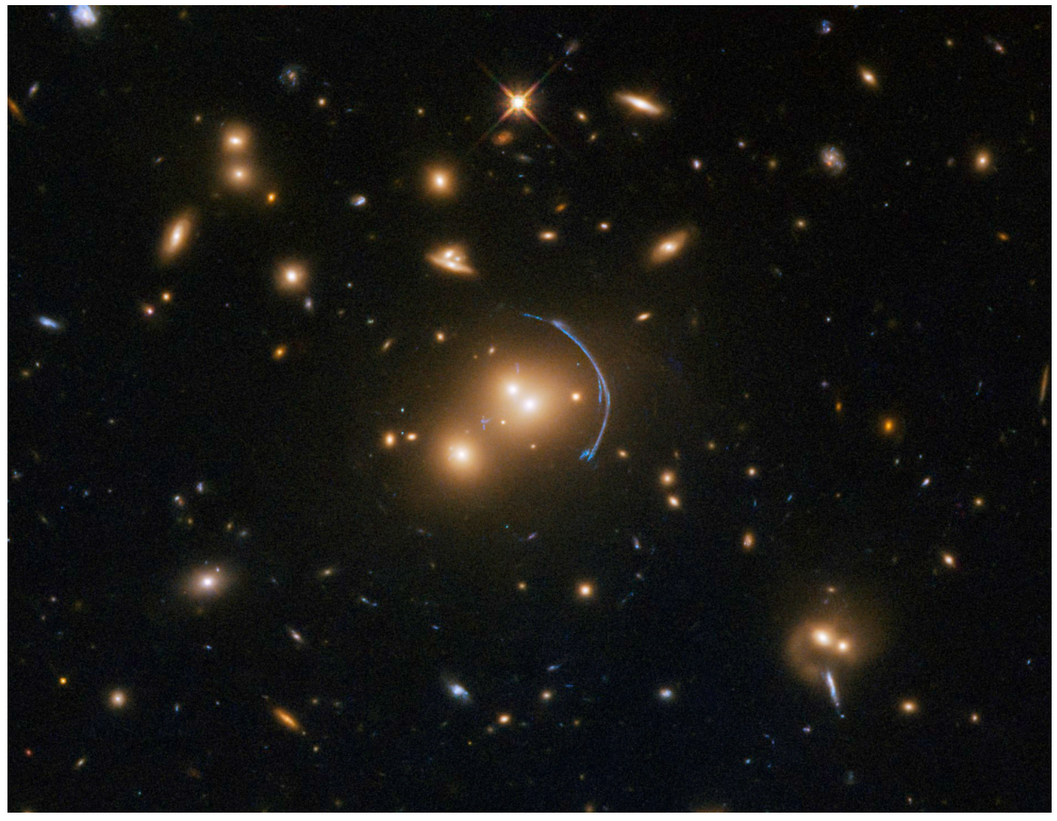
Axion-like particles at colliders

Susanne Westhoff | Radboud University & Nikhef

ALPs in the cosmos … and in the lab



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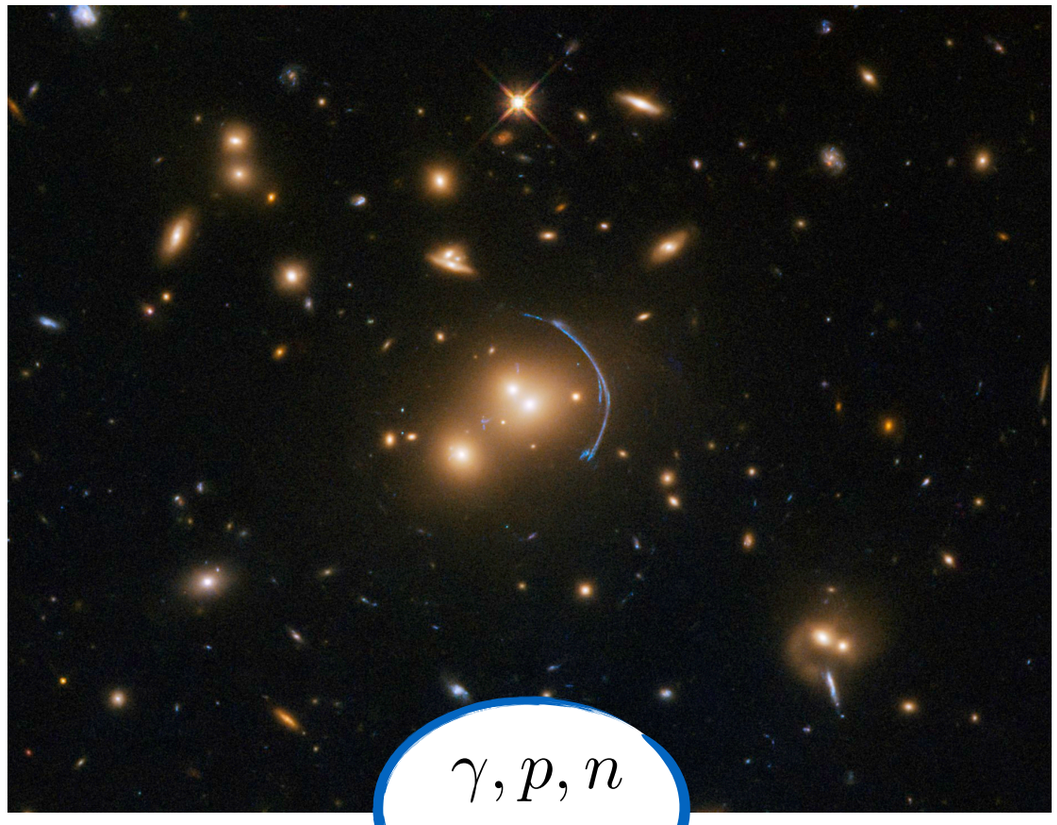
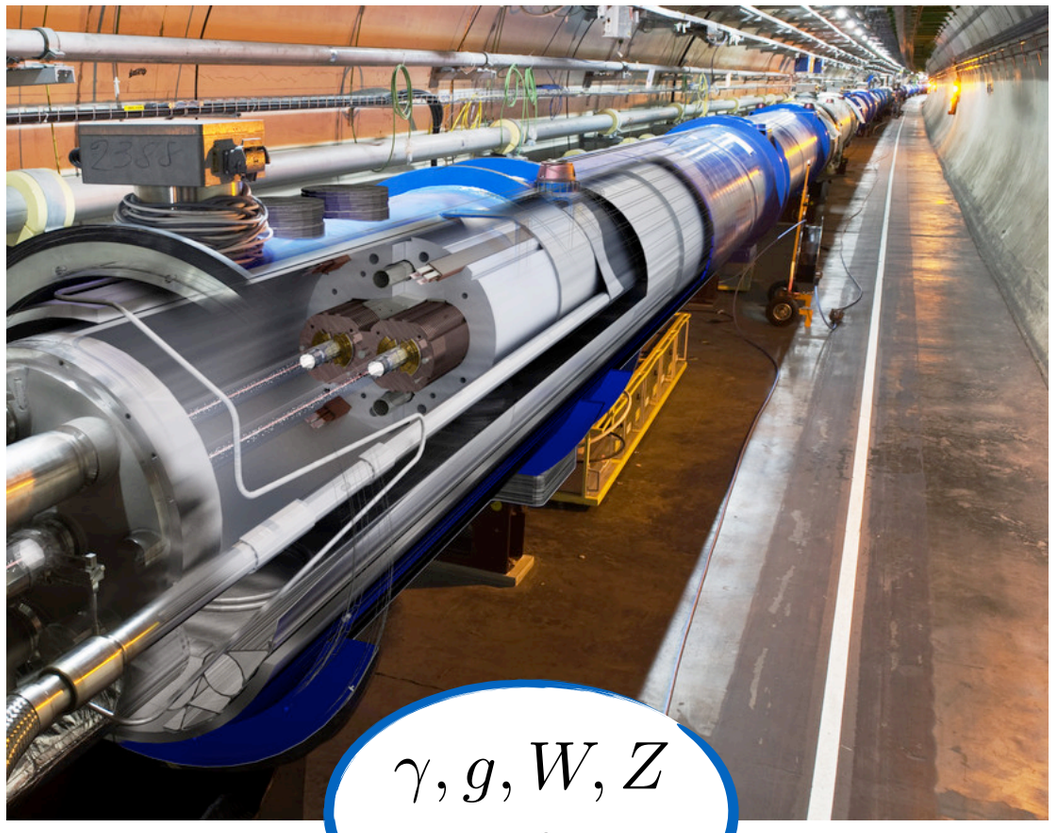


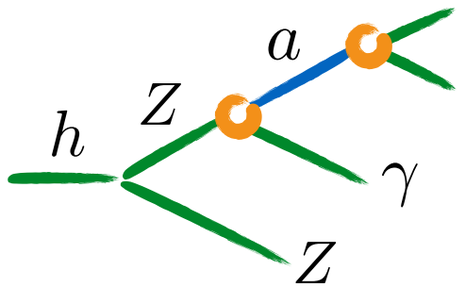
γ, p, n
e



γ, g, W, Z
q, ℓ, ν

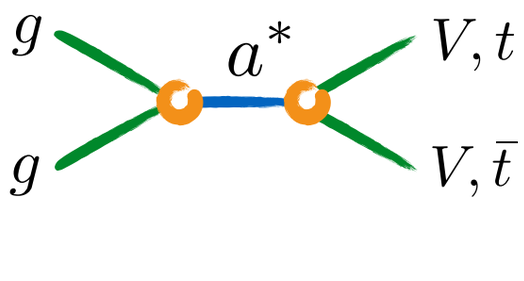
ALPs at colliders

Higgs decays

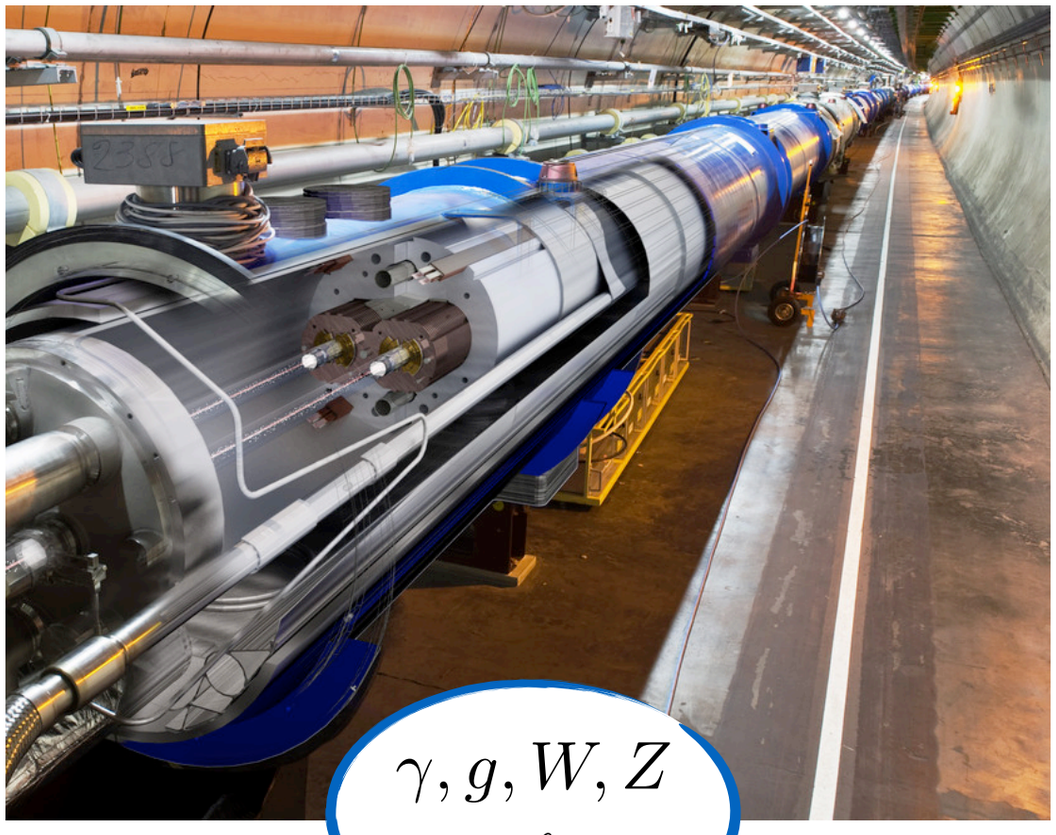


Bauer et al. 1708.00443

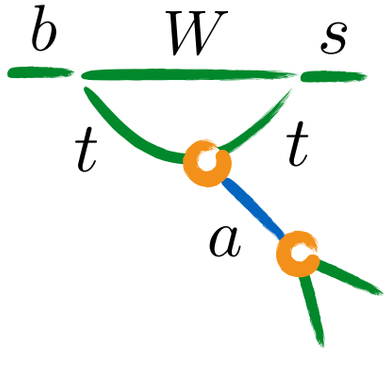
virtual ALPs



Gavela et al. 1905.12953



meson decays



Batell et al. 0911.4938

Camalich et al. 2002.04623

ALP effective theory

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_{V=G,B,W} c_{VV}\,\frac{a}{f_a}\,\frac{g_V^2}{(4\pi)^2}\,V_{\mu\nu}\widetilde{V}^{\mu\nu}$$
$$+ \sum_{F=Q,L} \frac{\partial^\mu a}{f_a}\,\overline{F}_i(C_F)_{ij}\gamma_\mu F_j + \sum_{f=U,D,E} \frac{\partial^\mu a}{f_a}\,\overline{f}_i(C_f)_{ij}\gamma_\mu f_j \; + \mathcal{O}(f_a^{-2})$$

Georgi, Kaplan, Randall 1986

General picture of ALP interactions?

ALP couplings: features

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_{V=G,B,W} c_{VV}\frac{a}{f_a}\frac{g_V^2}{(4\pi)^2}V_{\mu\nu}\widetilde{V}^{\mu\nu}$$

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Shift symmetry: $a \to a + c$

- Yukawa-like flavor hierarchy
- On-shell fermions have axial-vector couplings

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

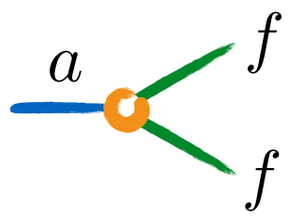
- Fermion couplings run; gauge couplings don't (at least up to 2-loop)

Top-quark induced running couplings

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

All fermion couplings get top contributions:

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



Choi et al. 1708.00021; Chala et al. 2012.09017; Bauer et al. 2012.12272

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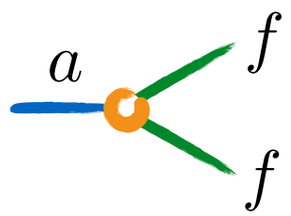
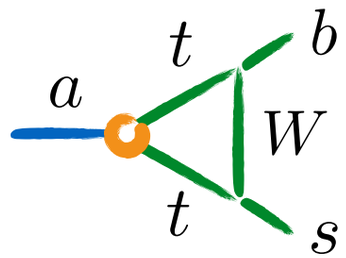


Flavor-changing neutral currents:



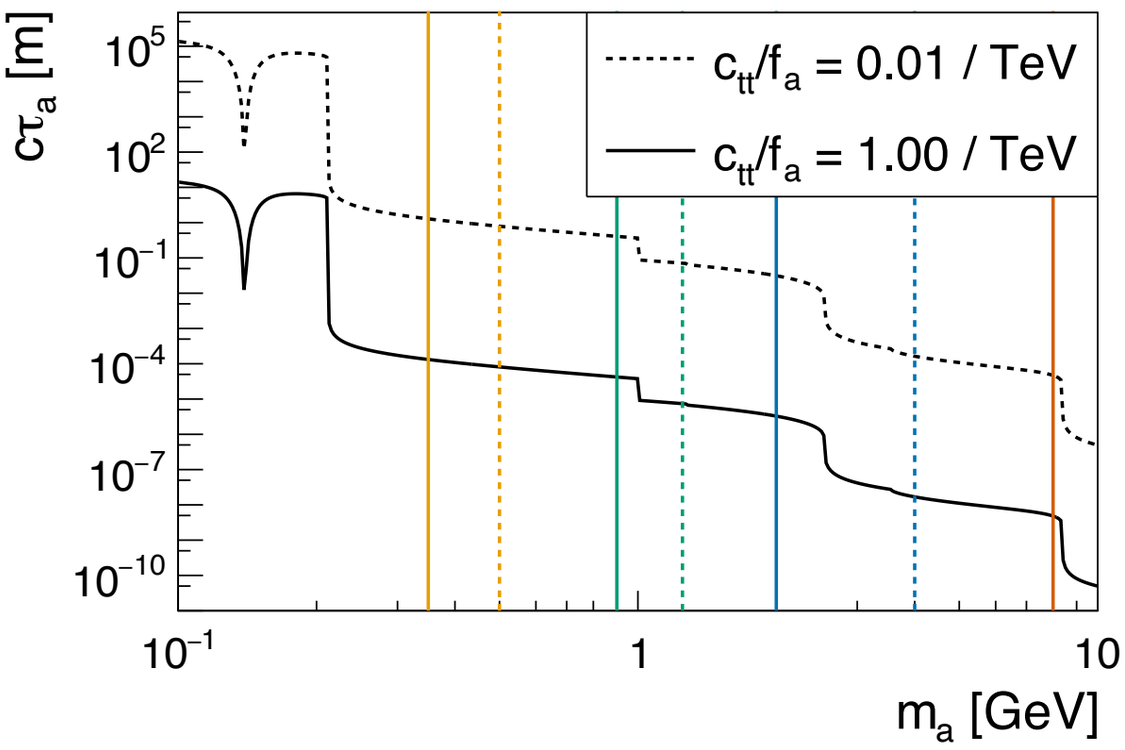
$$C_{sb}(\mu_w) = (7.5499\, c_{tt} - 0.0224\, c_{GG} - 0.0119\, c_{WW} - 0.0001\, c_{BB}) \cdot 10^{-4}$$

Choi et al. 1708.00021; Chala et al. 2012.09017; Bauer et al. 2012.12272

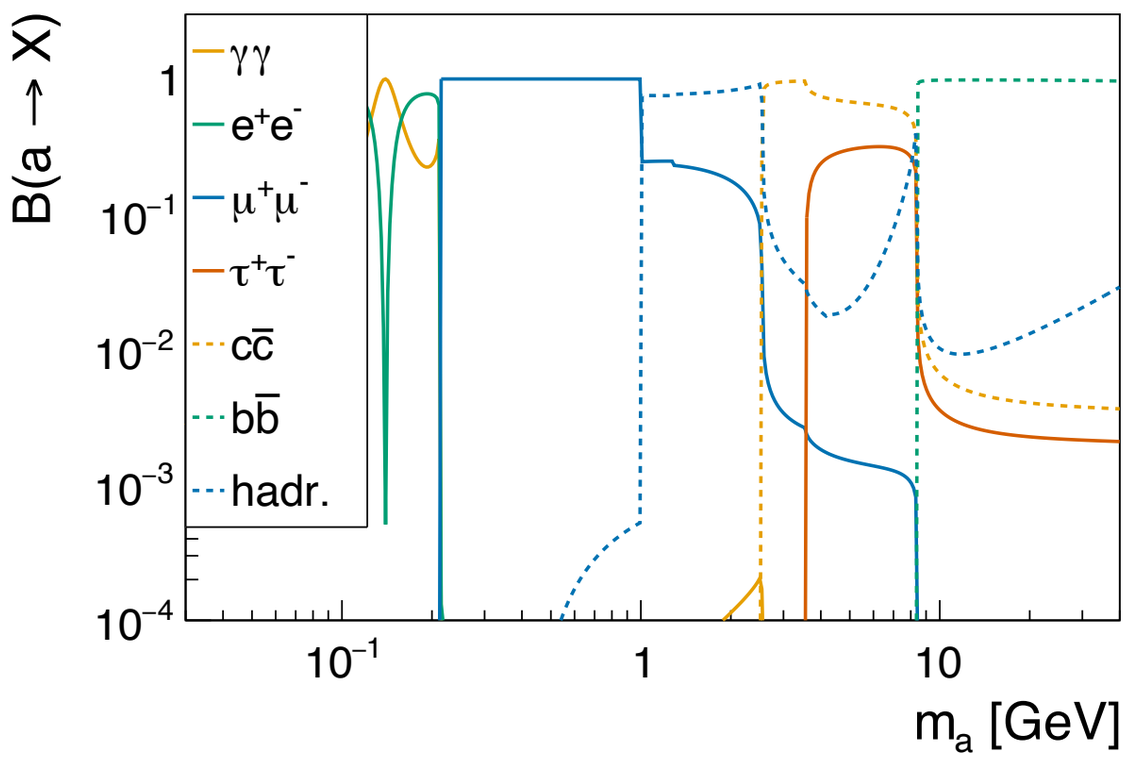
Top scenario

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

decay length

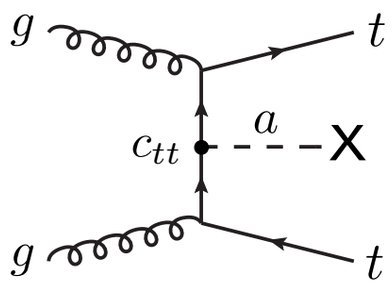


decay modes



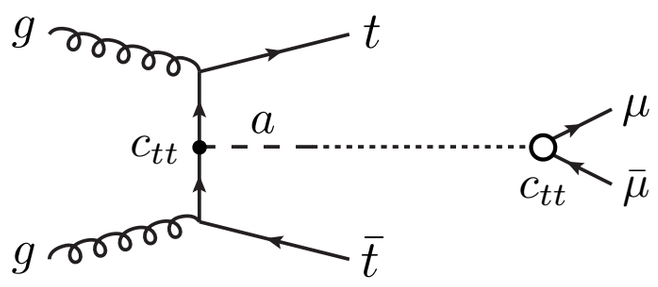
Rygaard, SW et al. 2306.08686

Probing the ALP-top coupling



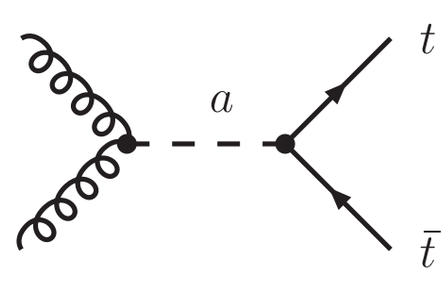
missing energy

Esser et al. 2303.17634



displaced vertex

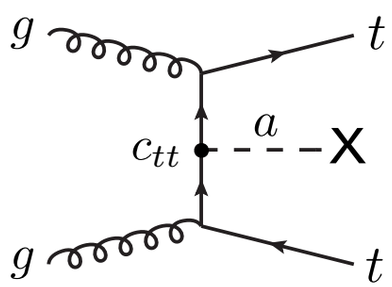
Rygaard, SW et al. 2306.08686

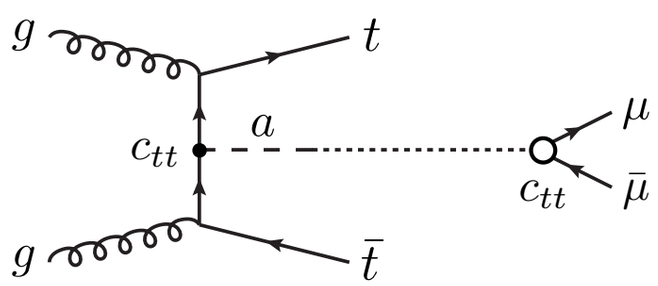


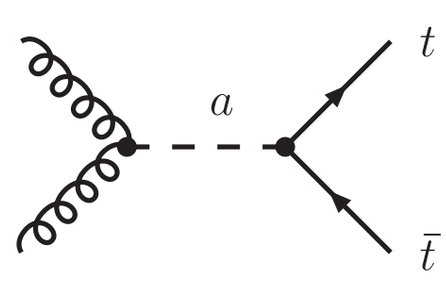
top-antitop resonance

Anuar et al. 2404.19014

Bounds and projections

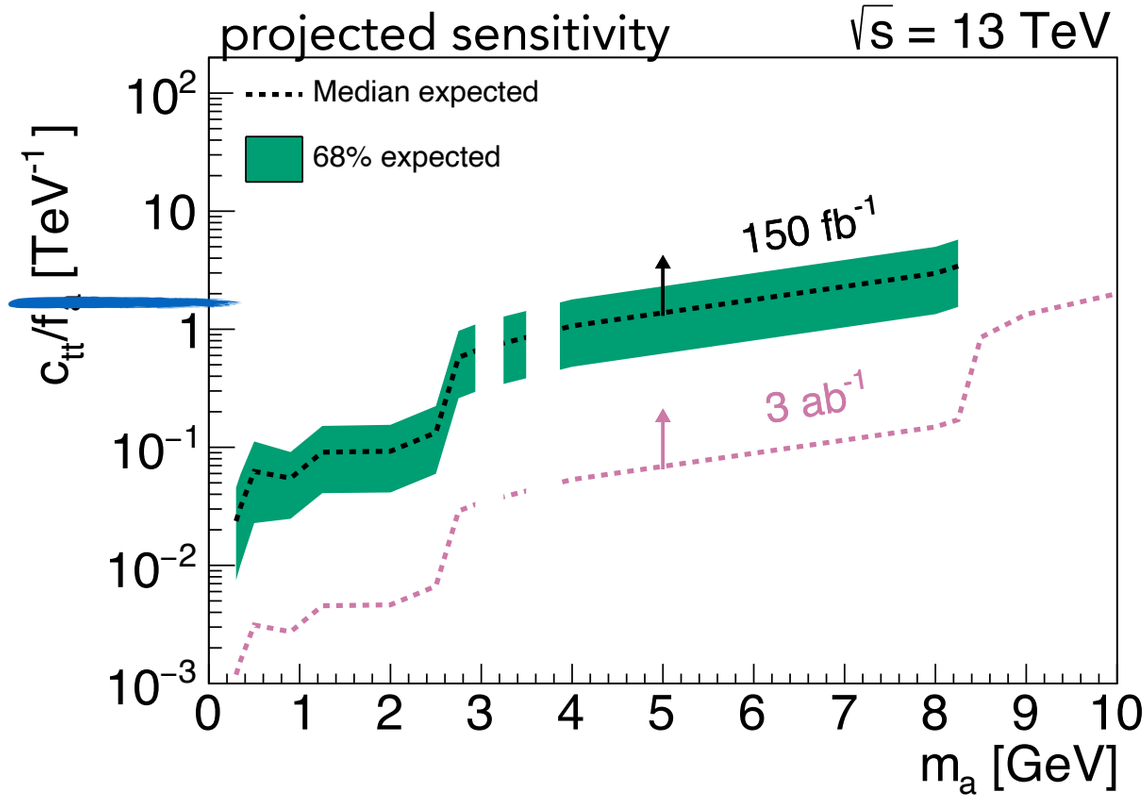






$t\bar{t}$ + MET

bound from
ATLAS 2102.01444

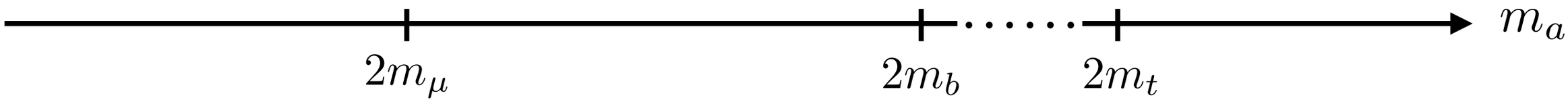


$t\bar{t}$ resonance

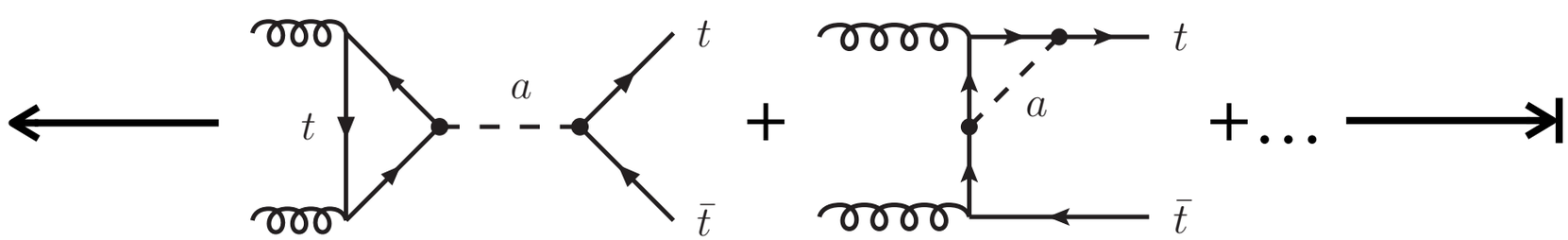
bound from
CMS 1908.01115

Rygaard, SW et al. 2306.08686

Mass-independent probe



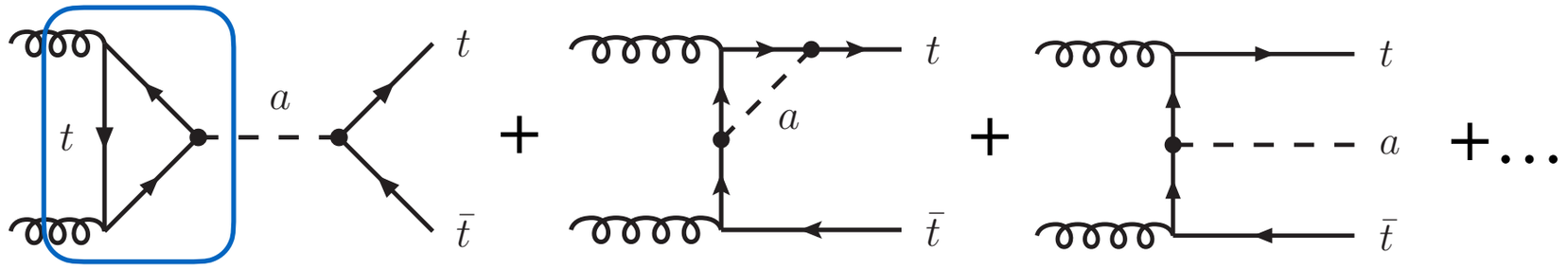
top-antitop kinematics



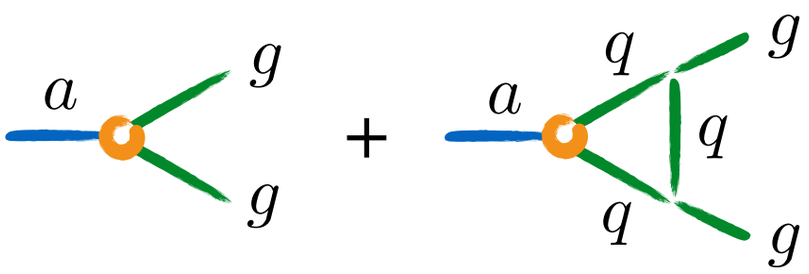
Phan, SW 2312.00872

Blasi et al. 2311.16048

Virtual ALPs in top-antitop production



top-induced ALP-gluon coupling from axial anomaly:

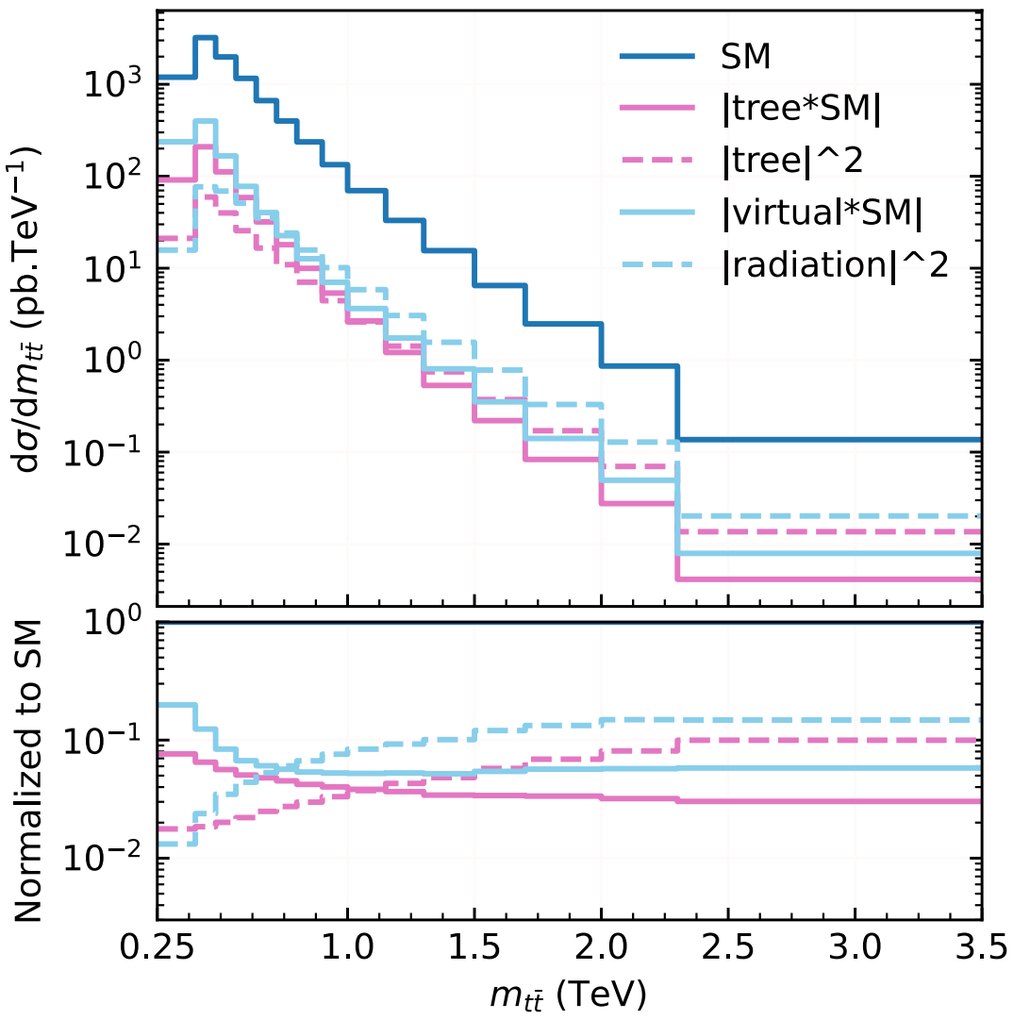


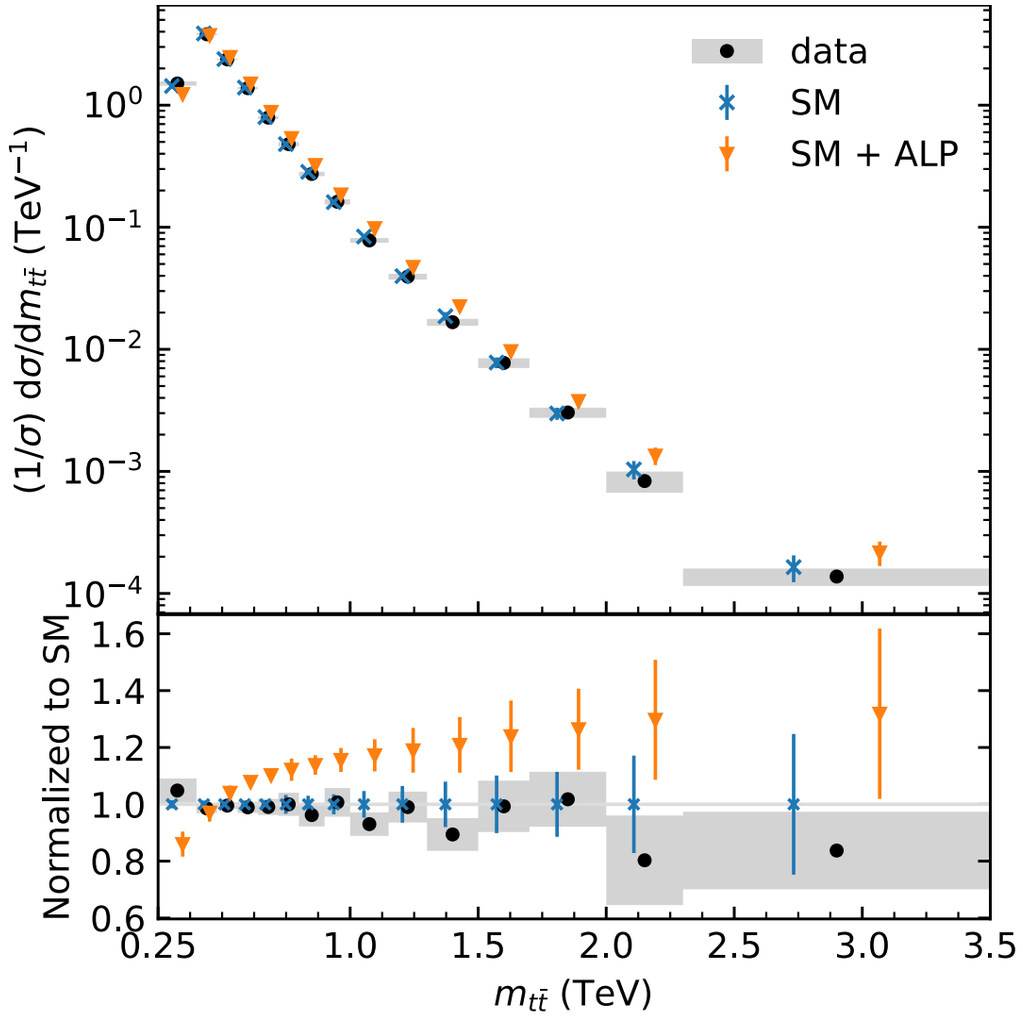
$$c_{GG}^{\text{eff}}(\mu) = c_{GG} + \sum_q \frac{c_{qq}(\mu)}{2}\Theta(\mu - m_q)$$

for leptons: Belen Gavela's talk and Bonilla et al. 2309.15910

… plus virtual and real corrections

ALPs in top differential distributions





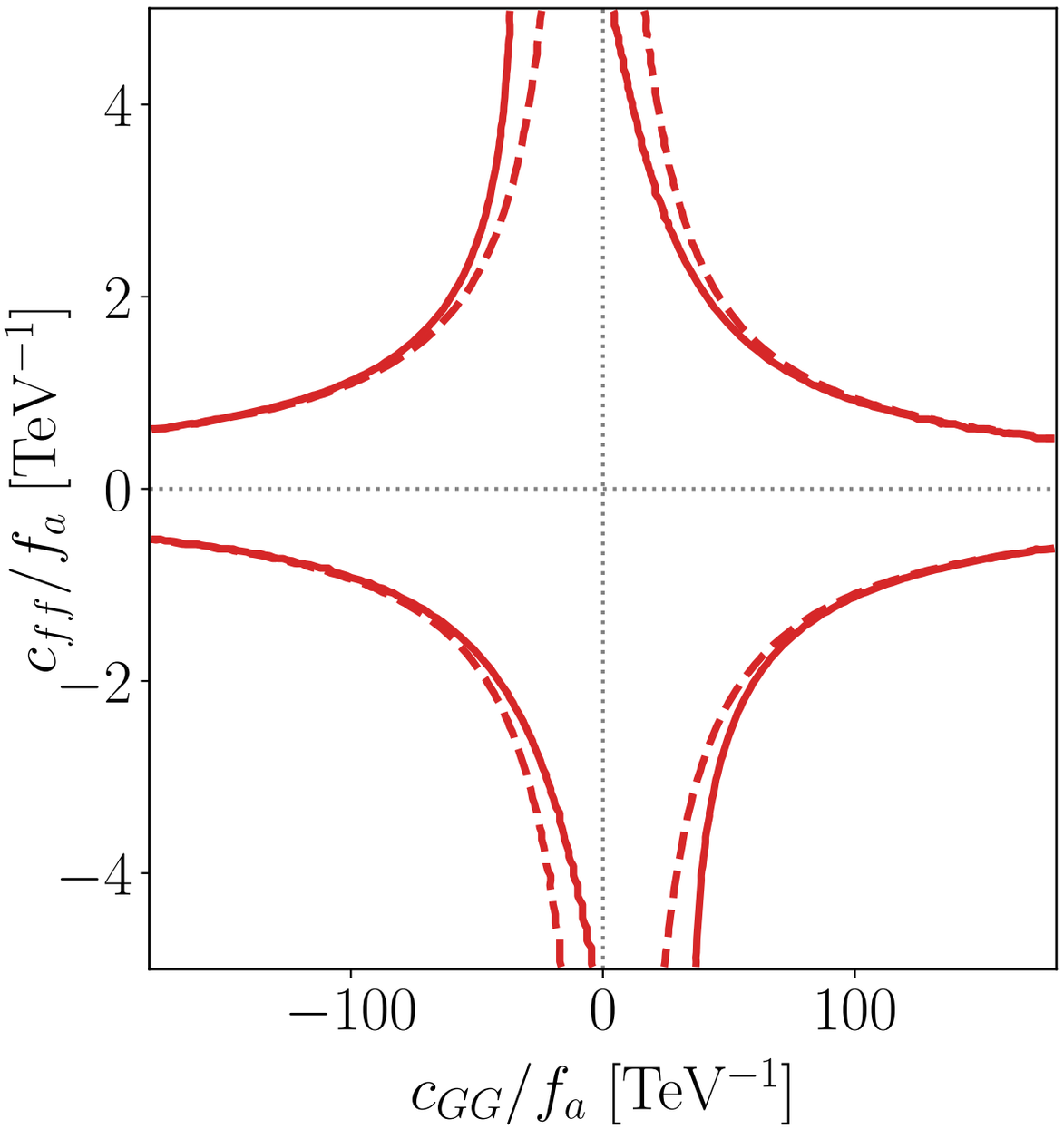
compare with CMS data:

$|c_{tt}|/f_a < 11.1/\mathrm{TeV}$ for $0 < m_a \lesssim 200\,\mathrm{GeV}$

Phan, SW 2312.00872

Beyond the top scenario

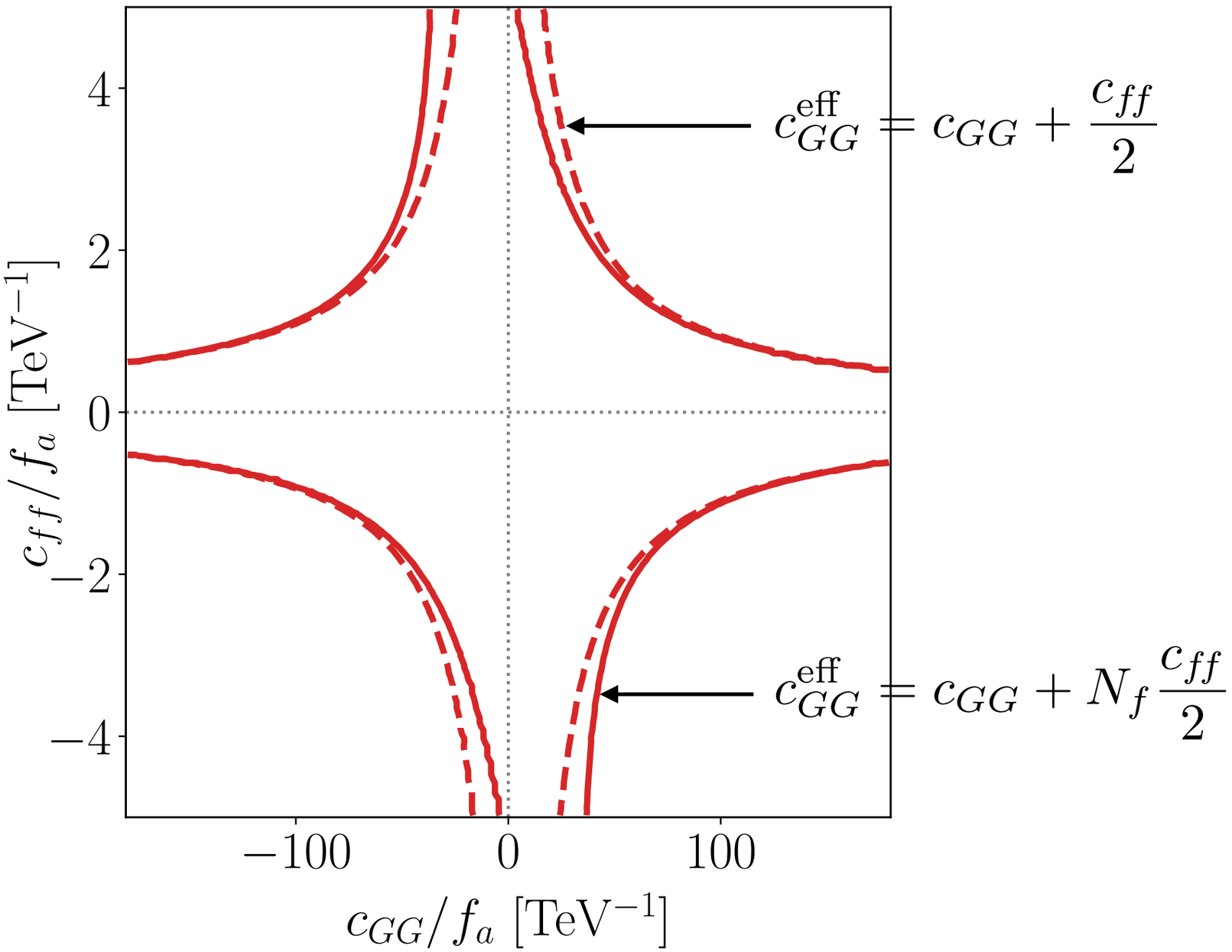
top-antitop production with gluon coupling:



Bruggisser, Grabitz, SW 2308.11703

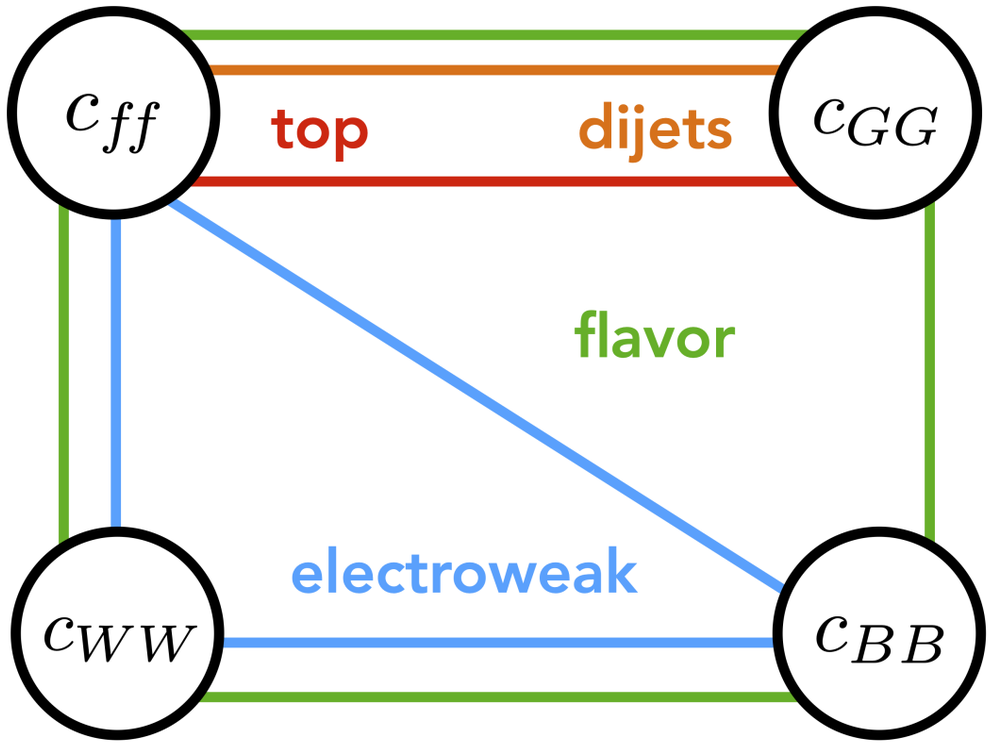
Beyond the top scenario

… and flavor-universal quark couplings:



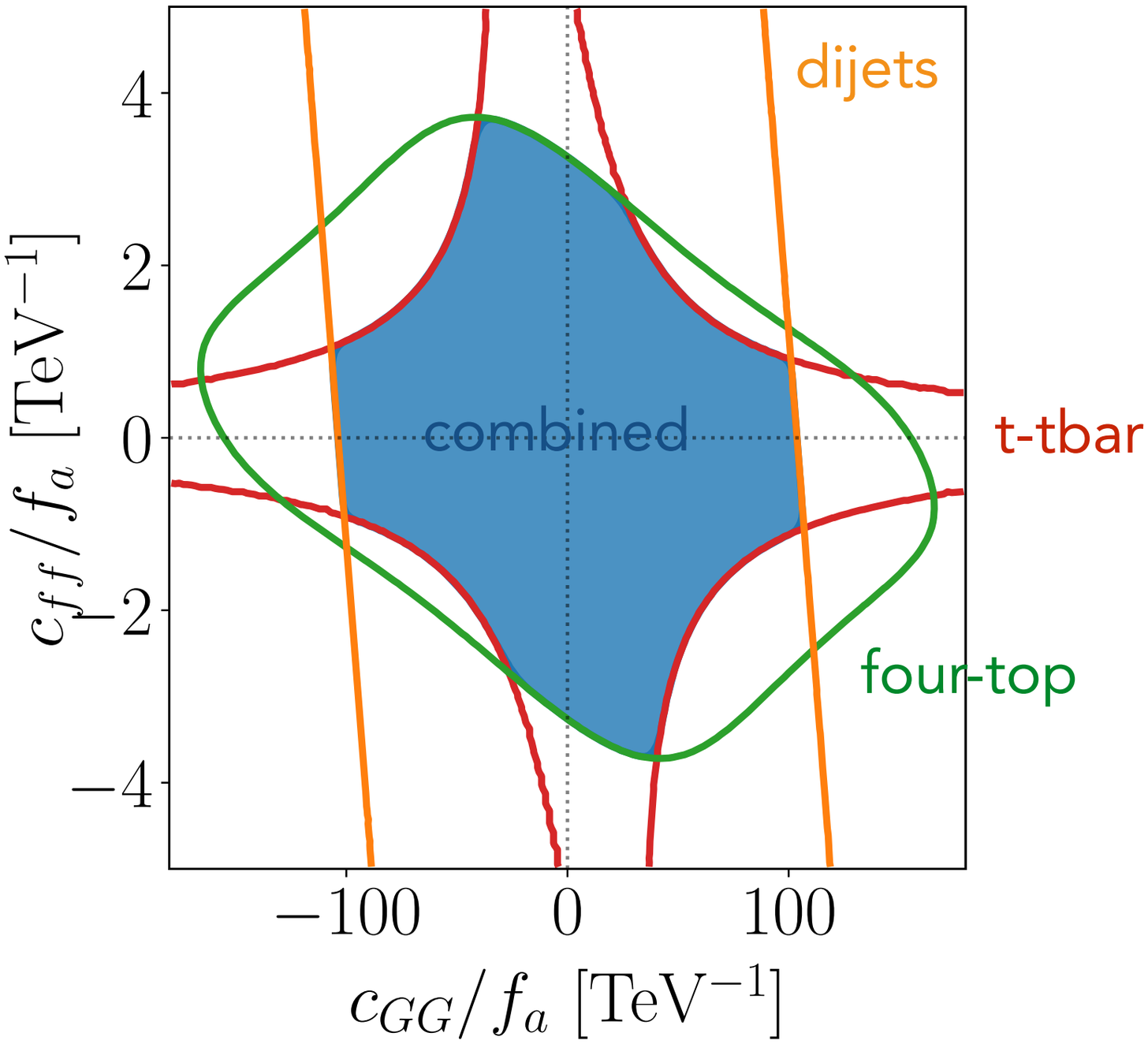
Global analysis of the ALP effective theory

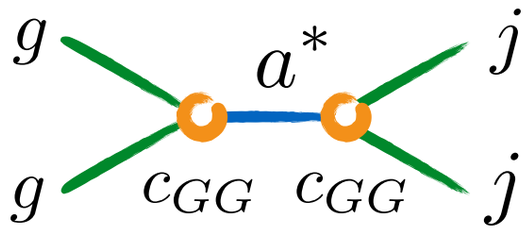
„All observables depend on all couplings.“

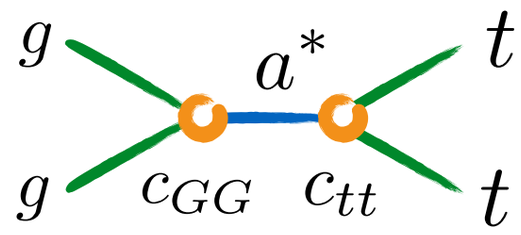


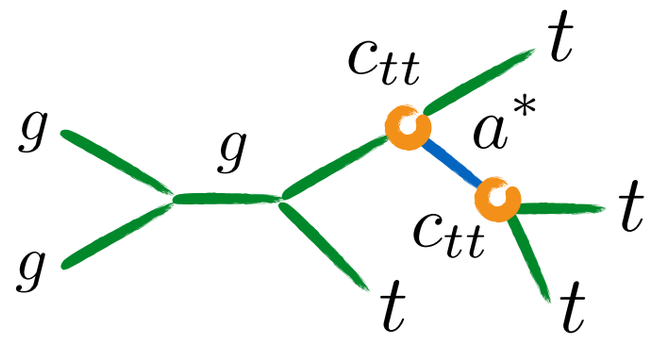
- resonant and virtual ALP effects — Bruggisser, Grabitz, SW 2308.11703
- ALP-induced SMEFT effects — Biekoetter et al. 2307.10372

Top and gluon couplings



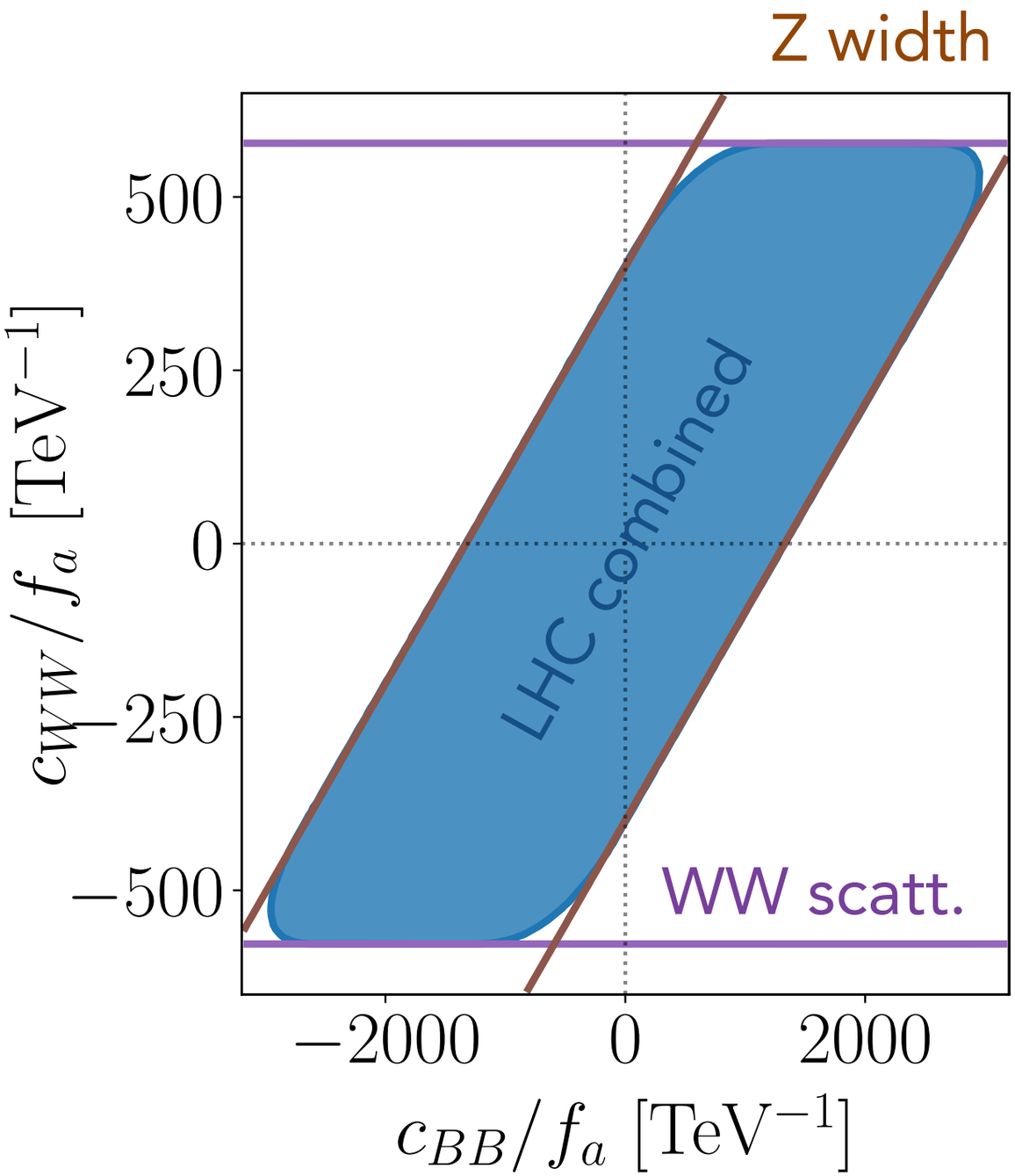


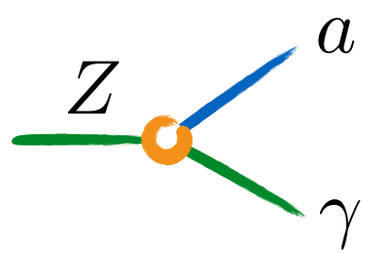




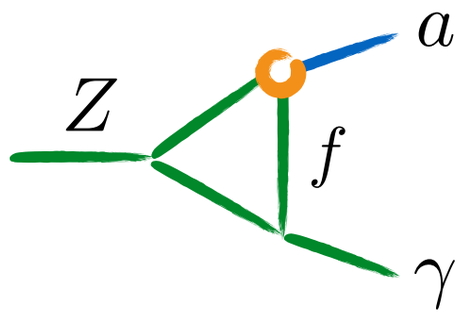
Bruggisser, Grabitz, SW 2308.11703

Electroweak couplings

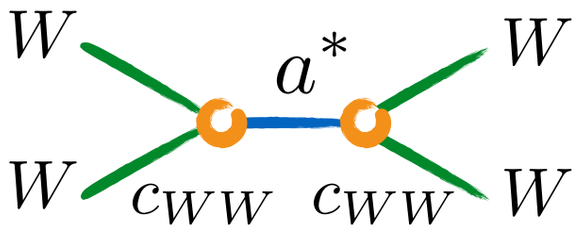




$$c_{\gamma Z} = c_w^2\, c_{WW} - s_w^2 c_{BB}$$



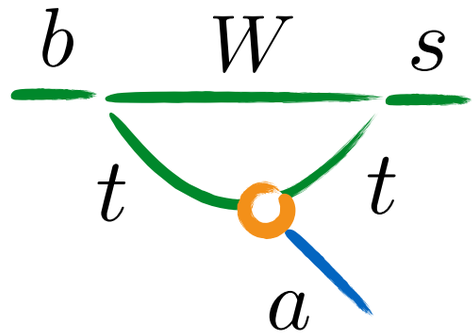
$$\sum_f N_c^f Q_f v_f c_{ff}$$

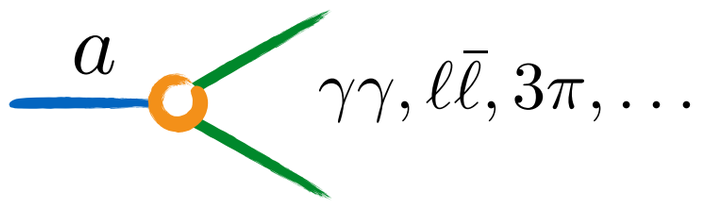


Bonilla et al.
2202.03450

Impact of flavor observables

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

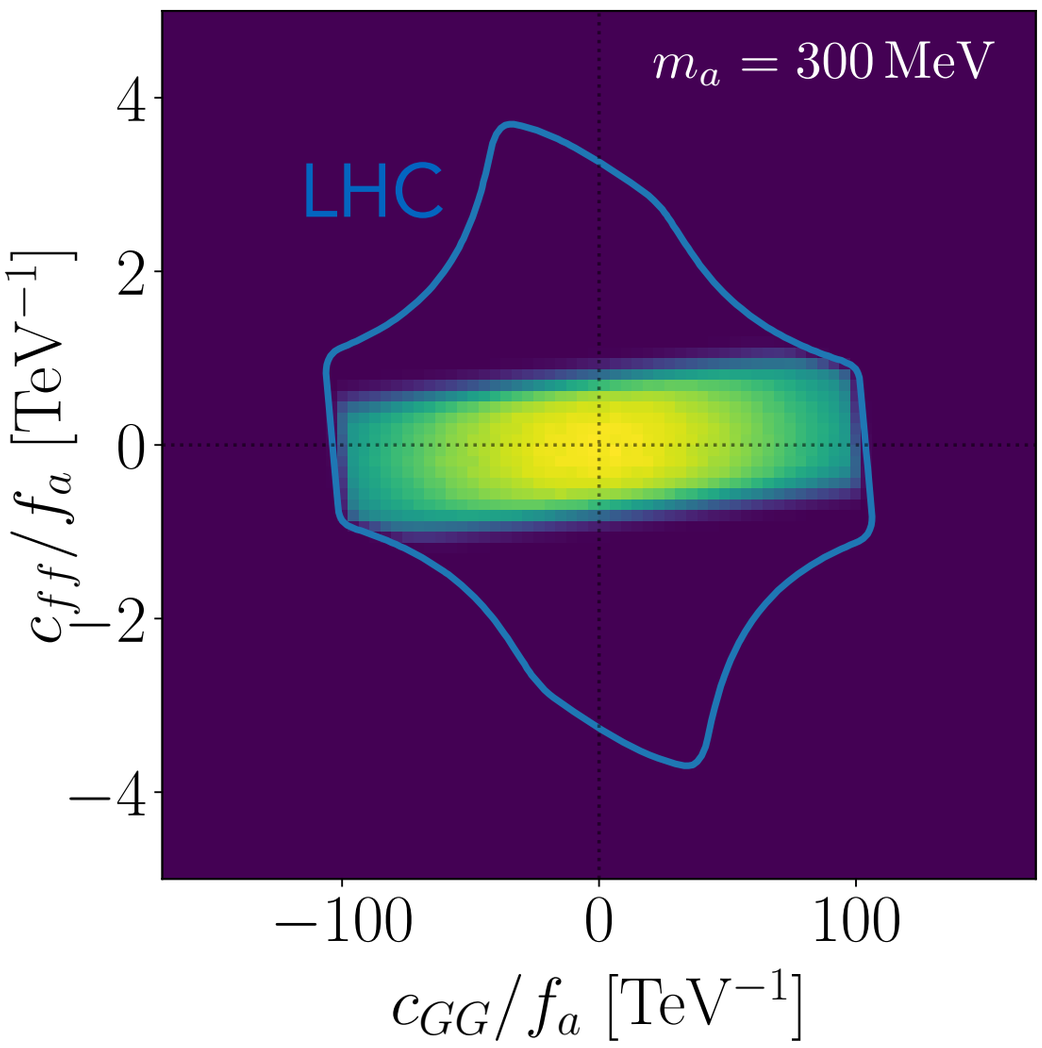


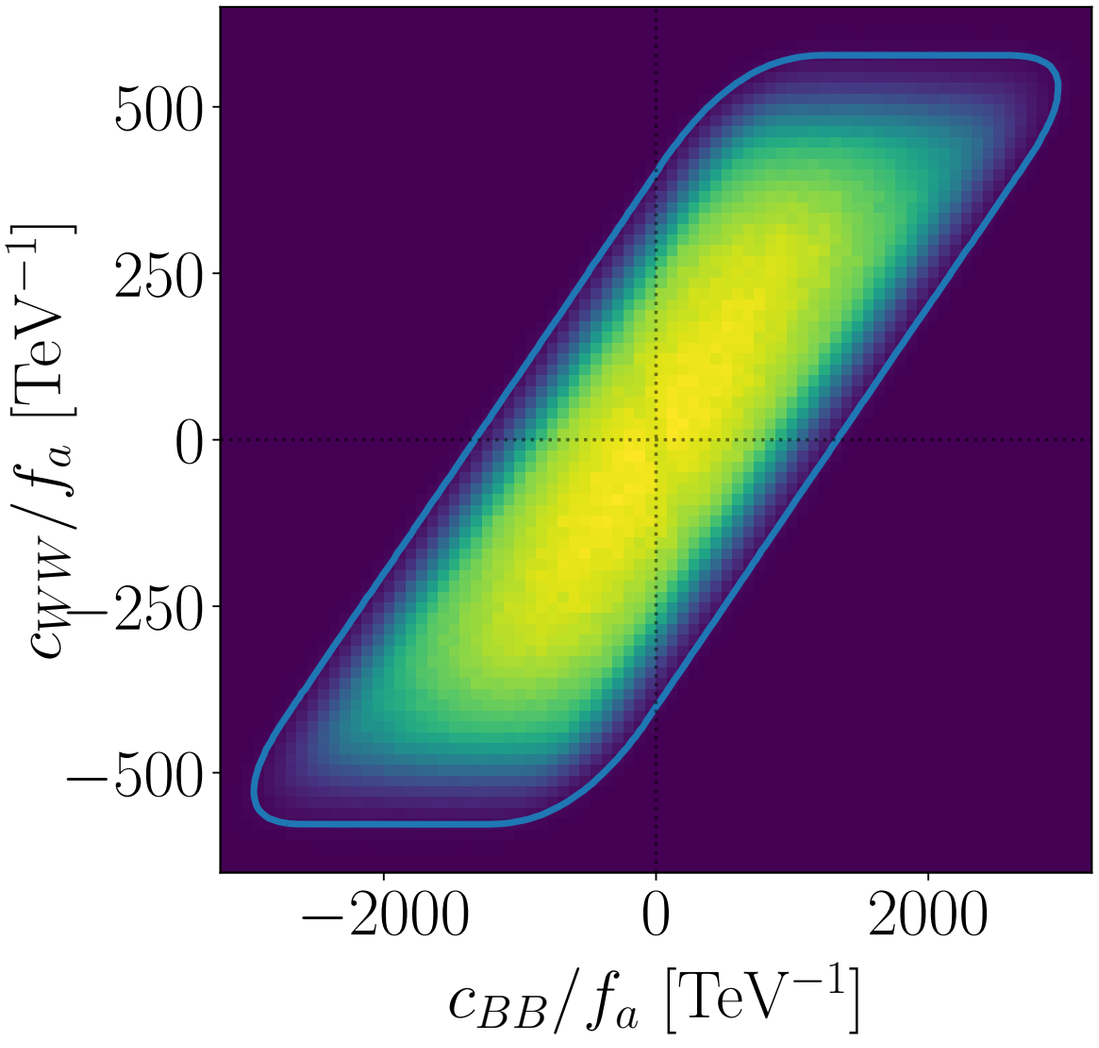


ALP production and decay depend on all couplings.

Global ALP fit with flavor

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





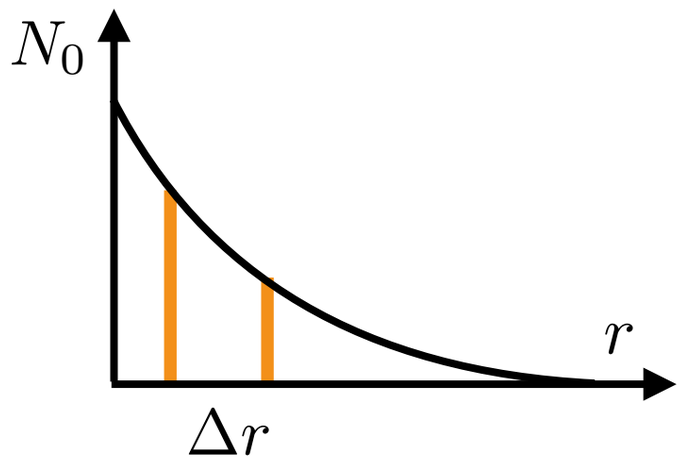
(*) BaBar 2013

Bruggisser, Grabitz, SW 2308.11703

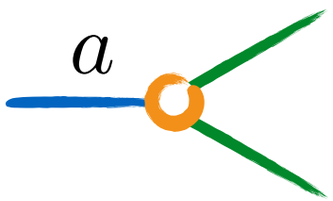
Impact of ALP lifetime

Events at distance from production point:

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



ALP lifetime depends on all couplings:

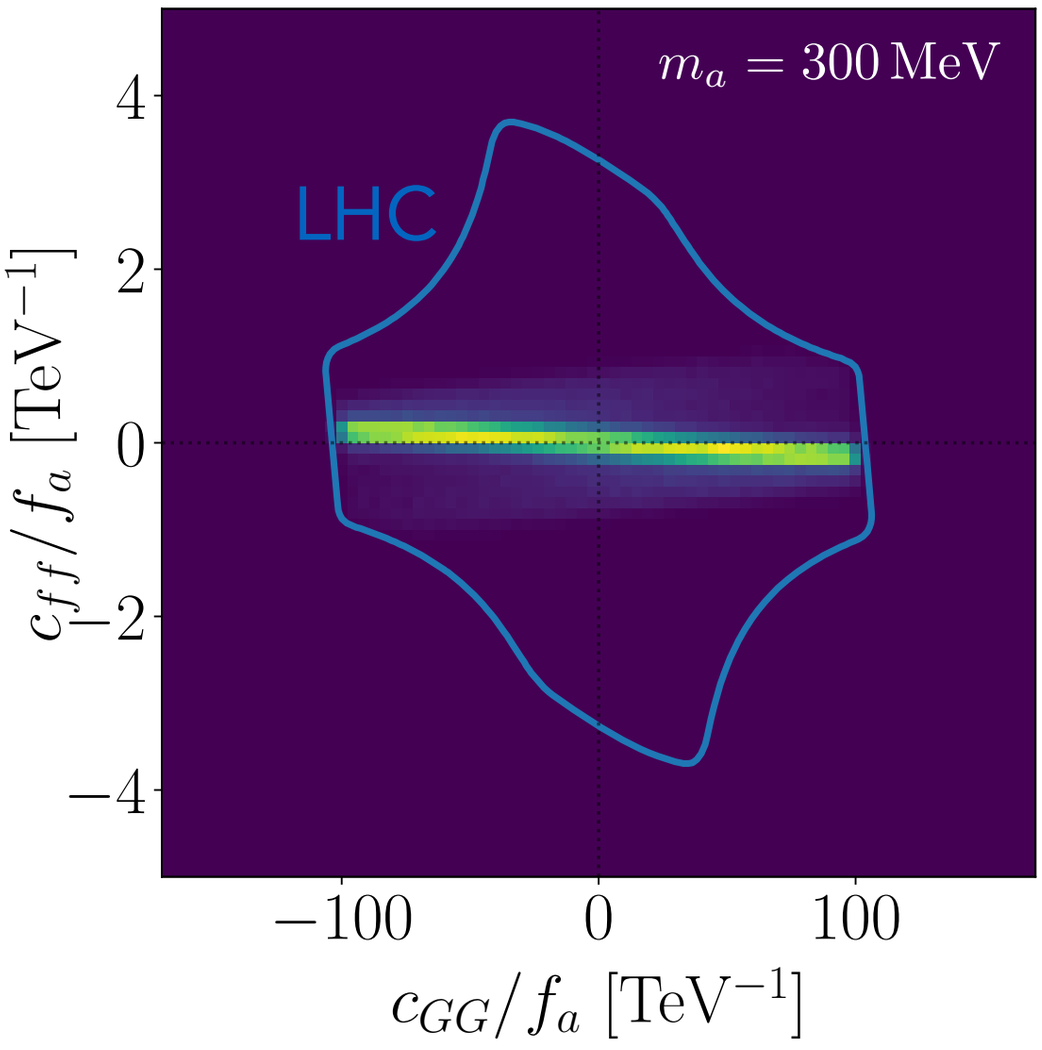


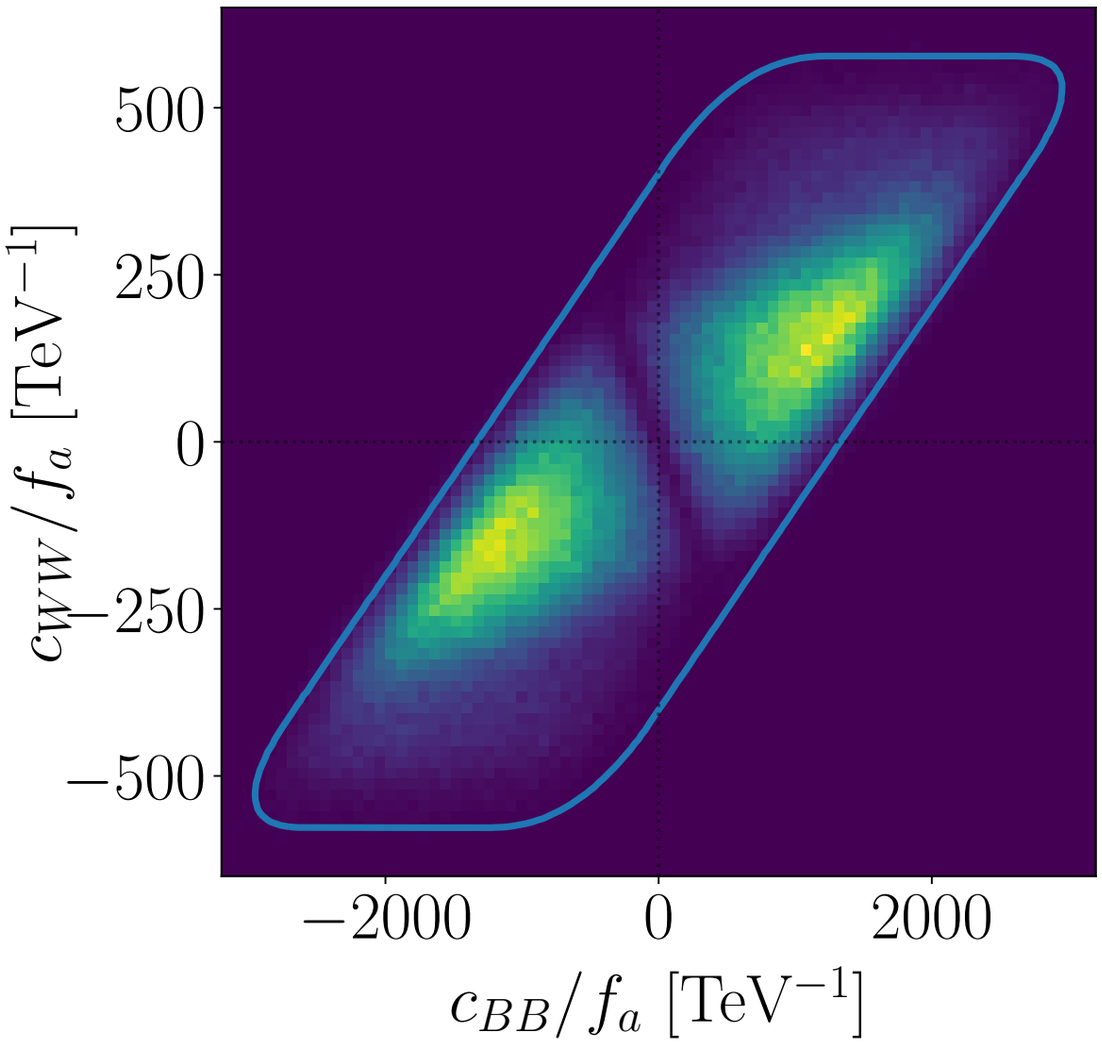
$$\Gamma_a = \sum_f \Gamma(a \to ff) \qquad \text{with} \quad ff = \{\gamma\gamma, \ell\bar{\ell}, 3\pi, \dots\}$$

Scan parameter space with searches for long-lived ALPs.

Prompt-displaced-invisible

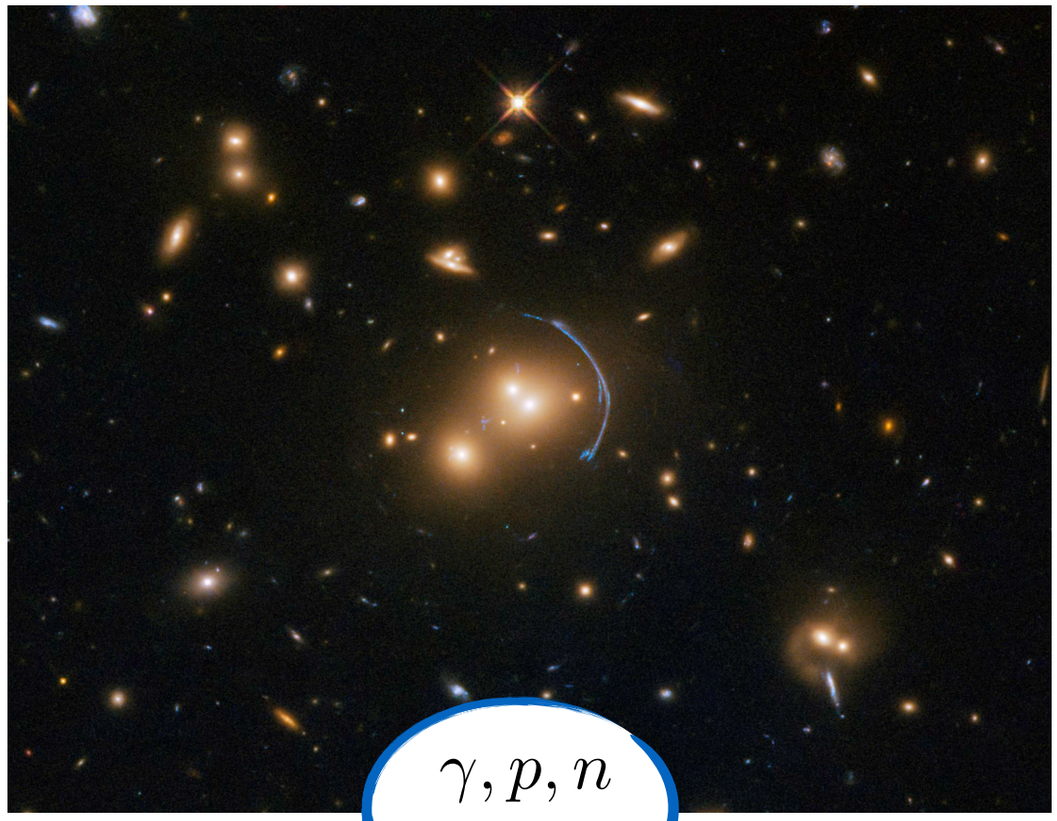
LHC + $B \to K^{(*)}\text{inv.}$ + $B \to K^{(*)} a, a \to \mu\bar{\mu}$



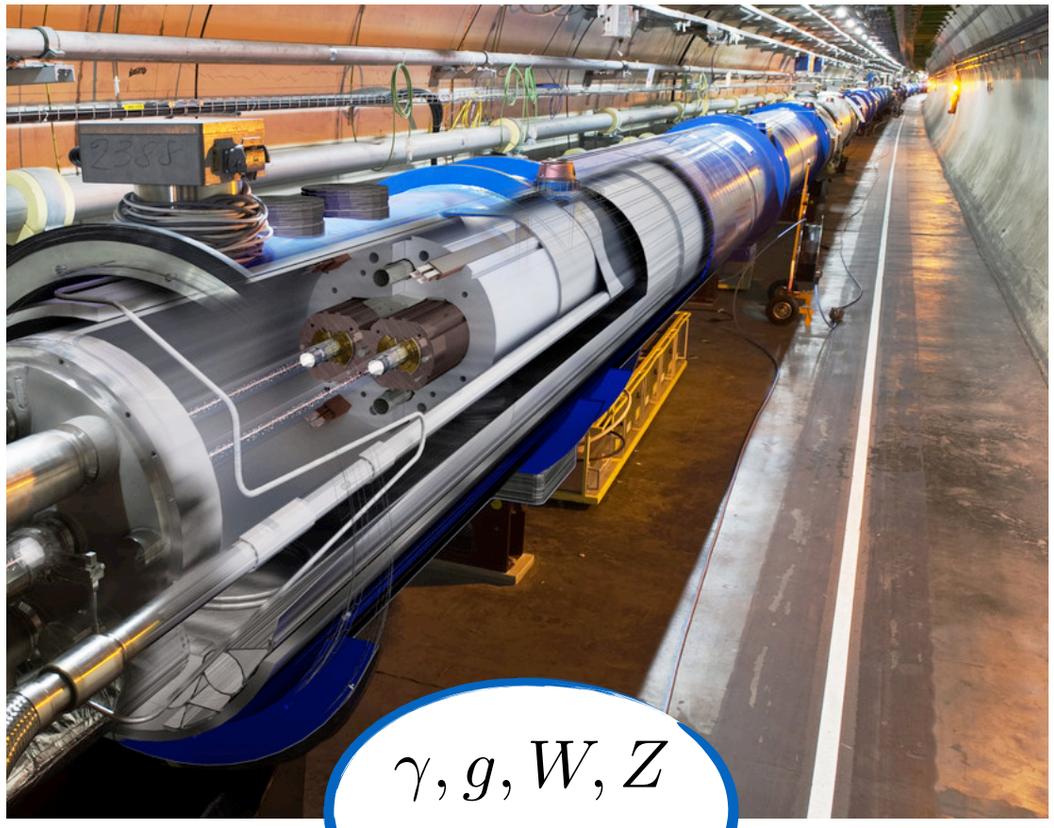


Optimal resolution through parameter correlations.

Summary

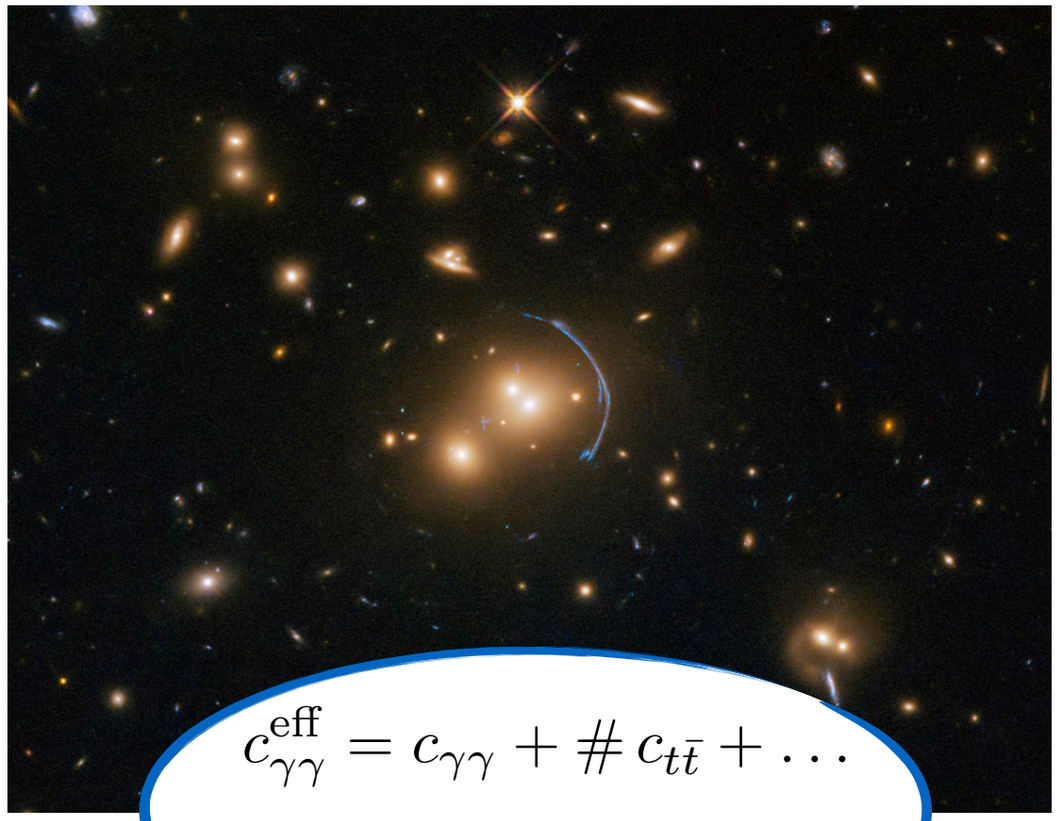


γ, p, n
e



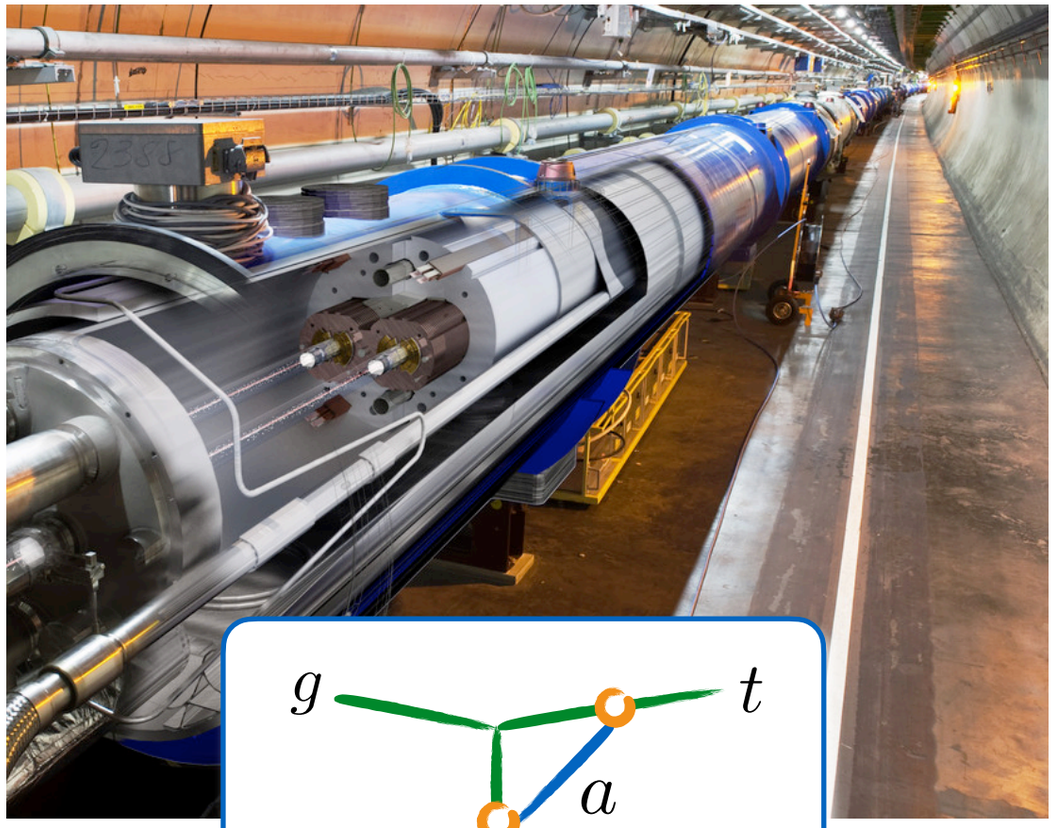
γ, g, W, Z
q, ℓ, ν

Summary



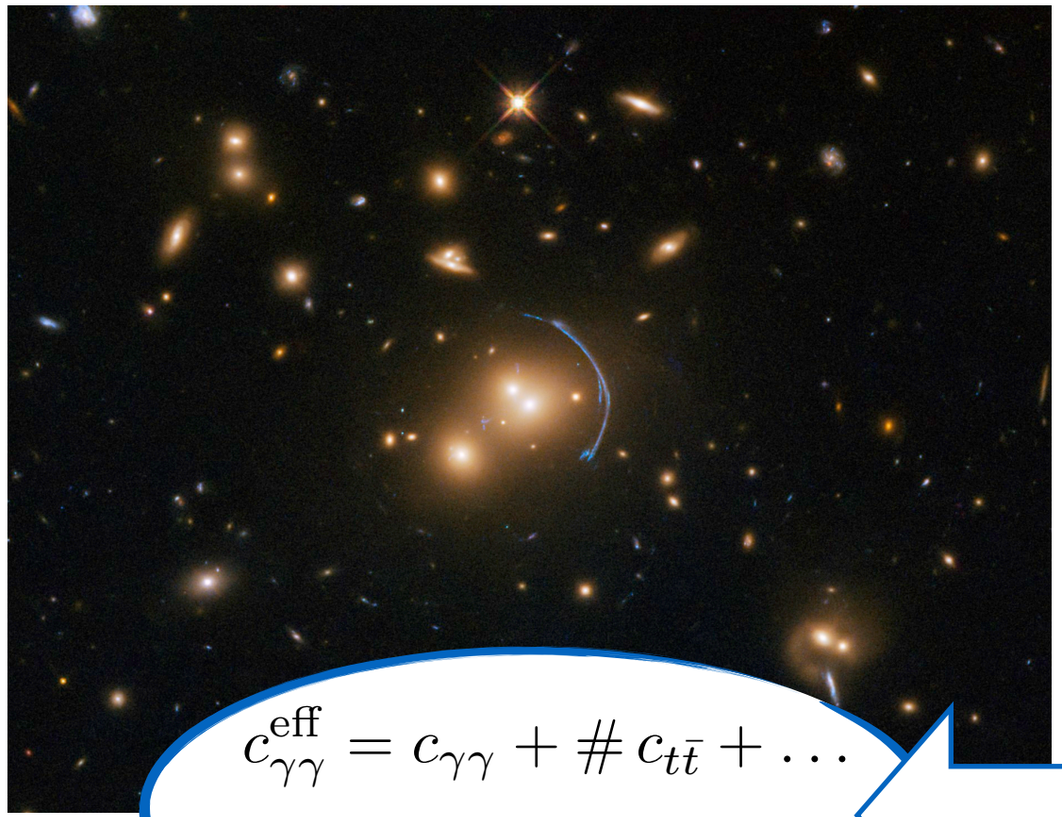
$$c_{\gamma\gamma}^{\text{eff}} = c_{\gamma\gamma} + \# c_{t\bar{t}} + \dots$$

$$c_{ee}^{\text{eff}} = c_{ee} + \# c_{t\bar{t}} + \dots$$



probe top coupling

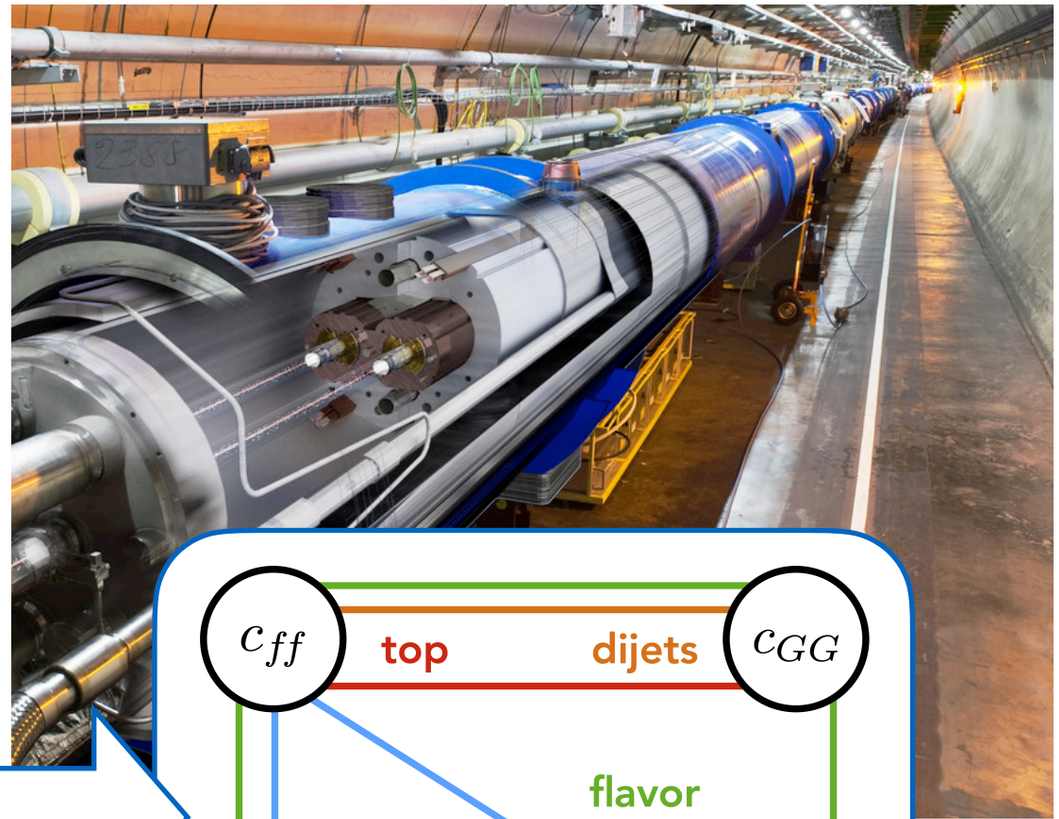
Summary



$$c^{\text{eff}}_{\gamma\gamma} = c_{\gamma\gamma} + \# c_{t\bar{t}} + \dots$$

$$c^{\text{eff}}_{ee} = c_{ee} + \# c_{t\bar{t}} + \dots$$

???

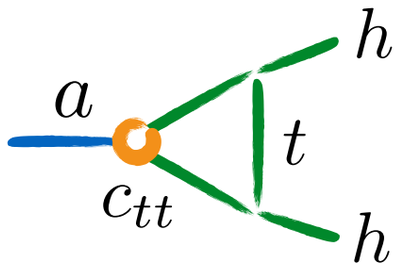


global analysis

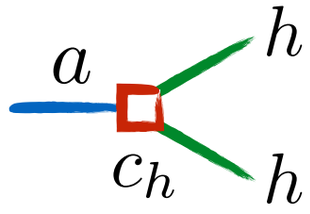
Thank you.

BACKUP

Top-induced leptonic ALP decays



+



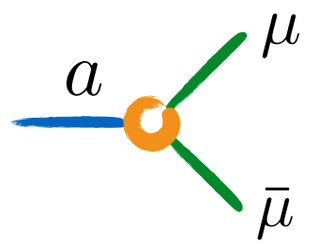
$$O_h = \frac{\partial_\mu a}{f_a}\left(H^\dagger i D^\mu H + h.c.\right)$$

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

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

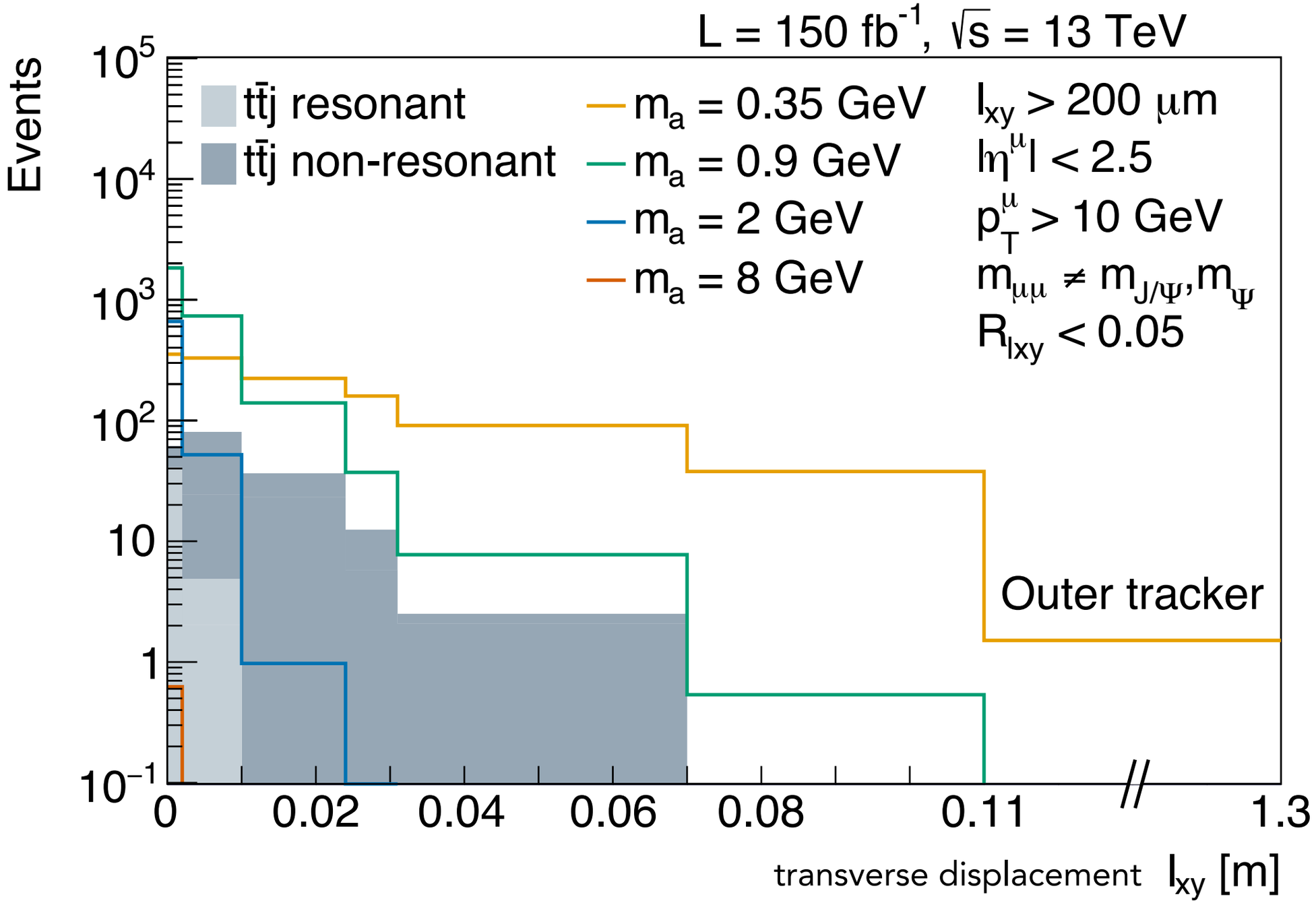
- universal top contributions to fermion couplings:

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



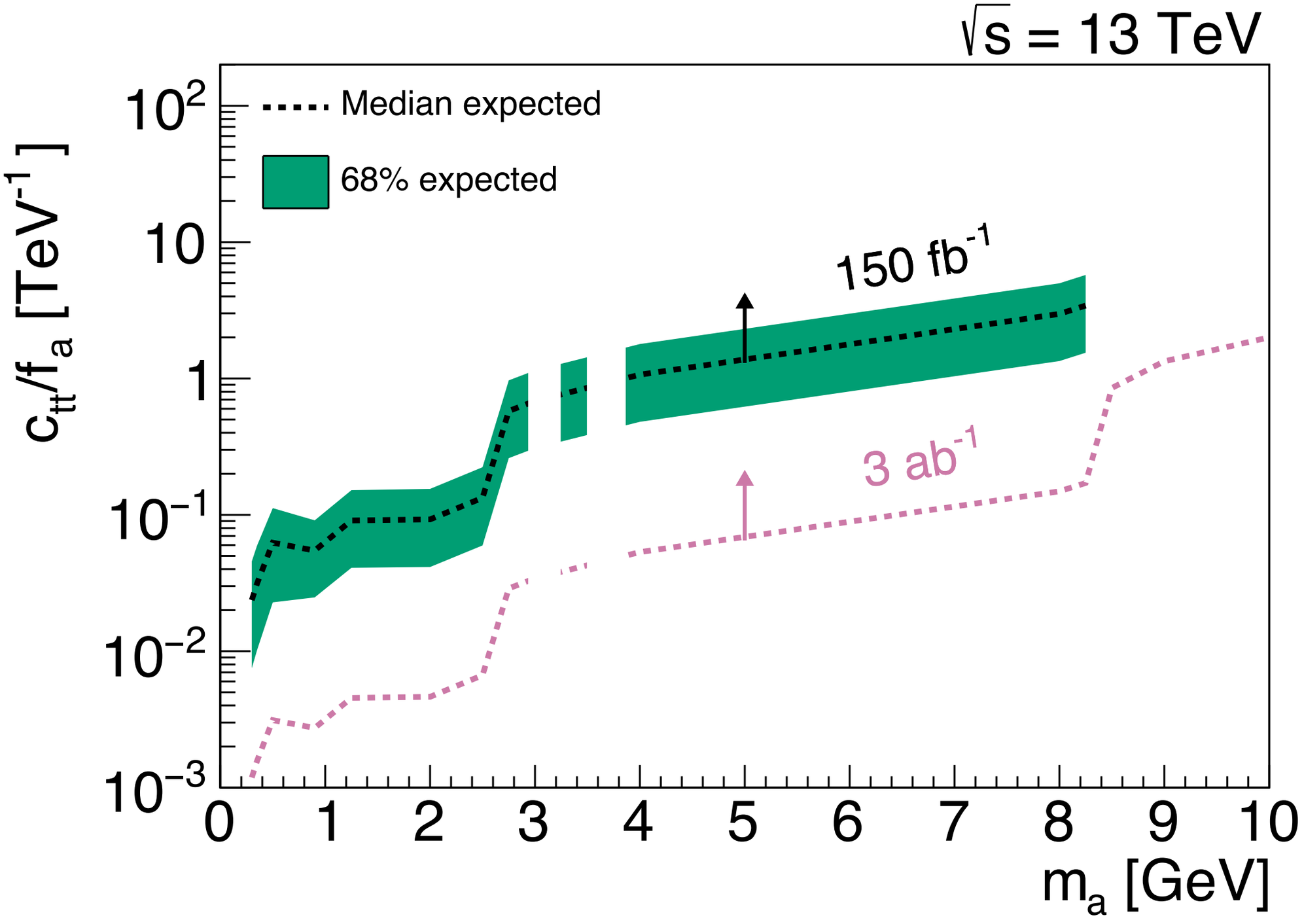
see Bauer et al. 2012.12272

Displaced ALPs in top production



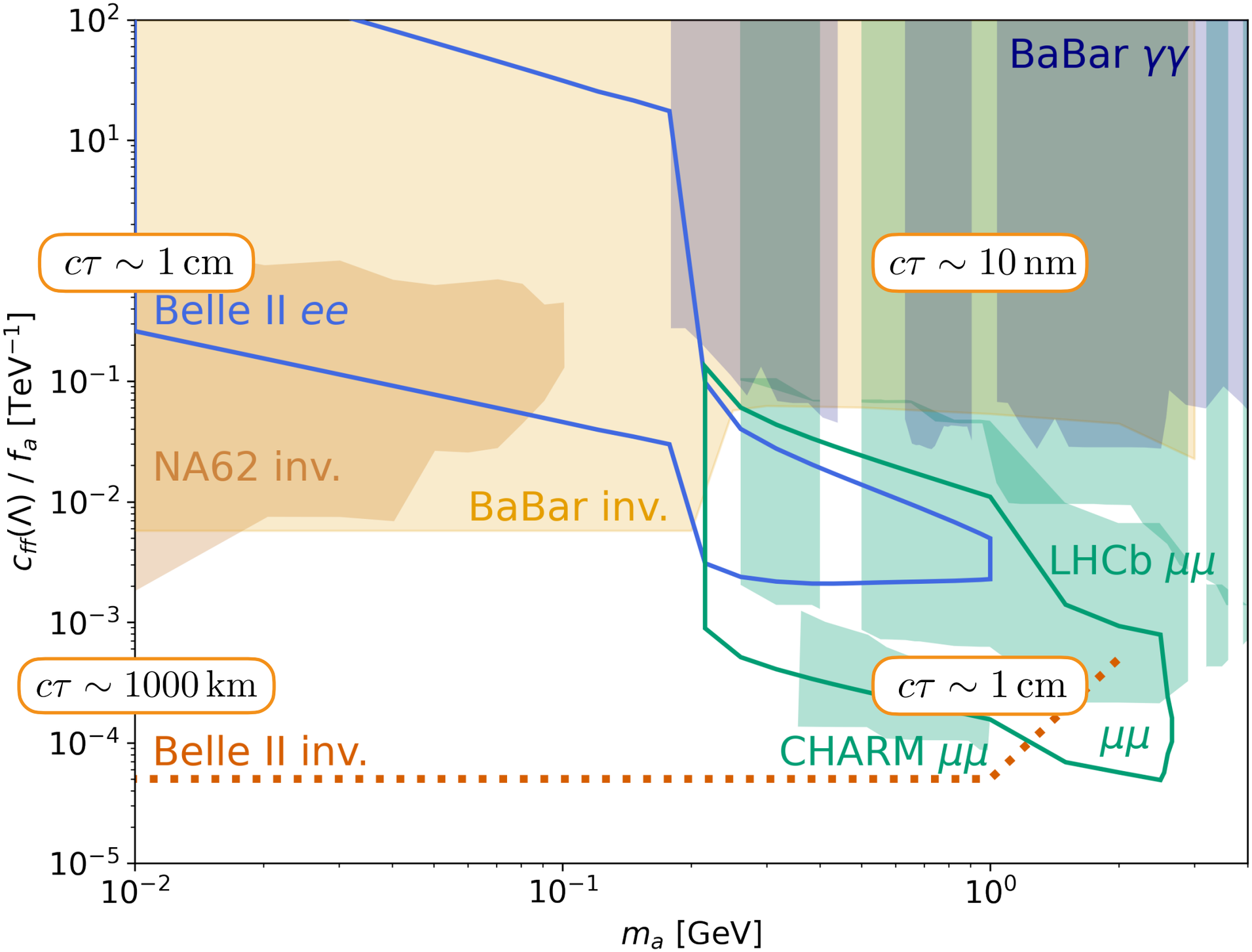
Rygaard, SW et al. 2306.08686

LHC predictions: ALP-top coupling



Rygaard, SW et al. 2306.08686

ALPs in meson decays



Ferber, Filimonova, Schaefer, SW 2201.06580