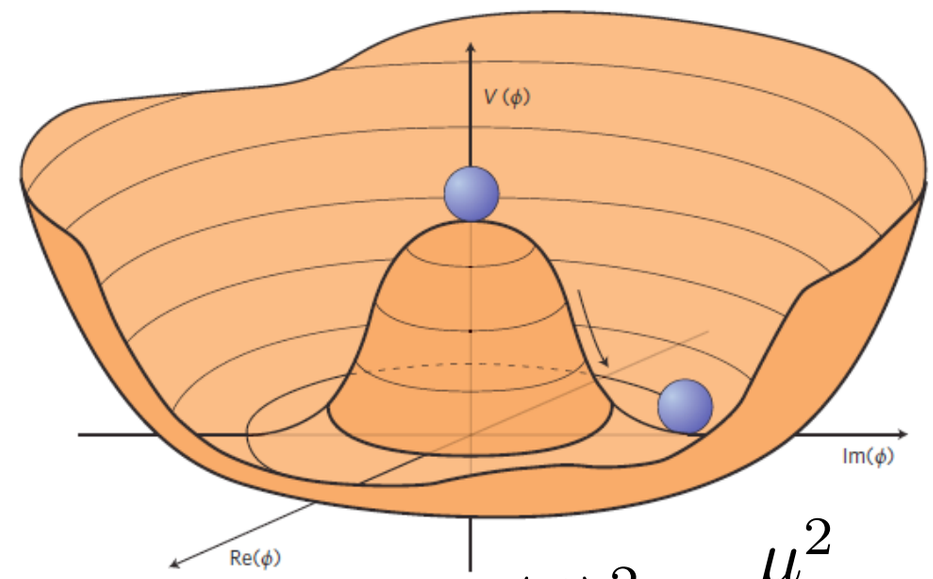
Susanne Westhoff
Radboud University . Nikhef

Light Dark World 2023 . September 19-21 . KIT Karlsruhe

Goldstone bosons

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

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



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

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

Goldstone boson (ALP): $m_a = 0$

U(1) symmetry		shift symmetry
$\phi(x) \to \phi(x)e^{i\frac{c}{f}}$	$\longleftrightarrow$	$a(x) \to a(x) + c$

ALP effective theory

$$\mathcal{L}_{\rm eff}(\mu) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_V c_{VV}(\mu)\,\frac{a}{f_a}\frac{g^2}{(4\pi)^2}\,V_{\mu\nu}\widetilde{V}^{\mu\nu}$$
$$+ \sum_{F=Q,L}\frac{\partial^\mu a}{f_a}\,\bar{F}_i\,(C_F)_{ij}\,\gamma_\mu\,F_j + \sum_{f=U,D,E}\frac{\partial^\mu a}{f_a}\,\bar{f}_i\,(C_f)_{ij}\,\gamma_\mu\,f_j$$

Georgi, Kaplan, Randall 1986

ALP effective theory

$$\mathcal{L}_{\rm eff}(\mu) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_V c_{VV}(\mu)\,\frac{a}{f_a}\frac{g^2}{(4\pi)^2}\,V_{\mu\nu}\widetilde{V}^{\mu\nu}$$
$$+ \sum_{F=Q,L}\frac{\partial^\mu a}{f_a}\,\bar{F}_i\,(C_F)_{ij}\,\gamma_\mu\,F_j + \sum_{f=U,D,E}\frac{\partial^\mu a}{f_a}\,\bar{f}_i\,(C_f)_{ij}\,\gamma_\mu\,f_j$$

Shift symmetry for ALP-fermion couplings:

- Yukawa-like flavor hierarchy ✓
- flavor-diagonal axial-vector couplings ✓ (*)

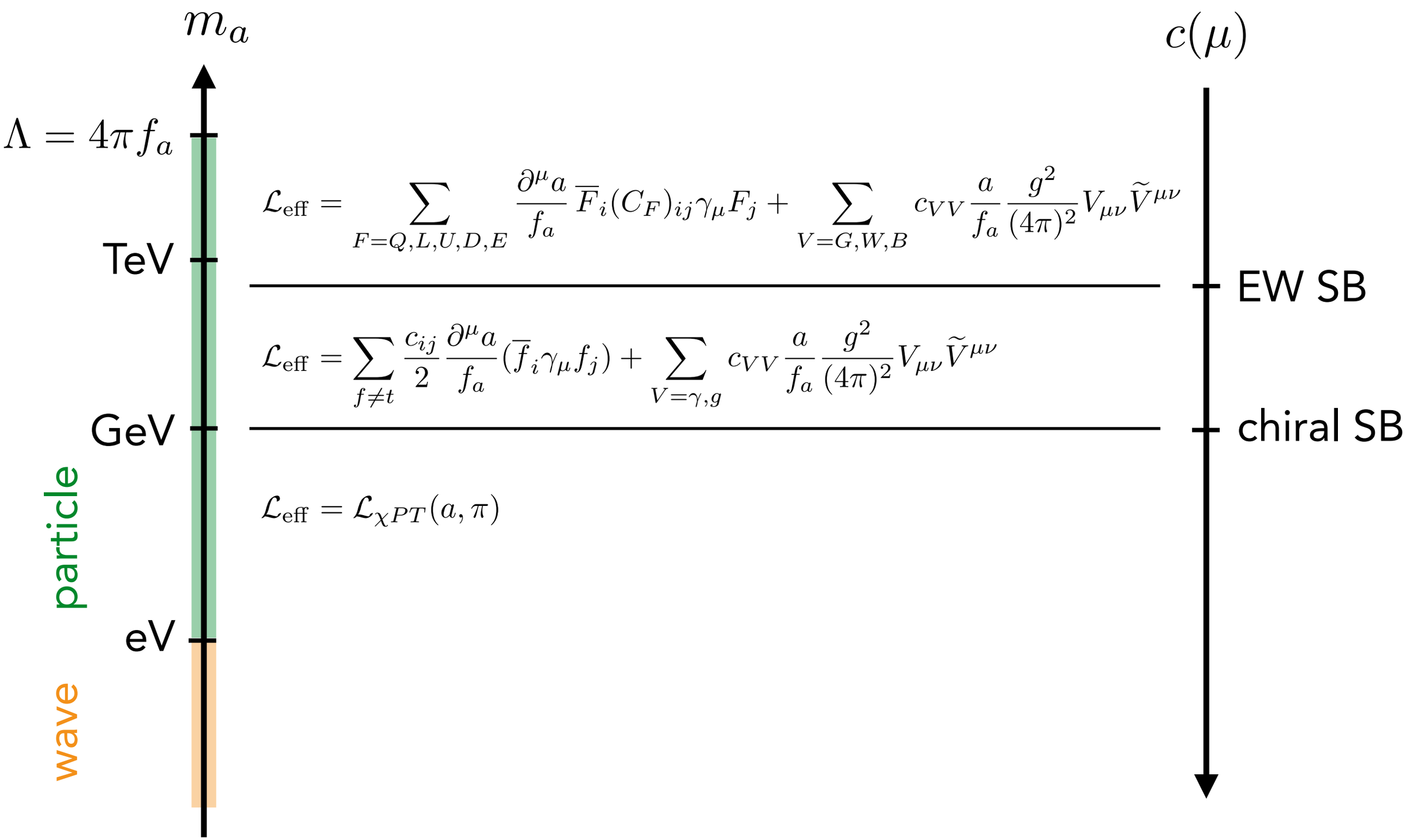
$$c_{ii} = (C_U)_{ii} - (C_Q)_{ii} \qquad i = \{u, c, t\}$$

Shift symmetry breaking: ALP mass ✗

(*) vector couplings observable in weak-interaction processes

e.g. Bonnefoy et al. 2206.04182

Running couplings



Chala et al. 2012.09017; Bauer et al. 2012.12272

Running couplings: top-driven

m_a $\qquad\qquad\qquad\qquad$ $c(\mu)$

$\Lambda = 4\pi f_a$

$$\mathcal{L}_{\rm eff} = \sum_{F=Q,L,U,D,E} \frac{\partial^\mu a}{f_a} \overline{F}_i (C_F)_{ij} \gamma_\mu F_j + \sum_{V=G,W,B} c_{VV} \frac{a}{f_a} \frac{g^2}{(4\pi)^2} V_{\mu\nu} \widetilde{V}^{\mu\nu}$$

$f_a = 1\,\text{TeV}$ — EW SB

GeV

$$c_{uu,cc}(m_t) = c_{uu,cc}(\Lambda) - 0.116\, c_{tt}(\Lambda)$$
$$c_{dd,ss}(m_t) = c_{dd,ss}(\Lambda) + 0.116\, c_{tt}(\Lambda)$$
$$c_{bb}(m_t) = c_{bb}(\Lambda) + 0.097\, c_{tt}(\Lambda)$$
$$c_{\ell\ell}(m_t) = c_{\ell\ell}(\Lambda) + 0.116\, c_{tt}(\Lambda), \quad \ell = \{e, \mu, \tau\}$$

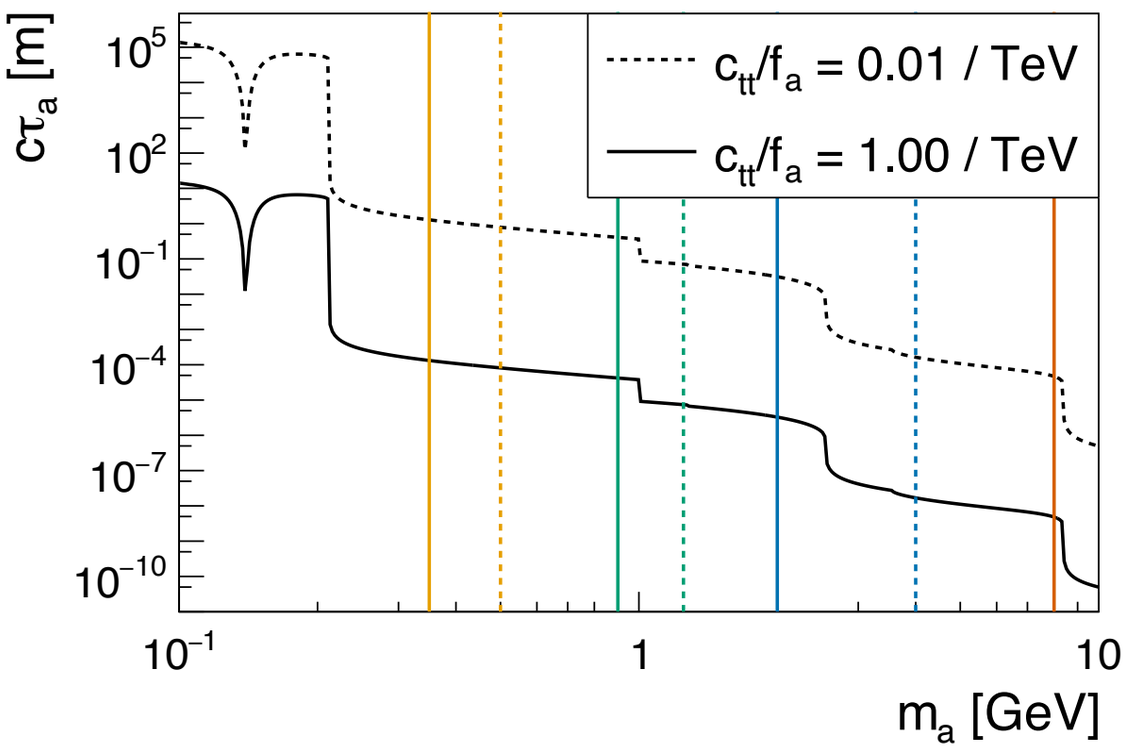
eV

$$C_{sb}(\mu_w) = (7.5499\, c_{ff} - 0.0224\, c_{GG} - 0.0119\, c_{WW} - 0.0001\, c_{BB}) \cdot 10^{-4}$$

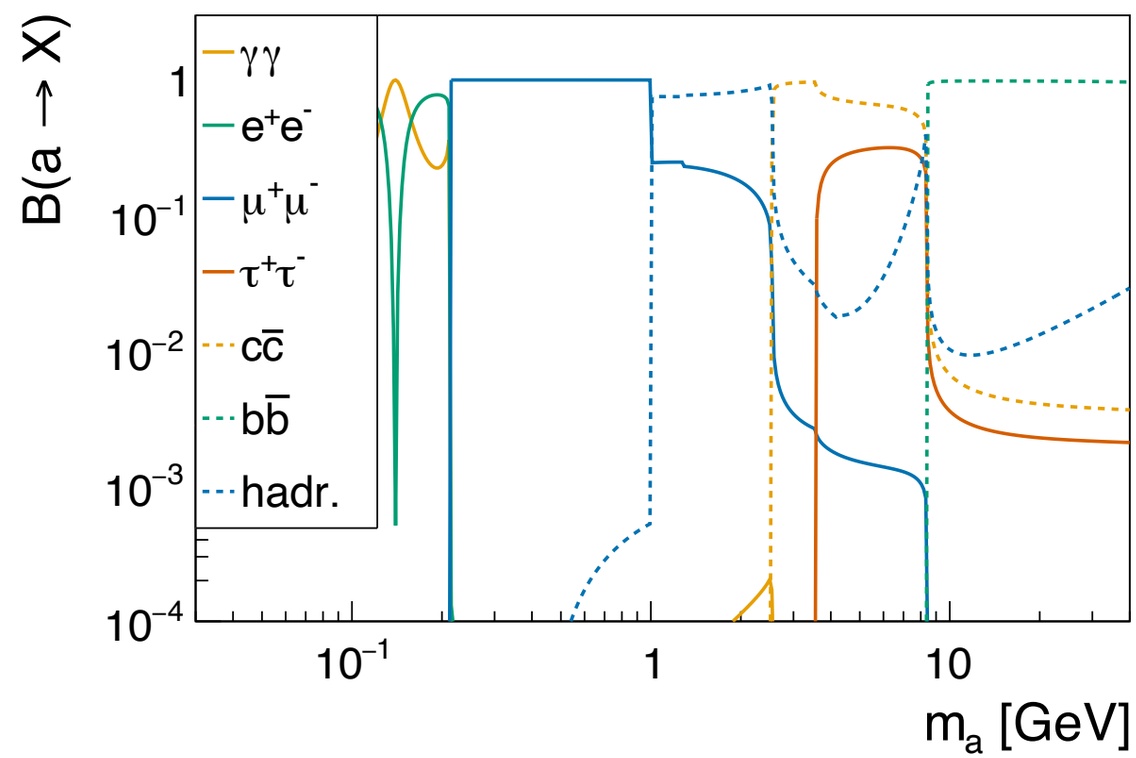
Top scenario

$$c_{tt}(\Lambda) \neq 0, \quad c_{ii}(\Lambda) = 0 \ (i \neq t)$$

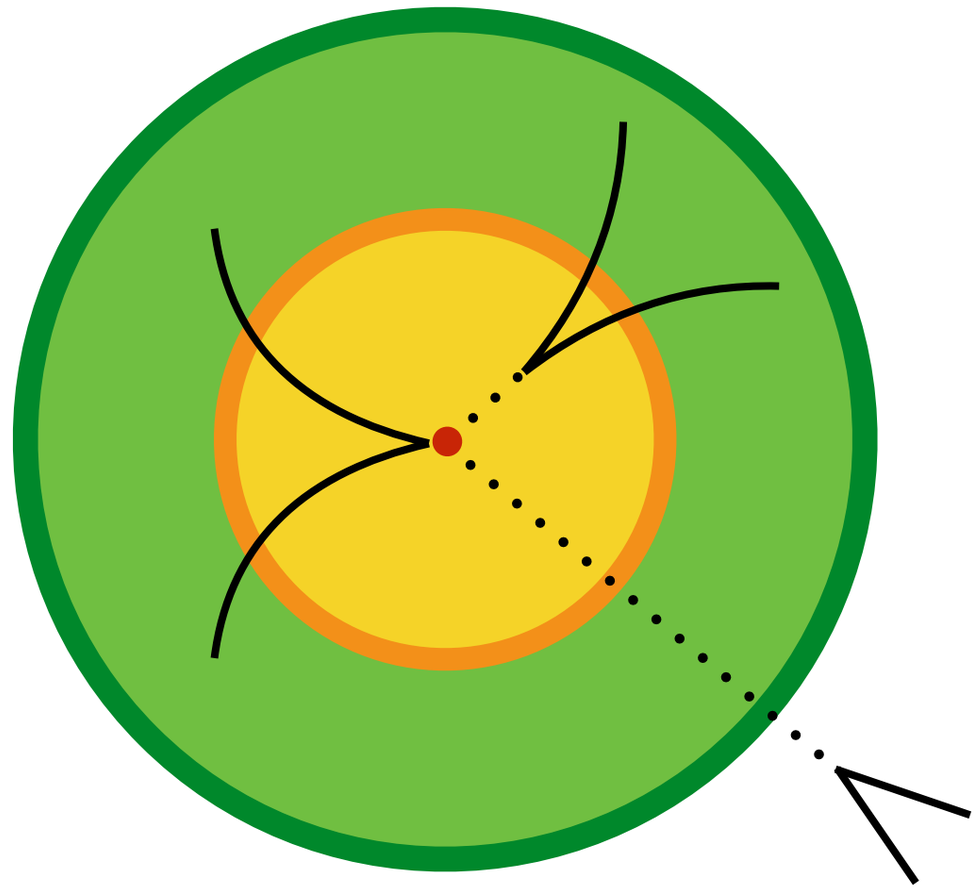
decay length



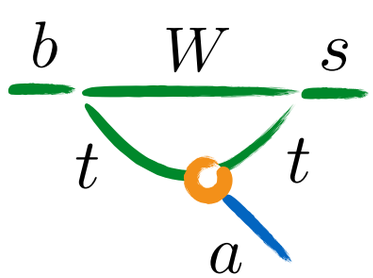
decay modes



At colliders: prompt-displaced-invisible

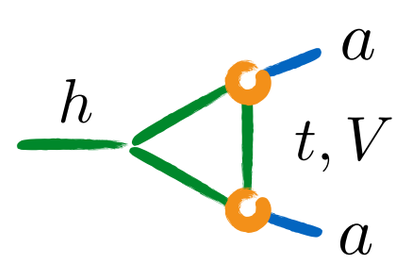


meson decays



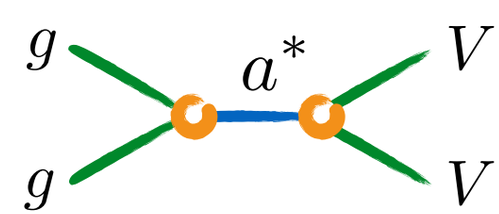
Batell et al. 0911.4938

Higgs decays



Bauer et al. 1708.00443

virtual ALPs



Gavela et al. 1905.12953

ALPs in top-antitop production

m_a

prompt hadronic decays

10 GeV

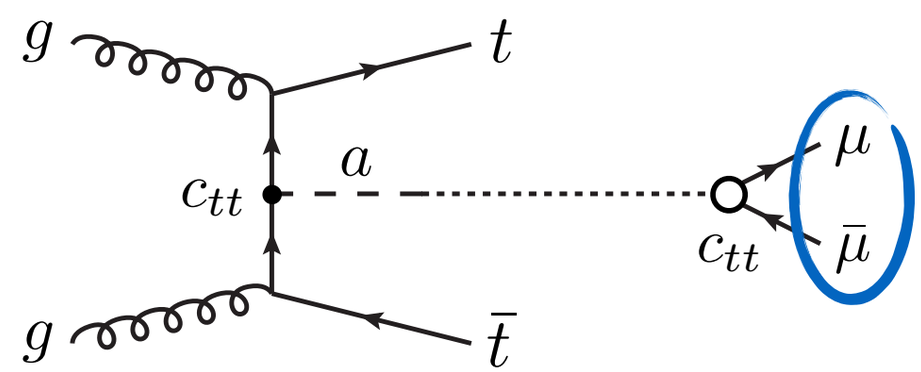
displaced vertex

$2\,m_\mu$

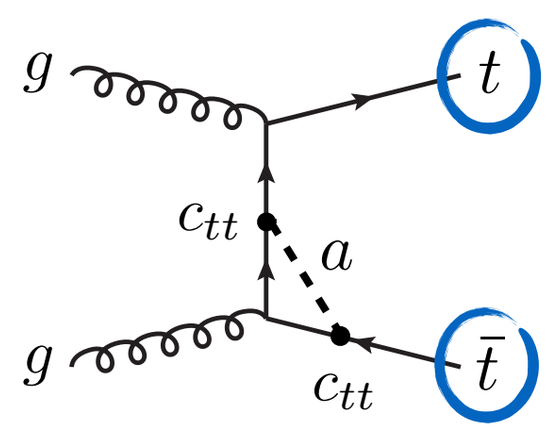
missing energy

any: top kinematics

Rygaard et al. 2306.08686

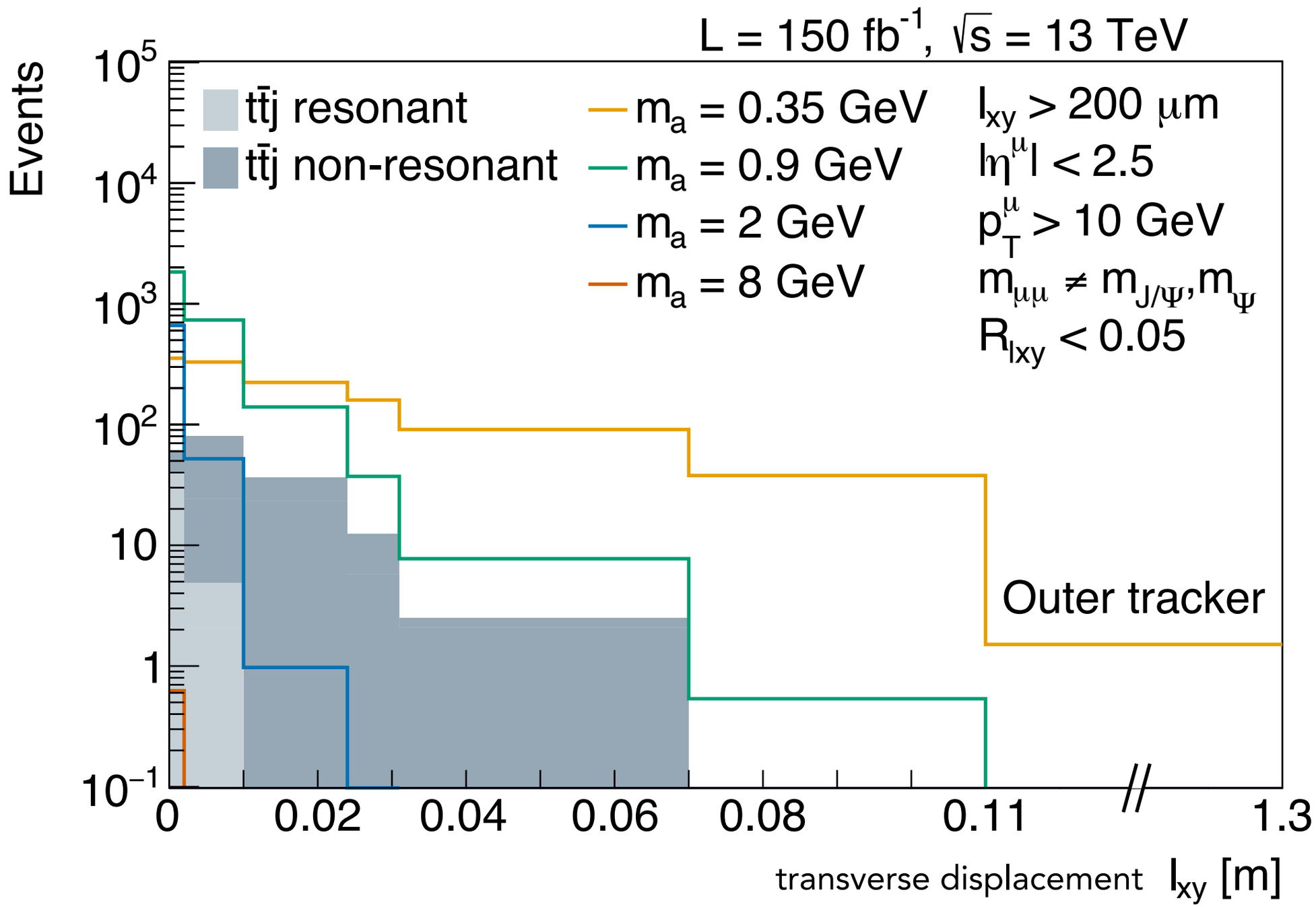


Esser et al. 2303.17634



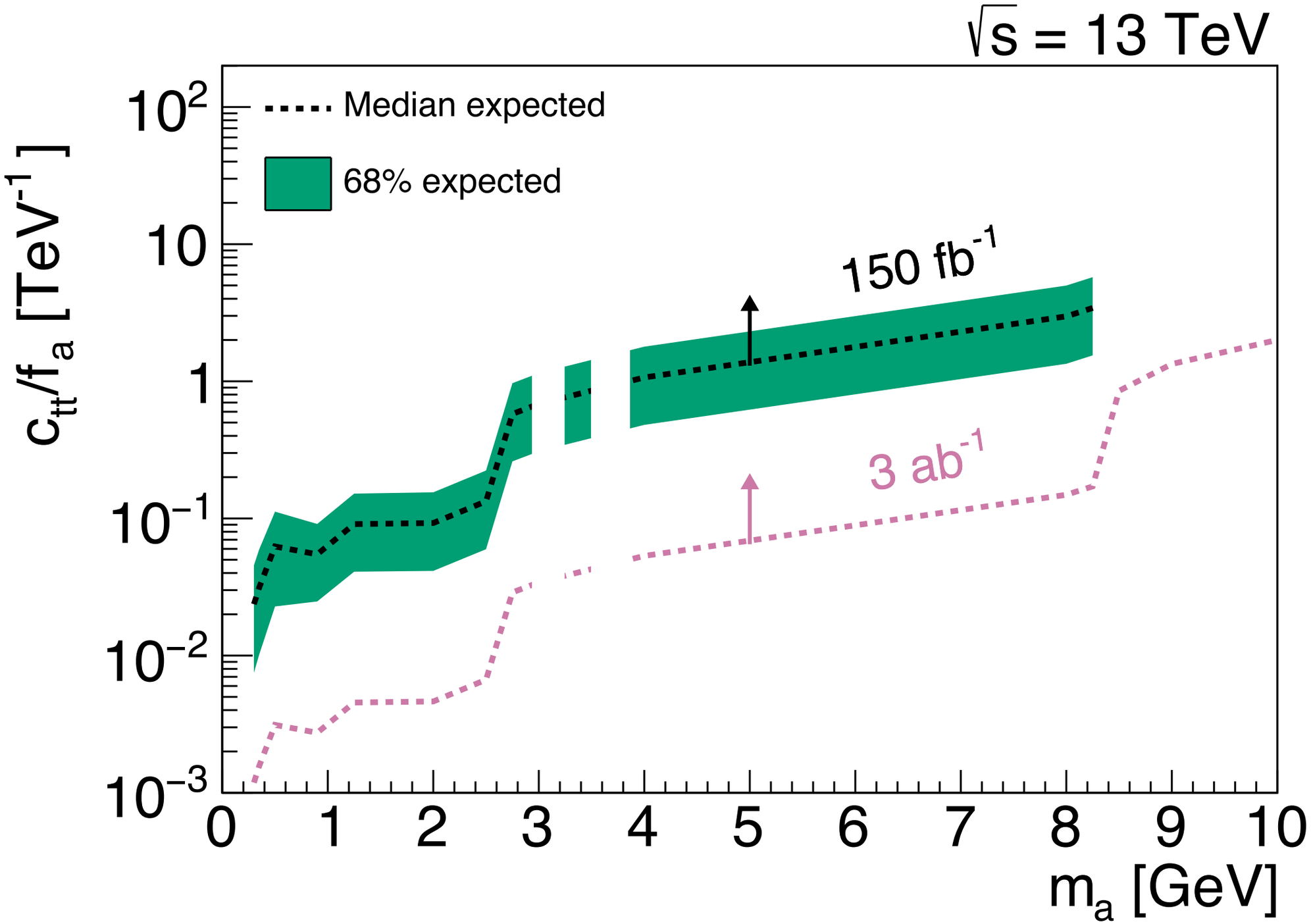
Phan, SW coming soon

Displaced ALPs in top production



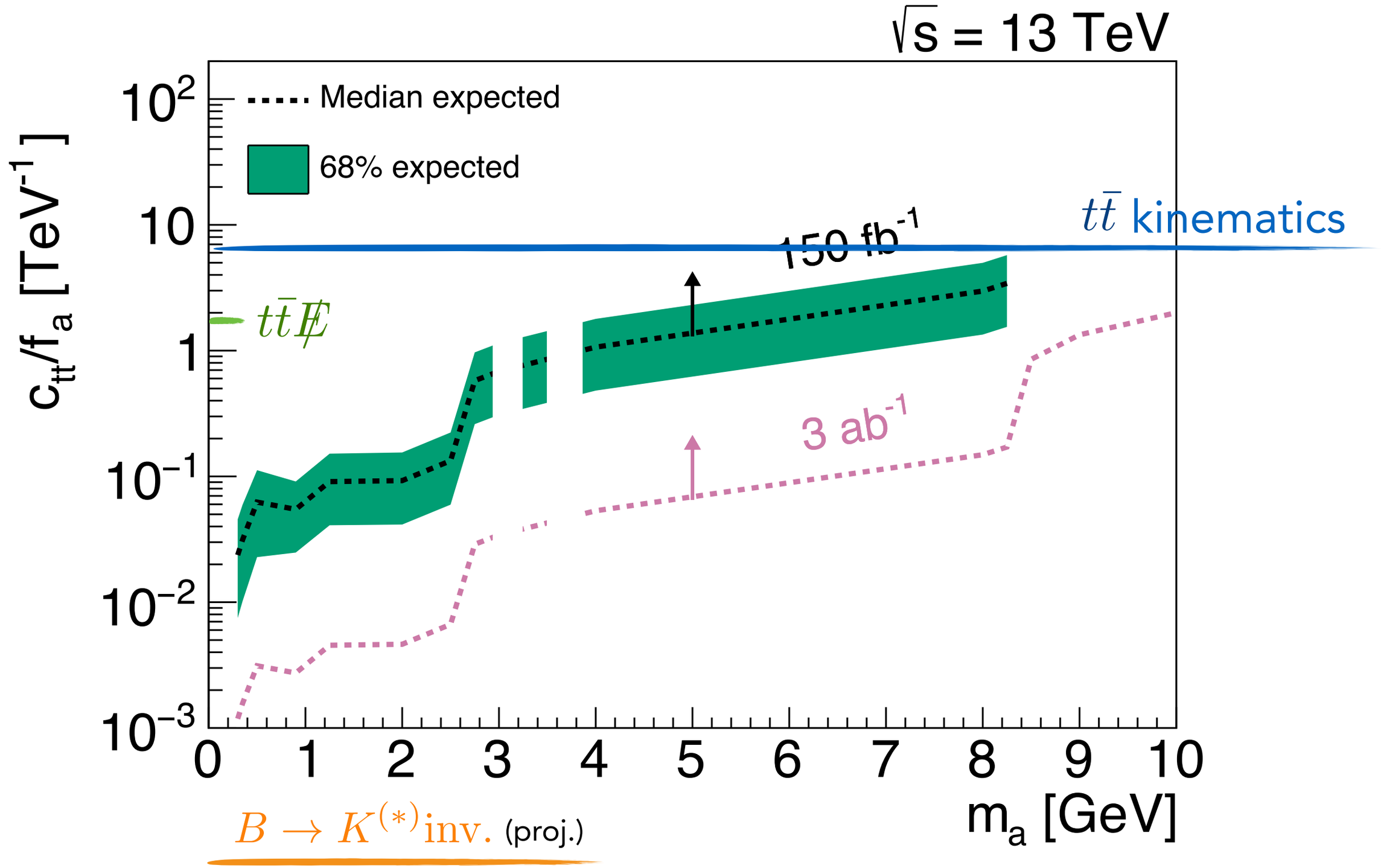
Rygaard, SW et al. 2306.08686

LHC predictions: ALP-top coupling



Rygaard, SW et al. 2306.08686

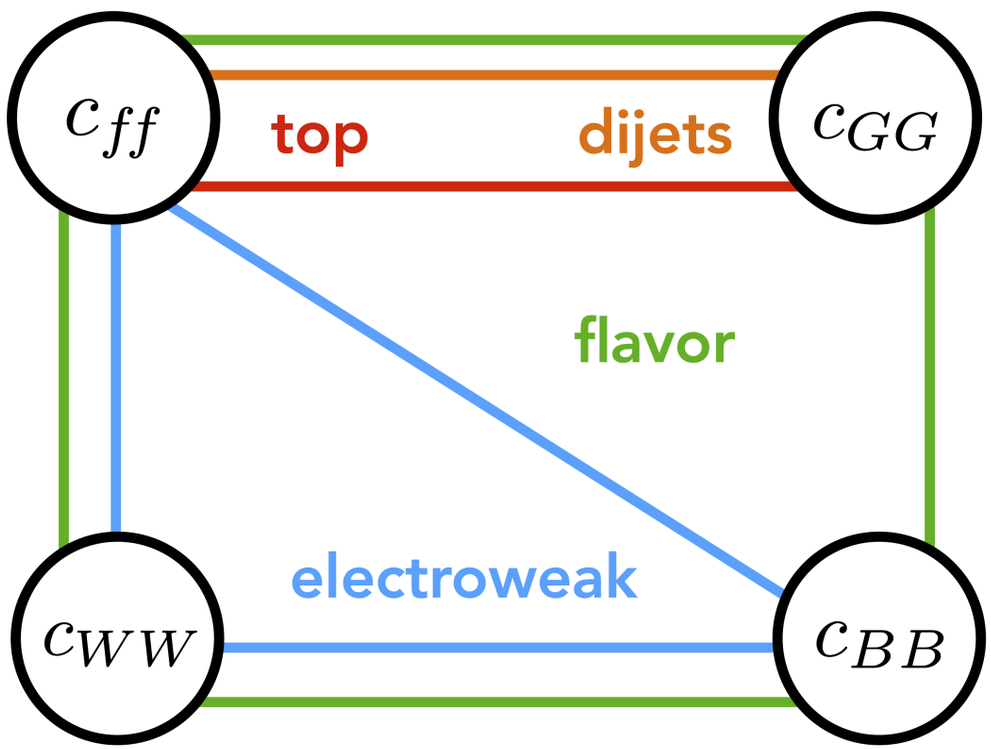
Probing the ALP-top coupling



Ferber, SW et al. 2201.06580

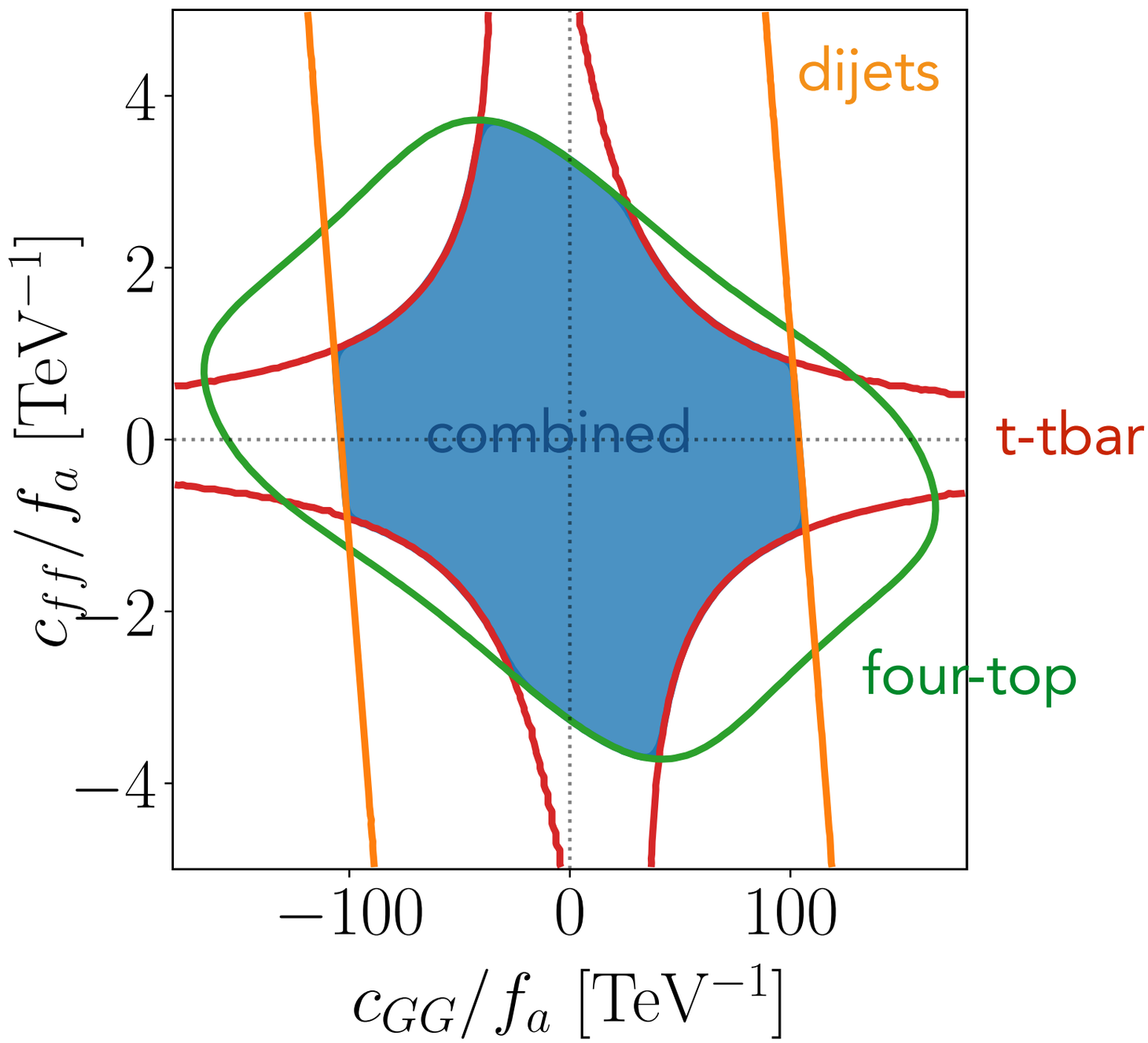
Global analysis of the ALP effective theory

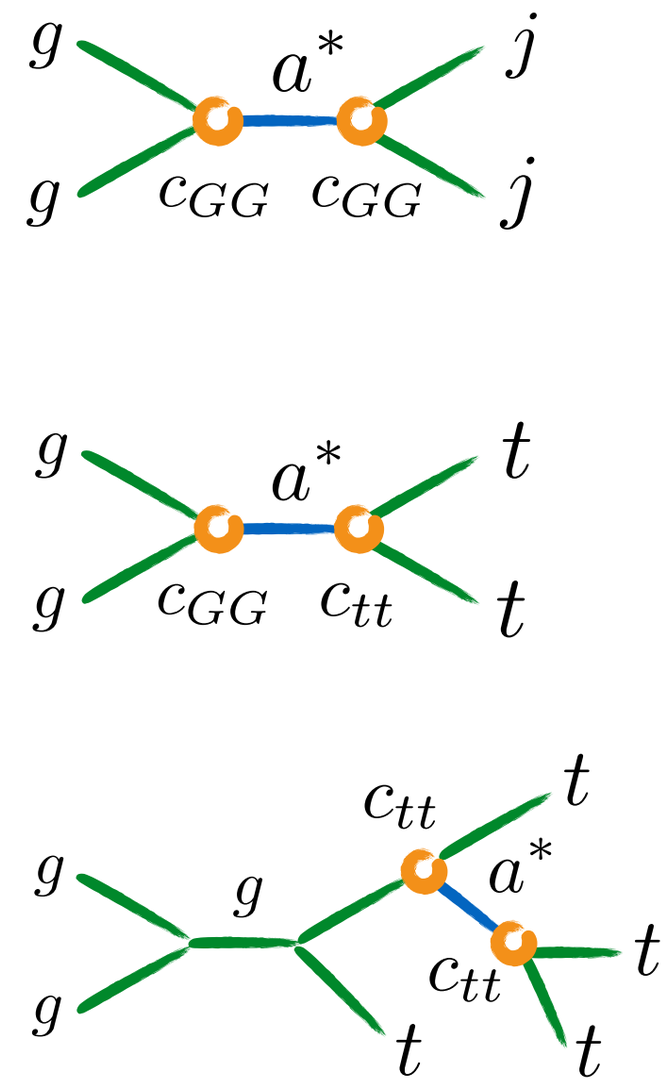
„All observables depend on all couplings."



- resonant and virtual ALP effects — Bruggisser, Grabitz, SW 2308.11703
- ALP-induced SMEFT effects — Biekoetter et al. 2307.10372

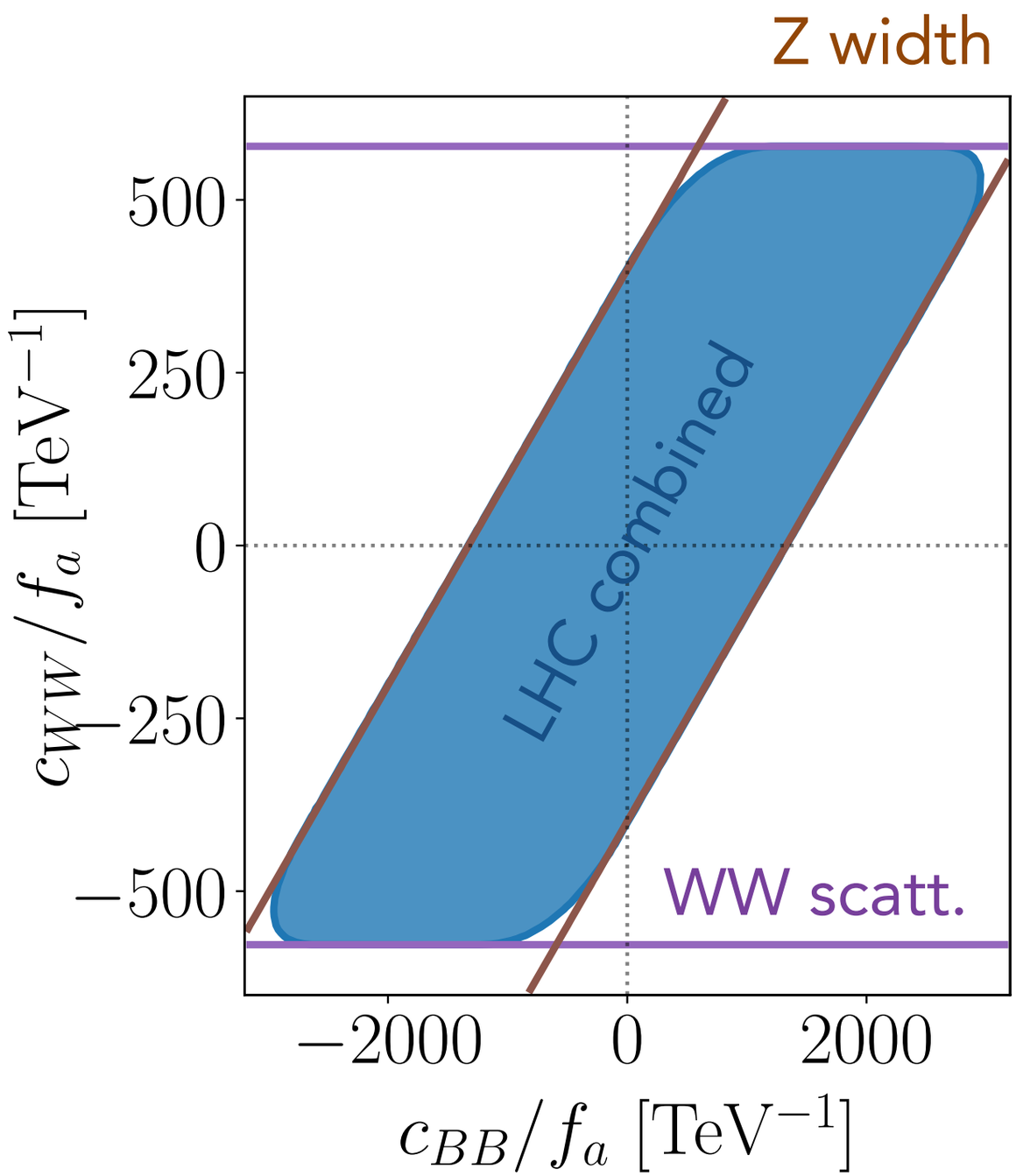
Top and gluon couplings

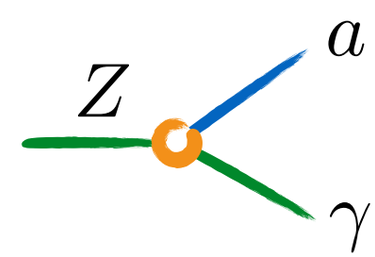




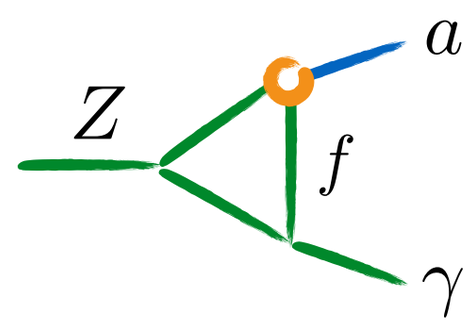
Bruggisser, Grabitz, SW 2308.11703

Electroweak couplings

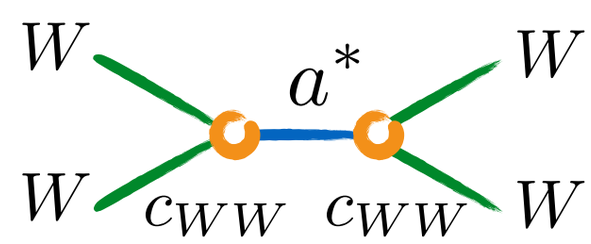




$$c_{\gamma Z} = c_w^2\, c_{WW} - s_w^2 c_{BB}$$

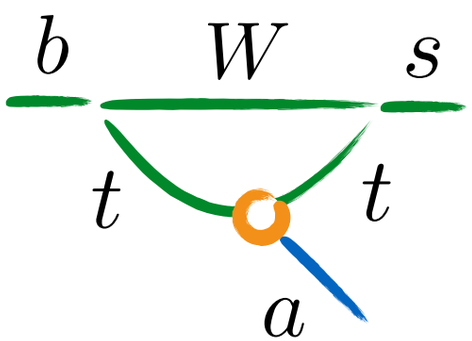


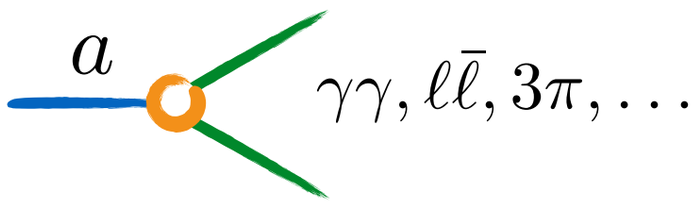
$$\sum_f N_c^f Q_f v_f c_{ff}$$



Impact of flavor observables

$$C_{sb}(\mu_w) = (7.5499\, c_{ff} - 0.0224\, c_{GG} - 0.0119\, c_{WW} - 0.0001\, c_{BB}) \cdot 10^{-4}$$

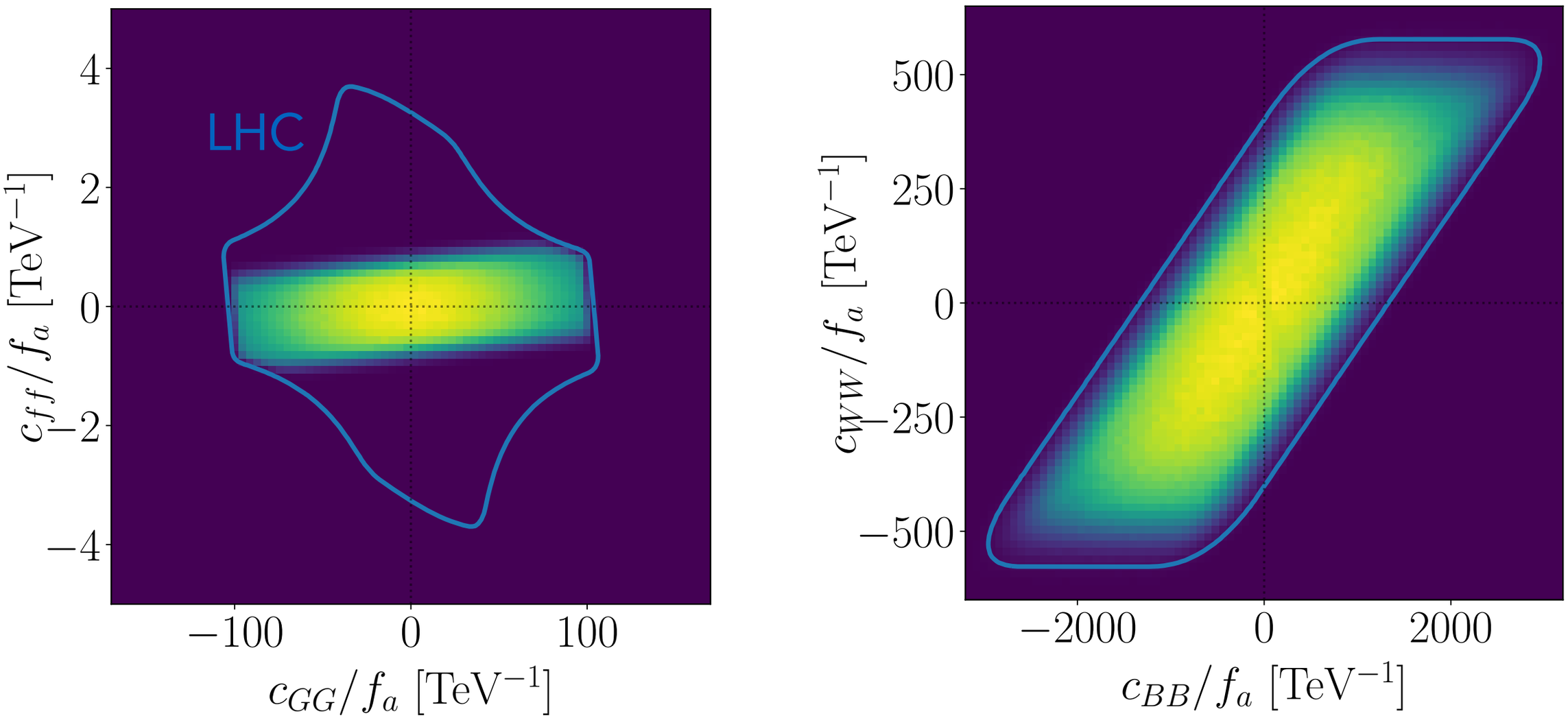




ALP production and decay depend on all couplings.

Global ALP fit with flavor

LHC + $B \to K^{(*)}\text{inv.}$ (*)

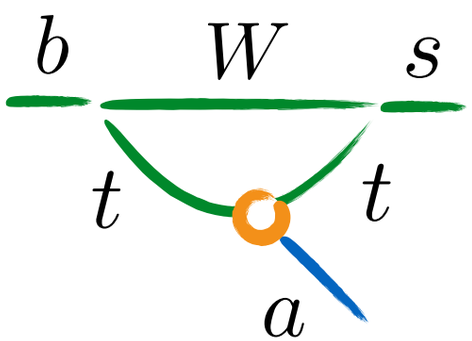


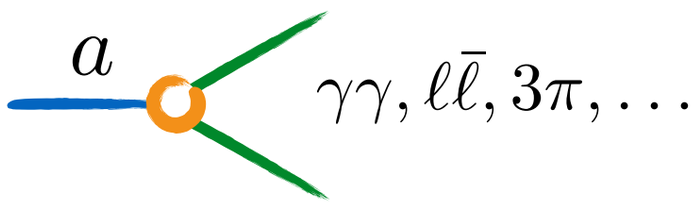
(*) BaBar 2013

Bruggisser, Grabitz, SW 2308.11703

Impact of ALP lifetime

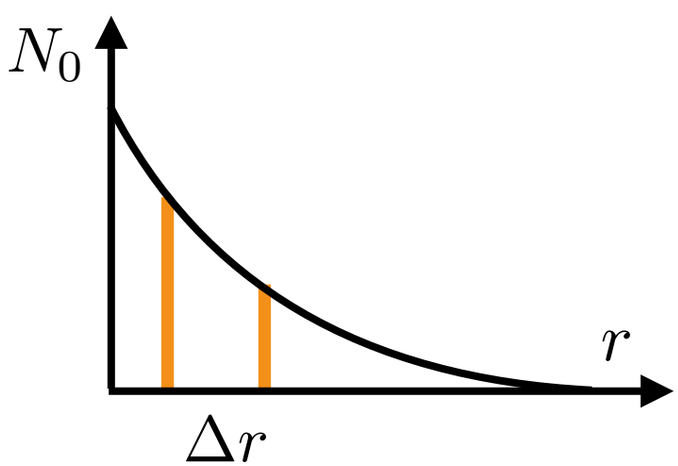
$$C_{sb}(\mu_w) = (7.5499\, c_{ff} - 0.0224\, c_{GG} - 0.0119\, c_{WW} - 0.0001\, c_{BB}) \cdot 10^{-4}$$





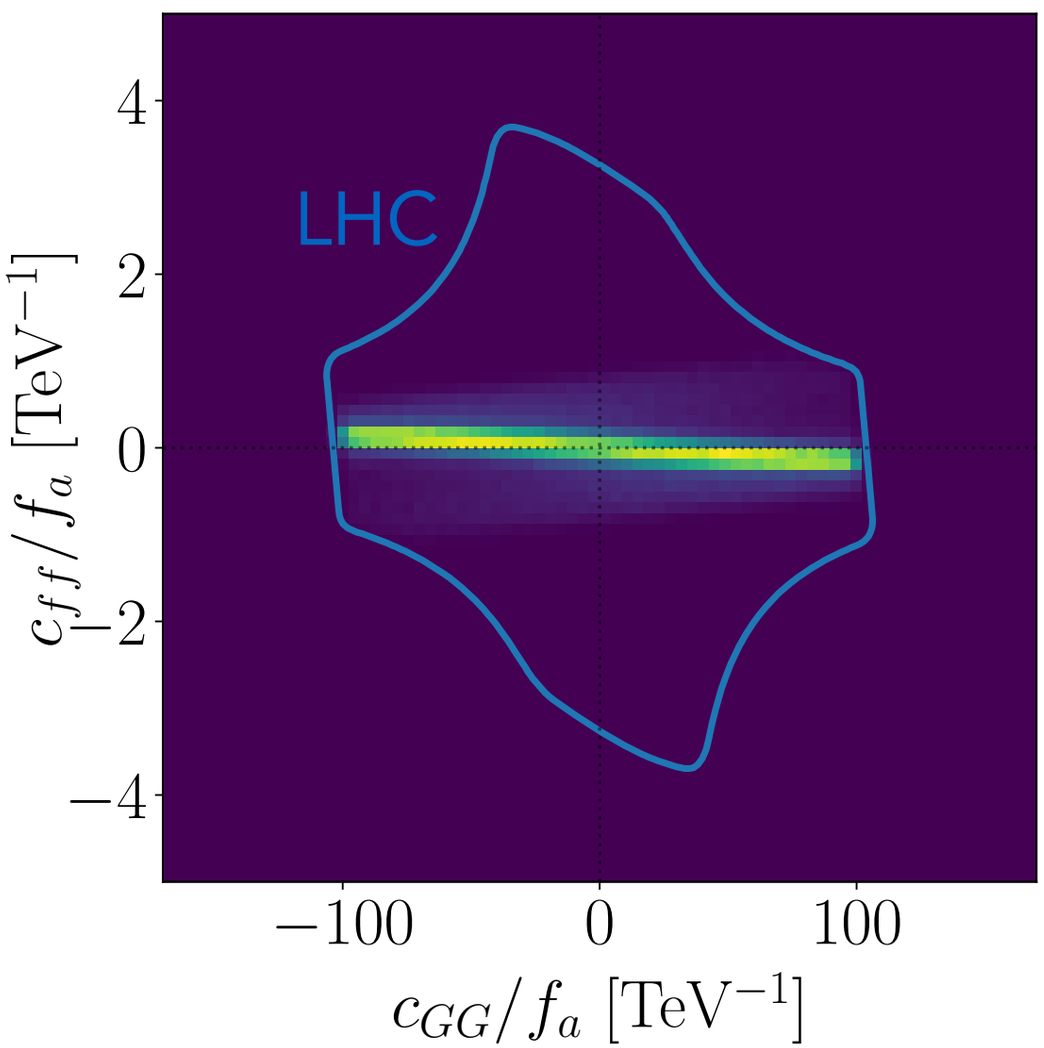
ALP lifetime depends on all couplings ⟶ scan parameter space.

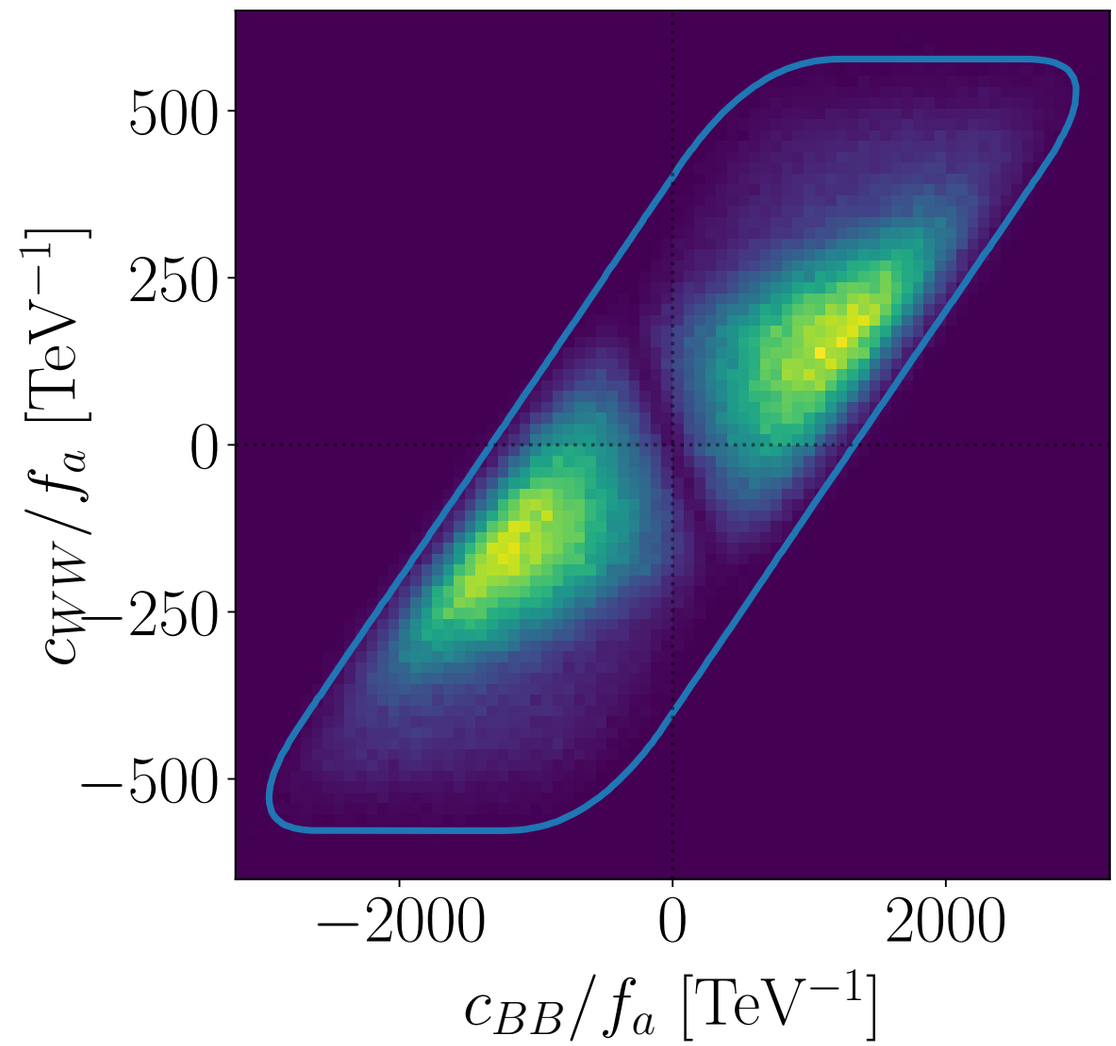
$$N \sim N_0 \left[\exp\left(-\frac{r}{\beta\gamma c\tau_a} \right) - \exp\left(-\frac{r + \Delta r}{\beta\gamma c\tau_a} \right) \right]$$



Prompt-displaced-invisible

LHC + $B \to K^{(*)}\text{inv.}$ + $B \to K^{(*)} a, a \to \mu\bar{\mu}$



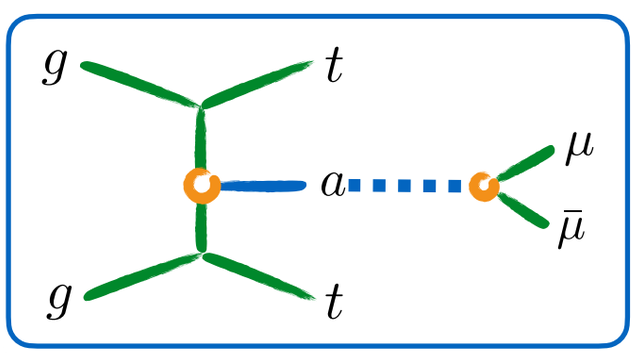


Optimal resolution through parameter correlations.

Summary

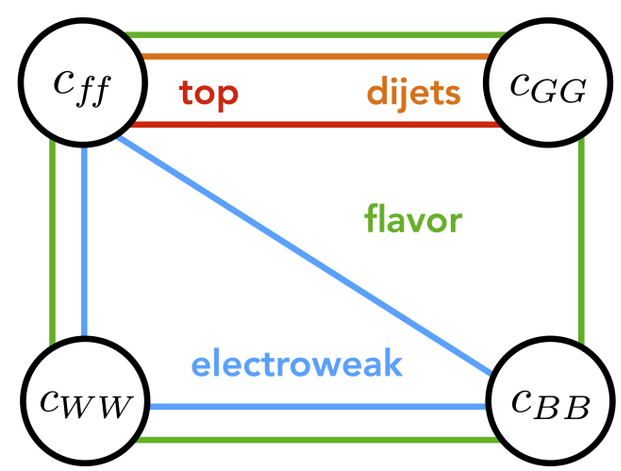
- shift-symmetric ALP couplings: effective theory
- running couplings and virtual ALPs: many observables

top coupling



direct bound on running

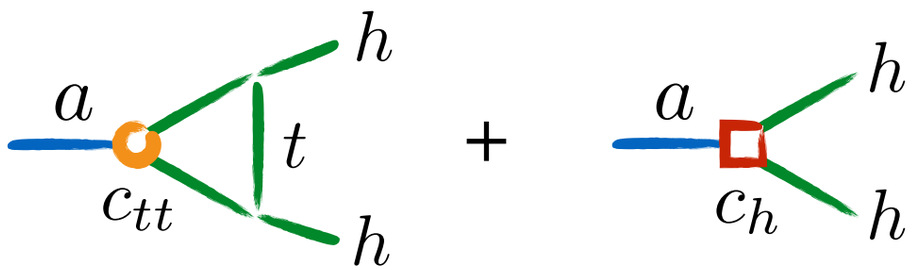
global analysis



pin down UV scenarios

BACKUP

Top-induced leptonic ALP decays



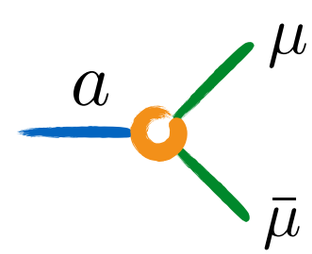
$$O_h = \frac{\partial_\mu a}{f_a}\left(H^\dagger i D^\mu H + h.c.\right)$$

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

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

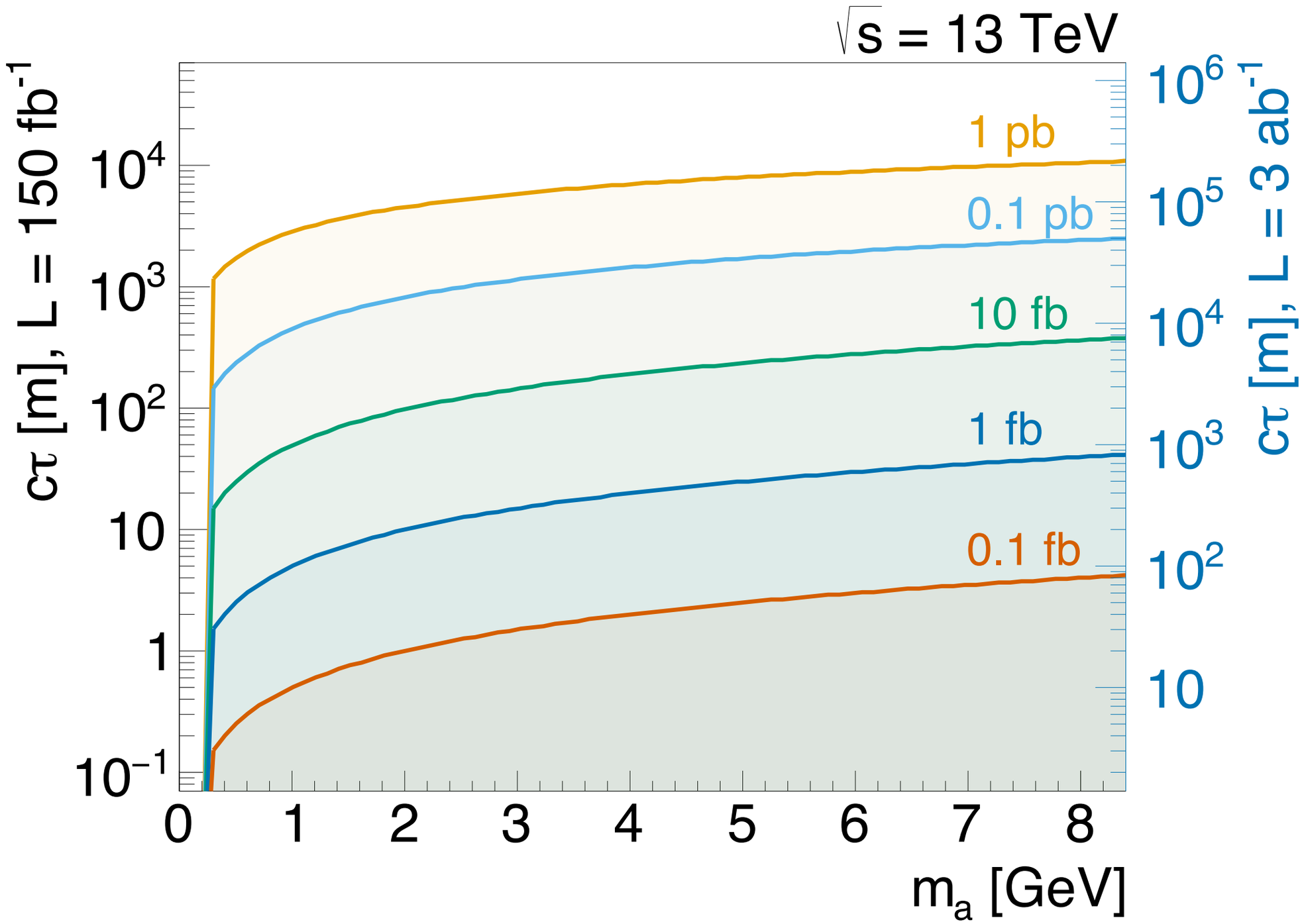
- universal top contributions to fermion couplings:

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



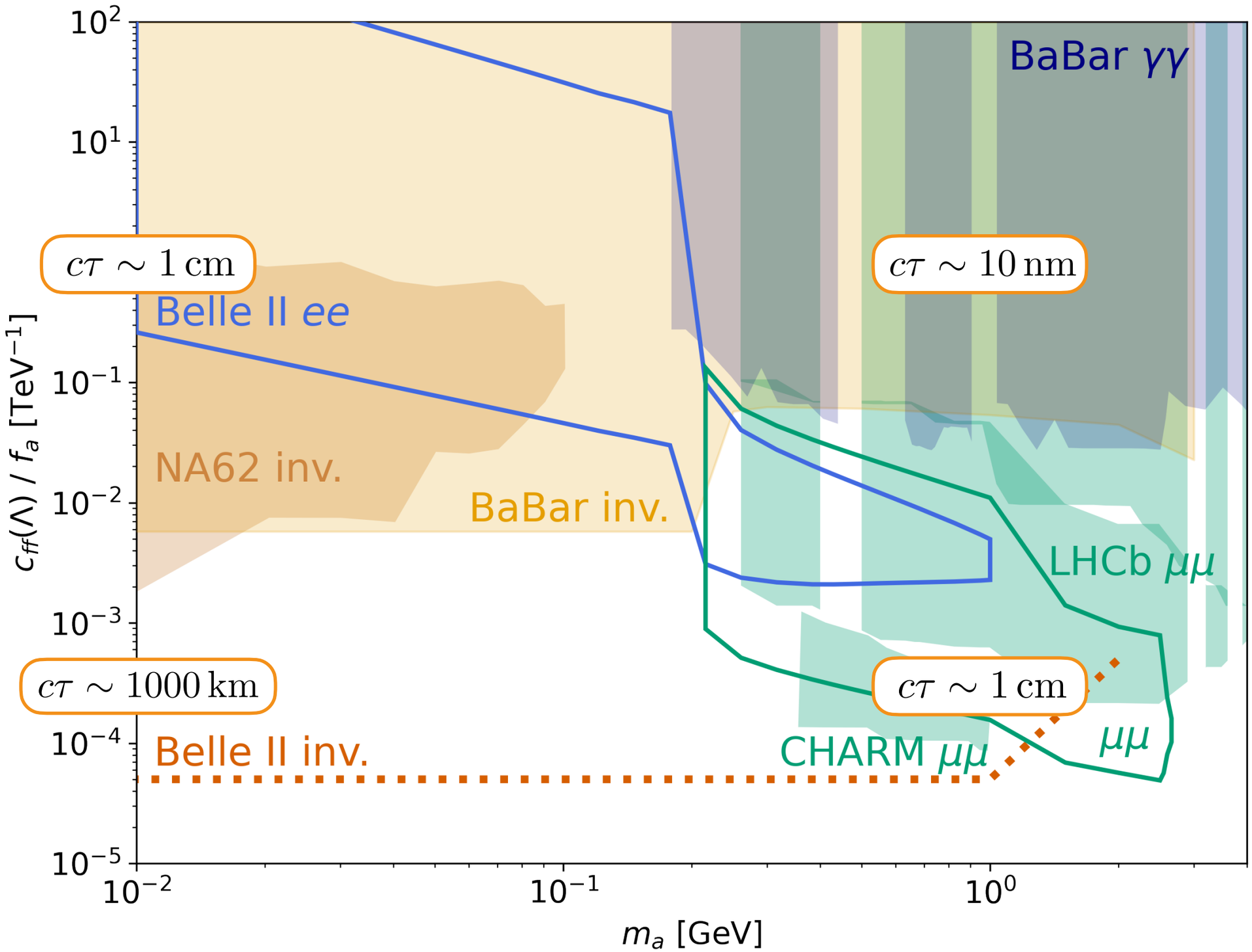
see Bauer et al. 2012.12272

Displaced ALPs in top production



Rygaard, SW et al. 2306.08686

ALPs in meson decays



Ferber, Filimonova, Schaefer, SW 2201.06580