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Couplings of axion-like particles in linear and chiral EFT realisations

with Maeve Madigan, Alexandre Salas-Bernardez, Veronica Sanz and Maria Ubiali

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Axion-Like Particles

Axion-Like Particles (ALPs)

- ALPs appear as (pseudo) Goldstone bosons in many SM extensions with a spontaneous breaking of a global symmetry
- CP odd $\Rightarrow$ pseudo-scalar couplings
- Shift symmetry $a \to a + c$

  $\to$ couplings momentum dependent

  $\Rightarrow$ energy scaling for processes involving ALPs differs from background processes
- Traditional ALP searches focus on couplings to vector bosons and e^+e^- pairs and small ALP masses

  $\to$ fill gaps in collider studies of ALP-fermion and ALP Higgs couplings in a large mass range

- ALP associated with a heavy new scale $f_a \gg v$

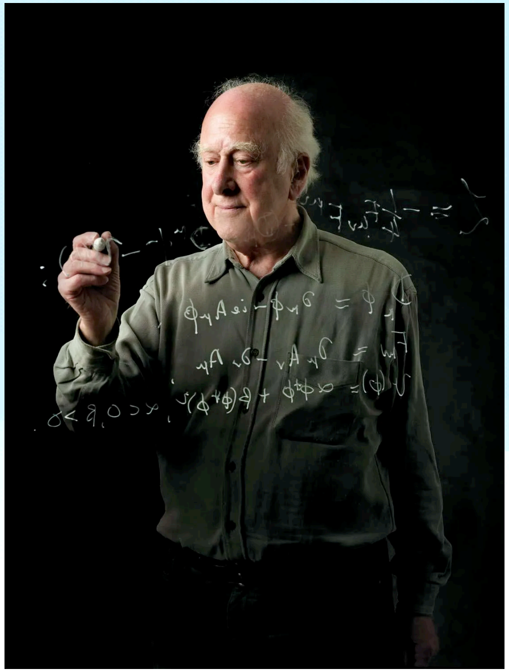
  $\to$ EFT approach

  $\to$ which EFT to use?

Linear and chiral ALP EFT

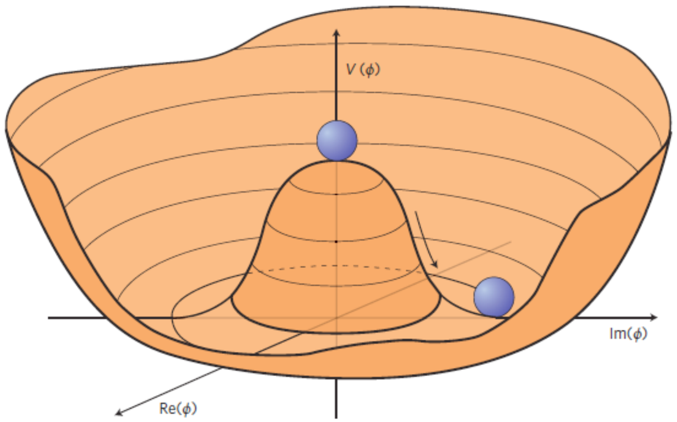
SMEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} \mathscr{O}_i$$



- linear realisation of electroweak symmetry $G = SU(3)_C \times SU(2)_L \times U(1)_Y$
- massless Higgs doublet $h \subset H$
- massless vector bosons
- SM: Higgs potential has a minimum at $v = \sqrt{\mu^2/\lambda}$
  $\rightarrow$ spontaneous symmetry breaking

$$\mathcal{L}_{SM} = -\frac{1}{4} G^A_{\mu\nu} G^{A,\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \sum_{\psi=q,u,d,l,e} \bar{\psi} i \not{D} \psi$$
$$+ (D_\mu H)^\dagger (D^\mu H) - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$
$$- \left[H^{\dagger j} \bar{d} Y_d q_j + \tilde{H}^{\dagger j} \bar{u} Y_d q_j + H^{\dagger j} \bar{e} Y_e l_j + h.c.\right]$$



NB: Higgs potential can be modified in SMEFT with respect to the SM!

HEFT

- Non-linear realisation of Electroweak Symmetry $G = SU(3)_C \times U(1)_Q$
- massive singlet scalar h with arbitrary polynomial couplings functions
- massive vector bosons $W^\pm, Z$
- allows most general parametrisation of the Higgs potential

$$\mathcal{L}_{\rm HEFT}^{\rm LO} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - V(h) + \\ - \frac{v^2}{4}{\rm Tr}[\mathbf{V}_\mu \mathbf{V}^\mu]\,\mathcal{F}_C(h) + c_T\, v^2 {\rm Tr}[\mathbf{T}\mathbf{V}_\mu]{\rm Tr}[\mathbf{T}\mathbf{V}^\mu]\mathcal{F}_T(h) + i\bar{Q}\not{D}Q + i\bar{L}\not{D}L + \\ - \frac{v}{\sqrt{2}}\left(\bar{Q}_L \mathbf{U}\mathcal{Y}_Q(h)Q_R + {\rm h.c.}\right) - \frac{v}{\sqrt{2}}\left(\bar{L}_L \mathbf{U}\mathcal{Y}_L(h)L_R + {\rm h.c.}\right) + \\ - \frac{g_s^2}{16\pi^2}\theta G^\alpha_{\mu\nu}\tilde{G}^{\alpha\mu\nu},$$

$$\mathcal{F}_i(h) = 1 + a_i h/v + b_i (h/v)^2 + \dots$$

$$\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$$

$$\mathbf{T}(x) \equiv \mathbf{U}(x)\sigma_3\mathbf{U}(x)^\dagger,$$

$$\mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu \mathbf{U}(x))\,\mathbf{U}(x)^\dagger$$

Linear ALP EFT

- As for SMEFT start from linear realisation of EW symmetry $\Rightarrow \mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_a$
- Expand in powers of a/f_a , NLO has one insertion

$$\mathscr{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{1}{2}m_a^2 a^2 + c_{\tilde{W}}\mathscr{A}_{\tilde{W}} + c_{\tilde{B}}\mathscr{A}_{\tilde{B}} + c_{\tilde{G}}\mathscr{A}_{\tilde{G}} + \sum_{f=u,d,e,Q,L} c_f \mathscr{A}_f$$

- couplings to gauge bosons: $\mathscr{A}_{\tilde{X}} = -\frac{a}{f_a} X^a_{\mu\nu}\tilde{X}^{\mu\nu,a}$

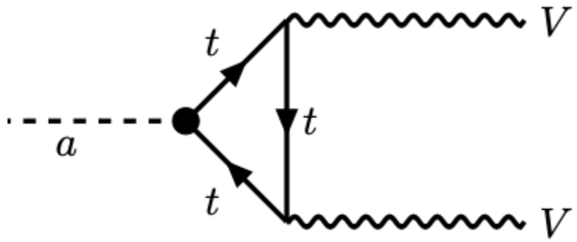
- couplings to fermions: $\mathscr{A}_f = \frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu f$

- for top quark using EOM: $\mathscr{L} \supset -ic_t \frac{m_t a}{2f_a}\left(\bar{t}\gamma^5 t\right)$

$\Rightarrow$ Couplings are proportional to the fermion mass!

$\Rightarrow$ Focus on **ALP-top coupling** c_t and

set all other couplings to zero



- couplings to vector bosons are generated at 1-loop level

[Bonilla, Brivio, Gavela, Sanz, 2021]

Chiral ALP EFT

- As for HEFT, start from non-linear realisation of EW symmetry $\Rightarrow \mathscr{L} = \mathscr{L}^{LO}_{HEFT} + \mathscr{L}_a$

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D}\mathcal{A}_{2D}(h) + c_{\tilde{W}}\mathcal{A}_{\tilde{W}} + c_{\tilde{B}}\mathcal{A}_{\tilde{B}} + c_{\tilde{G}}\mathcal{A}_{\tilde{G}} + \sum_{i=1}^{17} c_i \mathcal{A}_i(h)$$

[Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17]

- many more terms at NLO, all with arbitrary Higgs polynomial functions

$$\mathcal{A}_{2D}(h) = iv^2 \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\mathcal{F}_{2D}(h)$$

$$\mathcal{A}_1(h) = \frac{i}{4\pi}\tilde{B}_{\mu\nu}\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\mathcal{F}_1(h)$$

$$\mathcal{A}_2(h) = \frac{i}{4\pi}\mathrm{Tr}[\tilde{W}_{\mu\nu}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\mathcal{F}_2(h)$$

$$\mathcal{A}_3(h) = \frac{1}{4\pi}B_{\mu\nu}\partial^\mu \frac{a}{f_a}\partial^\nu \mathcal{F}_3(h)$$

$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}_\nu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\mathcal{F}_4(h)$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\nu]\partial_\nu \frac{a}{f_a}\mathcal{F}_5(h)$$

$$\mathcal{A}_6(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\partial^\nu \frac{a}{f_a}\mathcal{F}_6(h)$$

$$\mathcal{A}_7(h) = \frac{i}{4\pi}\mathrm{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\mathcal{F}_7(h)$$

$$\mathcal{A}_8(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[[\mathbf{V}_\nu,\mathbf{T}]\mathcal{D}_\mu\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\mathcal{F}_8(h)$$

$$\mathcal{A}_9(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}_\nu]\partial^\nu \frac{a}{f_a}\mathcal{F}_9(h)$$

$$\mathcal{A}_{10}(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}W_{\mu\nu}]\partial^\mu \frac{a}{f_a}\partial^\nu \mathcal{F}_{10}(h)$$

$$\mathcal{A}_{11}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\Box \frac{a}{f_a}\partial^\mu \mathcal{F}_{11}(h)$$

$$\mathcal{A}_{12}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\partial^\nu \frac{a}{f_a}\partial_\nu \mathcal{F}_{12}(h)$$

$$\mathcal{A}_{13}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\Box\mathcal{F}_{13}(h)$$

$$\mathcal{A}_{14}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu \frac{a}{f_a}\partial^\mu\partial^\nu \mathcal{F}_{14}(h)$$

$$\mathcal{A}_{15}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\partial_\nu \mathcal{F}_{15}(h)\partial^\nu \mathcal{F}'_{15}(h)$$

$$\mathcal{A}_{16}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu \frac{a}{f_a}\partial^\mu \mathcal{F}_{16}(h)\partial^\nu \mathcal{F}'_{16}(h)$$

$$\mathcal{A}_{17}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{\Box a}{f_a}\mathcal{F}_{17}(h)\,.$$

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$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}_\nu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu \ldots$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu \mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\nu]\partial_\nu \frac{a}{f_a}\mathcal{F}_5(h)$$

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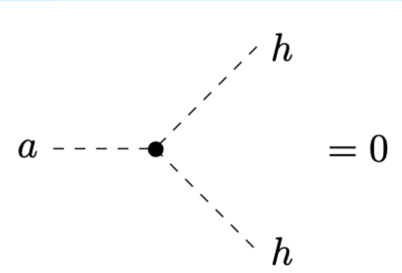
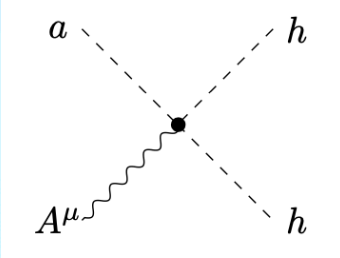
- Many more terms at NLO than SMEFT
- More general description
- ALP-Higgs-Z couplings ah^nZ at NLO

ALP-Higgs couplings in chiral ALP EFT

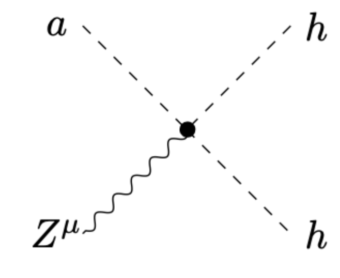


No ALP-hh vertex, excluded by parity



$$\frac{1}{2\pi v^2 f_a}\left(\tilde{b}_3 c_W + \tilde{b}_{10} s_W\right)\left(p_\gamma^\mu p_a^2 - p_\gamma^2 p_a^\mu\right) \overset{\text{on shell}}{=} 0$$

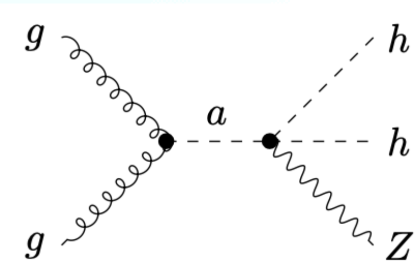
ALP-hh-photon vanishes on-shell
→ need longitudinal polarisation



$$\frac{g}{4\pi^2 c_W v^2 f_a}\Big[p_{hh}^\mu (p_a^2 \tilde{b}_{11} + p_a \cdot p_{hh} \tilde{b}_{14}) + p_a^\mu (p_{hh}^2 \tilde{b}_{13} + p_a \cdot p_{hh} \tilde{b}_{12})$$
$$+ 2\tilde{a}_{16}(p_{h1}^\mu p_a \cdot p_{h2} + p_{h2}^\mu p_a \cdot p_{h1}) + 4\tilde{a}_{15} p_a^\mu p_{h1} \cdot p_{h2}$$
$$- p_a^\mu (16\pi^2 v^2 \tilde{b}_{2D} - \tilde{b}_{17} p_a^2) + 2\pi s_{2W} \tilde{b}_{310}(p_Z^2 p_a^\mu - p_Z^\mu p_a \cdot p_Z)/e\Big]$$

$\tilde{a}_i = c_i a_i$
$\tilde{b}_i = c_i b_i$

dominant contributions!



ALP-mediated Di-Higgs + Z production from gluon fusion
is TREE LEVEL in chiral ALP EFT

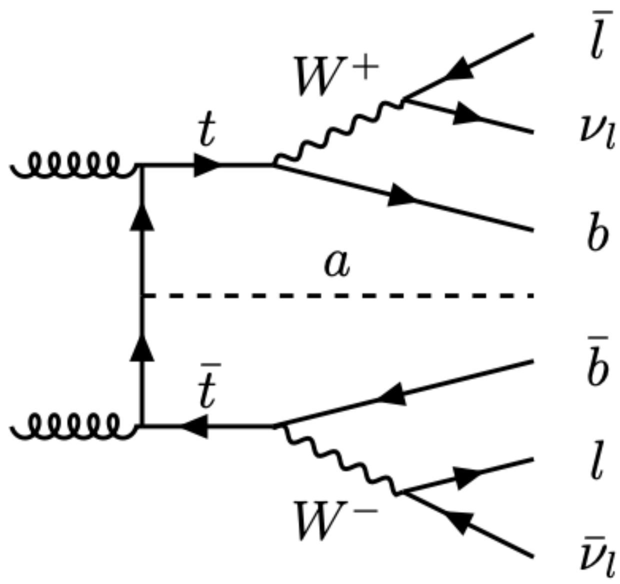
Constraining c_t in linear ALP EFT

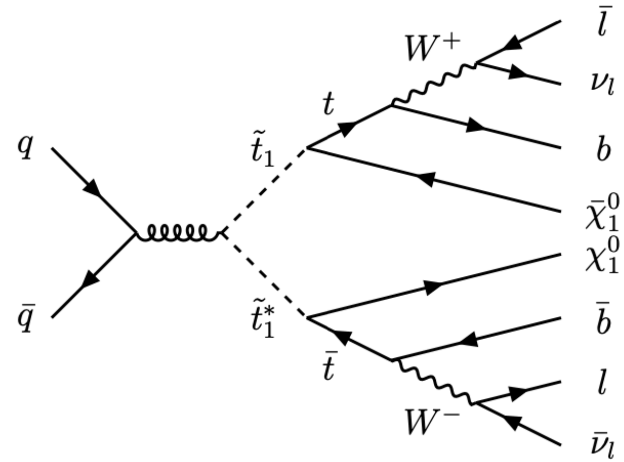
1. Direct constraints on c_t

- obtained from processes in which an ALP is produced in association with a $t\bar{t}$ pair
- assume ALP collider stable, escapes the detector as missing transverse energy (MET)
- Reinterpret a Run II **ATLAS search for top squarks** in events with 2 leptons, 2 b-jets and MET at $\sqrt{s} = 13$ TeV, $\mathscr{L} = 139$ fb^{-1} [2102.134929]
- SUSY benchmark: pair production of stops with prompt decay into top quarks and neutralinos
- SM background, ALP signal and SUSY benchmarks all lead to the **same final state topology** of

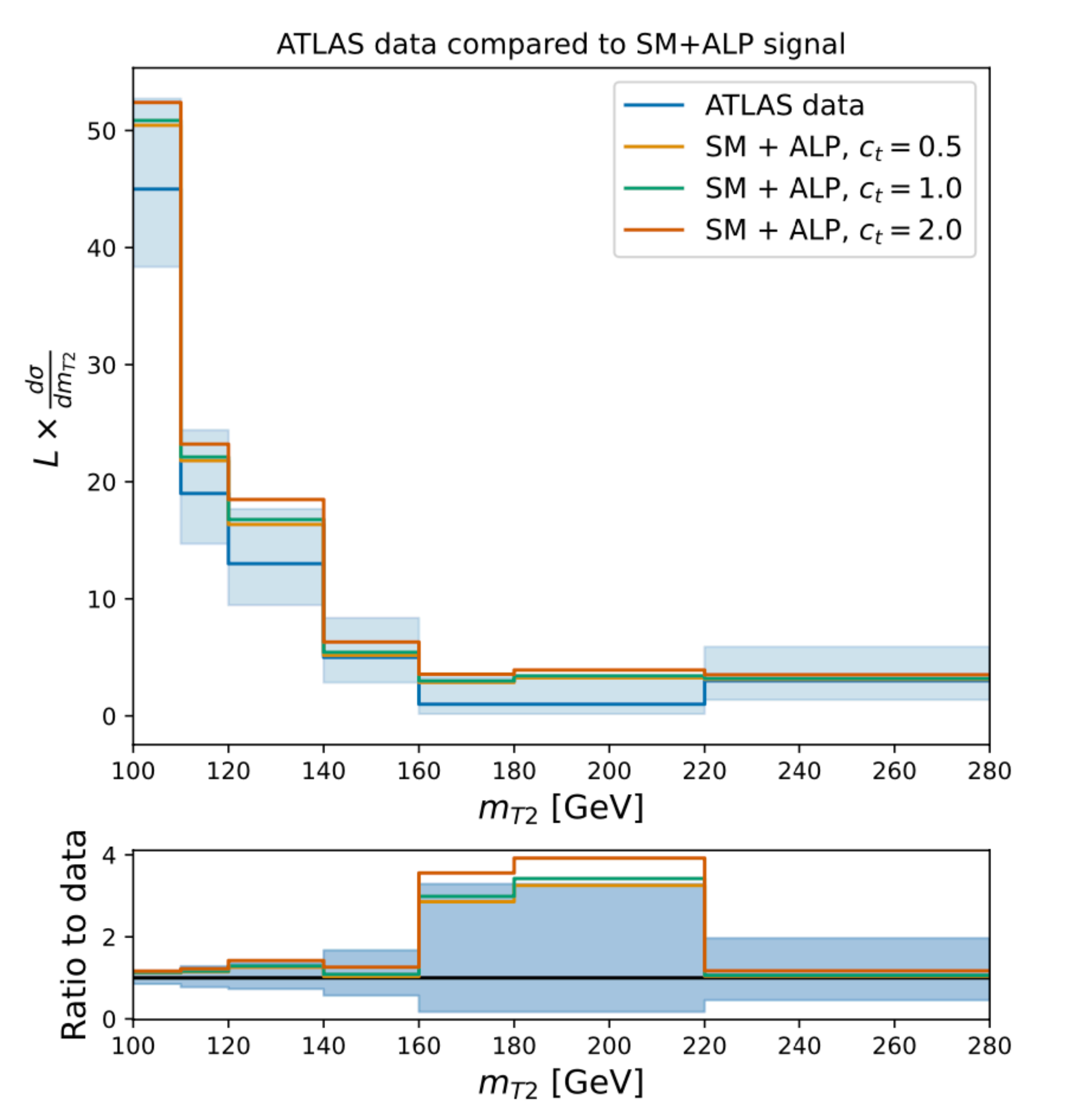
$$2l + 2j + MET$$

$$\text{with } MET = \begin{cases} \nu & SM \\ \nu + a & ALP \\ \nu + \tilde{\chi}^0 & SUSY \end{cases}$$





ALP signal



- compare ALP signal + SM background for different c_t to data
- MadGraph and SM background uncertainties negligible compared to experimental uncertainties
- $t\bar{t}a$ vertex proportional to c_t/f_a, global factor $(c_t/f_a)^2$ in the signal events
- Assume a Poisson likelihood

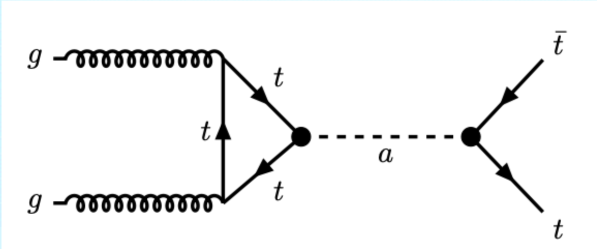
$$\mathcal{L}(c_t) = \prod_{k=1}^{N_{\text{bins}}} \frac{\exp\left(-\left(\left(\frac{c_t}{f_a}\right)^2 s_k + b_k\right)\right)\left(\left(\frac{c_t}{f_a}\right)^2 s_k + b_k\right)^{n_k}}{n_k!}$$

- use the profile likelihood ratio to obtain limits on c_t:

$$\left|\frac{f_a}{c_t}\right| > 552.2 \text{ GeV at 95\% CL}$$

Indirect constraints on c_t

A. ALP mediated $t\bar{t}$ production:



light off-shell ALP contributing non-resonantly to $gg \to a \to t\bar{t}$,

calculate at tree-level with effective coupling $c_{agg}^{eff} = -\dfrac{\alpha_s}{8\pi} c_t$

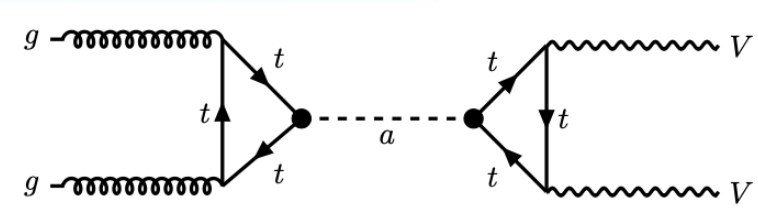
1. **CMS**: $m_{t\bar{t}}$ **distribution** in the lepton + jets channel, Run-II data [2108.02803], lower bins and ALP-SM interference dominate:

$$\left|\frac{f_a}{c_t}\right| > 103.1 \text{ GeV at 95\% CL}$$

2. **ATLAS:** p_T **spectrum** of the boosted hadronically decaying top-quark [2202.12134], dominated by high bins and pure ALP signal

$$\left|\frac{f_a}{c_t}\right| > 169.5 \text{ GeV at 95\% CL}$$

B. ALP mediated diboson production



Non-resonant searches with ALP as off-shell mediator of a 2→2 scattering process

Constraints on g_{aVV} through $gg \to VV$ diboson production, data from CMS search at $\sqrt{s} = 13$ TeV [Gavela, No, Sanz, Trocóniz, 2019] [Carra et al., 2021]

VV	lower limit on $\frac{f_a}{c_t}$
ZZ	3.5 GeV
$\gamma\gamma$	22.5 GeV
$Z\gamma$	11.0 GeV

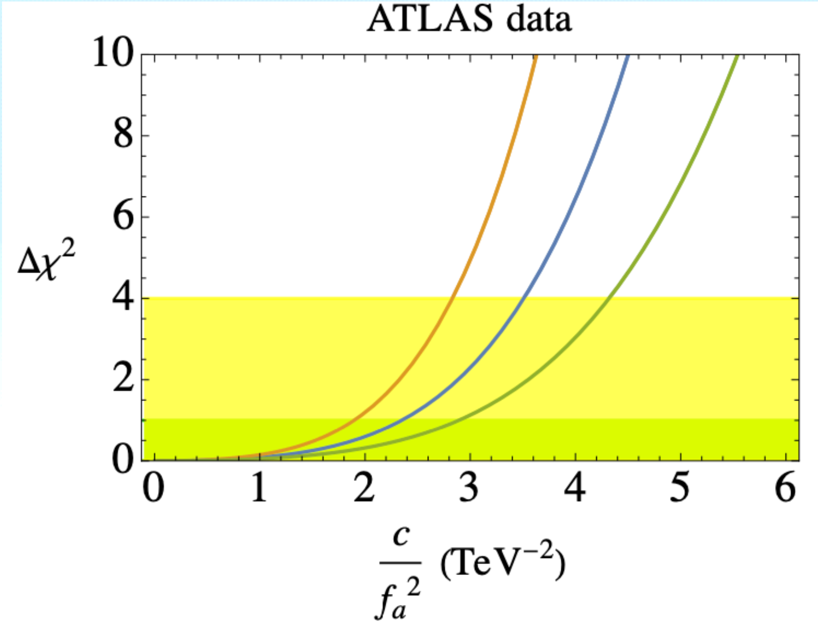
Di-Higgs production from ALPs in chiral ALP EFT

Di-Higgs production via ALPs

$$pp \to hh + X \to b\bar{b}\gamma\gamma + X$$

- currently no search for two Higgses in association with a vector boson
- Use di-Higgs searches in the $b\bar{b}\gamma\gamma$ final state as long as final state Z products are not vetoed:
  - Z boson decaying into neutrinos (no vetoes on missing energy)
  - Z boson decaying into jets (vetoes on additional jets are lax)
- three benchmark scenarios:
  1. Benchmark 1: all $\tilde{a}_i$ and $\tilde{b}_i$ equal 1
  2. Benchmark 2: only $\tilde{b}_{2D} = 1$
  3. Benchmark 3: only $\tilde{b}_{17} = 1$
- generate events in MadGraph, limits on f_a from χ^2 in high mass region:

$$f_a > (0.53, 0.59, 0.48) \times \sqrt{c}\ \text{TeV}$$

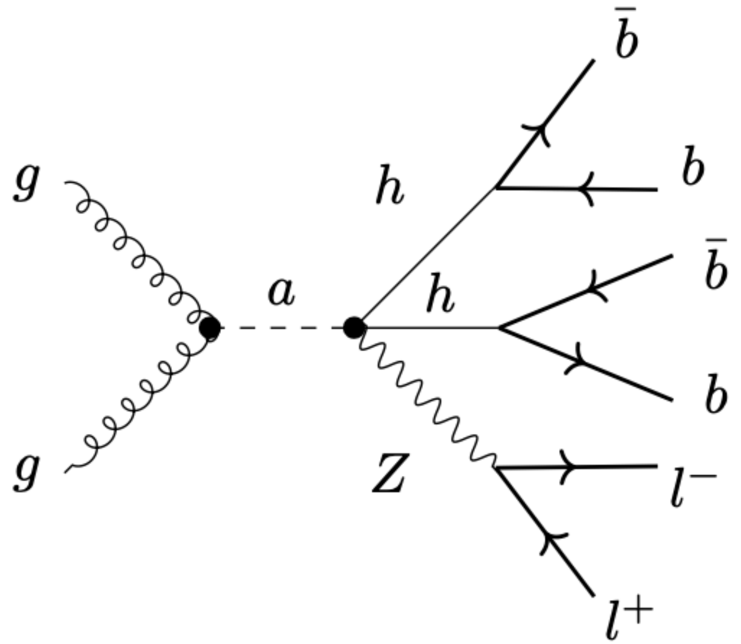


$$\chi^2\left(\frac{c}{f_a^2}\right) = \left(\frac{n_{\text{obs}} - n_{\text{BG}} - n_{\text{s}}(c/f_a^2)}{\Delta_{\text{BG}}}\right)^2$$

Increase sensitivity in Di-Higgs searches

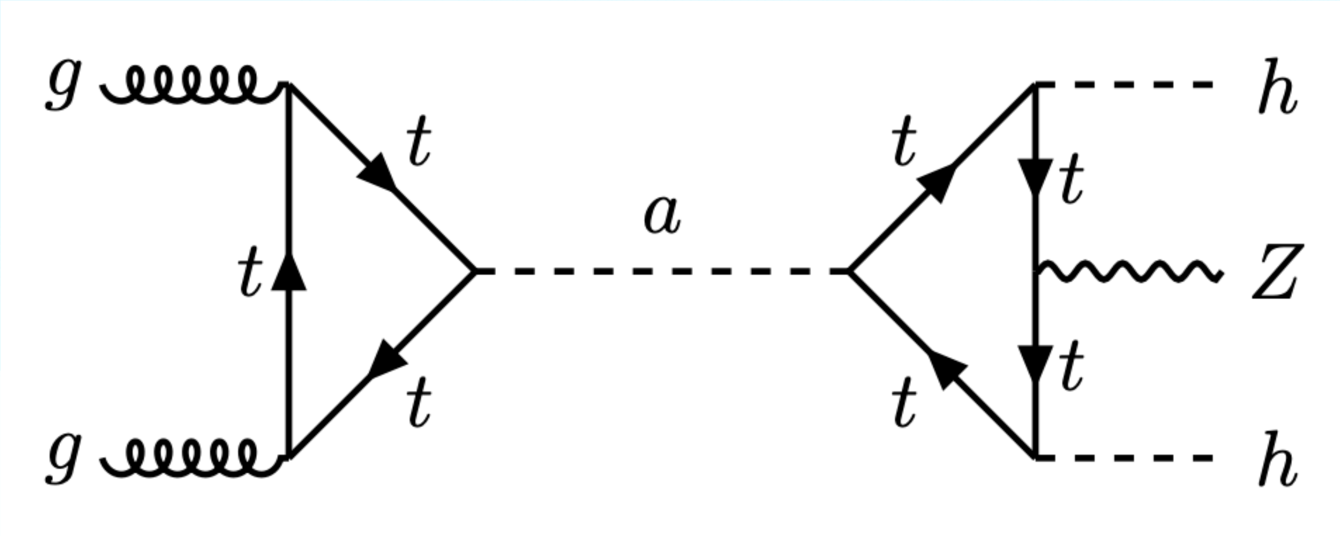
1. ATLAS analysis provides differential distributions for Di-Higgs invariant mass, transverse sphericity and $\Delta R_{\gamma\gamma}$
   BUT: distributions normalised to one and regions defined by BDT classifiers
   $\rightarrow$ If we had the full distribution we could have a higher sensitivity

2. Design a proper search for hhZ in the 4b + 2 lepton final state



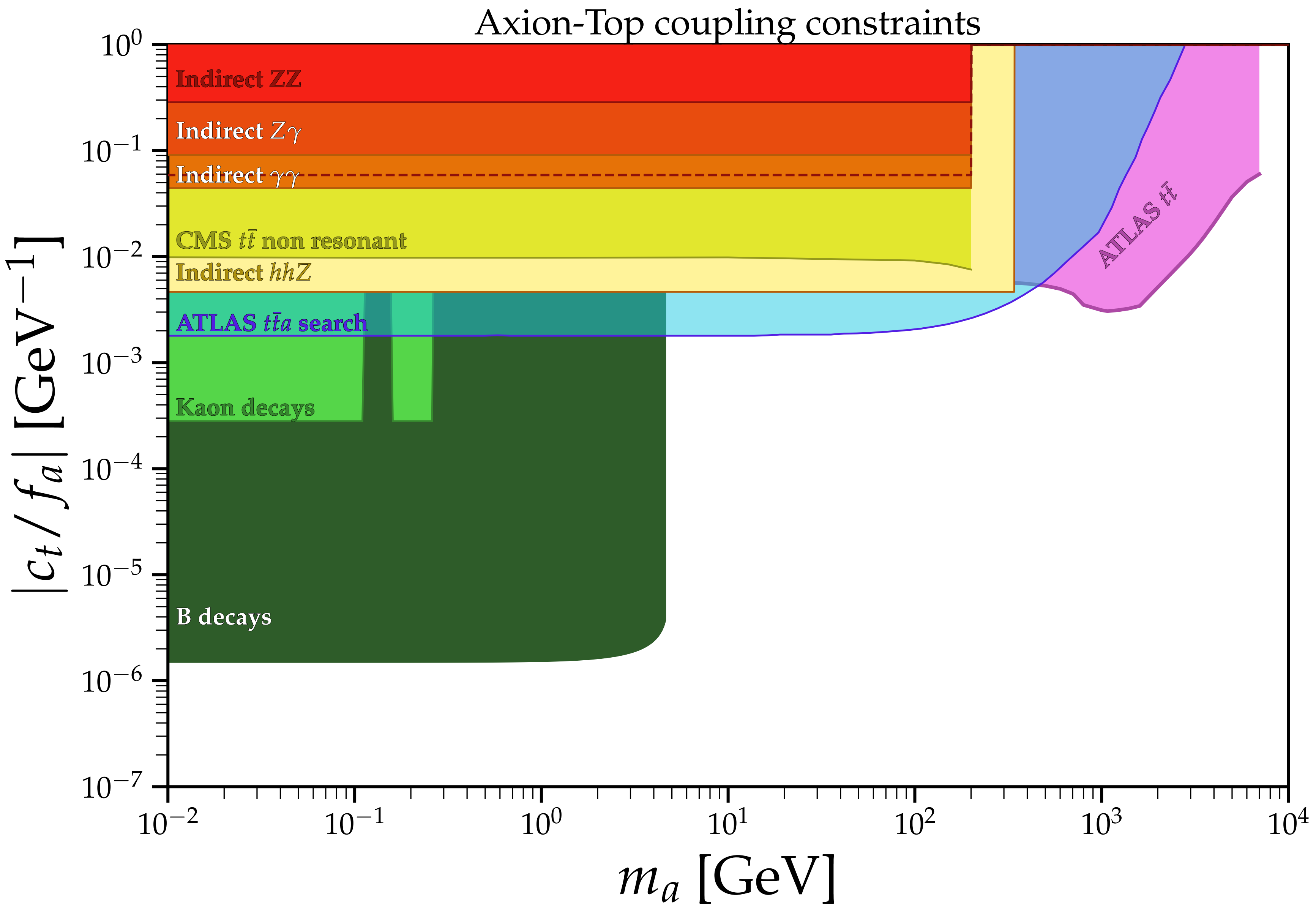
Chiral vs. Linear ALP EFT in Di-Higgs

recast these chiral ALP EFT limits into limits on c_t in the linear EFT using top quark loops



using Naive Dimensional Analysis: $$\frac{c}{f_a^2} \simeq \frac{\alpha_s}{8\pi c_W} \frac{c_t^2}{f_a^2}$$

Summary



Axion-Top coupling constraints
Indirect ZZ
Indirect $Z\gamma$
Indirect $\gamma\gamma$
CMS $t\bar{t}$ non resonant
Indirect hhZ
ATLAS $t\bar{t}a$ search
Kaon decays
B decays
ATLAS $t\bar{t}$
$|c_t/f_a|$ [GeV^{-1}]
m_a [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4

Conclusion & Outlook

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Linear and ***chiral*** ALP EFT differ by the realisation of the electroweak sector

→ chiral ALP EFT is more general with more couplings at NLO

Linear ALP EFT: focus on the ALP-top coupling c_t, proportional to the top mass

- direct constraints on c_t from reinterpretation of a SUSY search for stops ($t\bar{t} + MET$),
- indirect constraints from reinterpretation of non-resonant $t\bar{t}$ production at high invariant mass and recasting limits on ALP to vector boson couplings

Chiral ALP EFT: Di-Higgs + Z is produced at tree-level,

- reinterpret Di-Higgs searches in $b\bar{b}\gamma\gamma$ final state
- use top quark loop to translate to linear ALP theory

Dedicated (ALP-specific) experimental analyses would be interesting:

→ Dedicated HHZ search

→ study of decaying ALPs and LLPs

→ reinterpret Top-SMEFT studies as ALP searches (long tails), …


Thank you!

Thank you!

Back-up slides

ALP searches

- *traditional and still active studies:*

  → cosmological, astrophysical and detector signatures

  → focus on ALP couplings to photons and electron-positron pairs

  → rather limited mass range (keV - MeV)

- *using collider probes:*

  → ALPs can be searched for at colliders in a large mass range, shown in studies of ALP couplings to gluons and di-boson pairs [Mimasu, Sanz, 2015]

  → searches through both **resonant signatures** and **non-resonant production of light ALPs**

- *Here*:

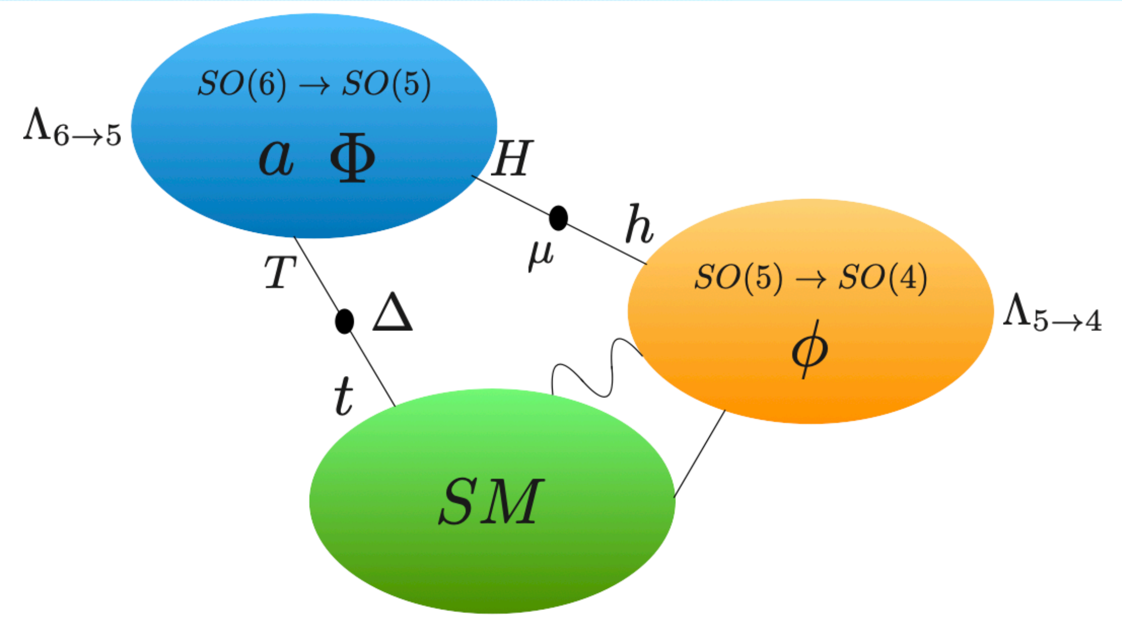
  → probe LHC production of ALPs in a large mass range

  → fill gaps in collider studies of ALP-fermion couplings

  → assume ALP collider stable and invisible (*complementary approach)*

c_t from model building

ALP-top coupling natural for example in models with partial compositeness:



→ induces an ALP top coupling $c_t \propto c_T \frac{\Delta^2}{m_T^2}$

- see-saw Composite Higgs: Higgs doublets mix pGB from both symmetry breakings
- ALPs are pGB associated with heavy scale $f_a \sim \Lambda_{6\to5}$
- EWSB involves new fermionic composites, the top partners T with $m_T \sim \Lambda_{6\to5}$
- T couples to a via
  $$\mathscr{L} \supset -c_T \frac{\partial_\mu a}{\Lambda_{6\to5}} (\bar{T}\gamma^\mu T)$$
- T mixes with top quarks through mass mixing $-\Delta \bar{t}_R T + h.c.$

Stransverse mass and signal generation

ATLAS: measurement of the ***stranverse mass*** m_{T2} distribution in the $2l + 2j + MET$ final state with different lepton flavours:

$$m_{T2}(\vec{p}_{T1}, \vec{p}_{T2}, \vec{p}_T^{miss}) = \min_{\vec{q}_{T1}+\vec{q}_{T2}=\vec{p}_T^{miss}} \left(\max \left[m_T(\vec{p}_{T1}, \vec{q}_{T1}), m_T(\vec{p}_{T2}, \vec{q}_{T2}) \right] \right)$$

leptons

neutrinos

with transverse mass of lepton-neutrino pairs

$$m_T(\vec{p}_T, \vec{q}_T) = \sqrt{2 |\vec{p}_T| |\vec{q}_T| (1 - cos(\Delta\Phi))}$$

Generate ALP signal with *MadGraph5_aMC@NLO* and *NNPDF4.0* in the 4-flavour scheme

$f_a = 1$ TeV
$m_a = 1$ MeV
$c_{a\Phi} = 1$

K-factor:

We generate the ALP signal at LO, no higher order corrections, hadronisation or detector effects

⇒ need a ***normalisation factor*** between our simulation and ATLAS background simulation

⇒ generate $pp \to t\bar{t}$ (dominant background) and calculate normalisation from first bin

Phase space cuts for ATLAS search

Phase space cuts defining the signal region in the ATLAS search for $t\bar{t}$ + MET:

parameter	value
p_T leading lepton	> 25 GeV
p_T subleading lepton	> 20 GeV
m_{ll}	> 20 GeV
$m_{T2}(ll)$	> 110 GeV
$\lvert m_Z - m_{ll} \rvert$	> 20 GeV
$n_{\text{b-jets}}$	≥ 1
$\Delta\Phi_{\text{boost}}$	< 1.5 rad

ALP mediated $t\bar{t}$ production

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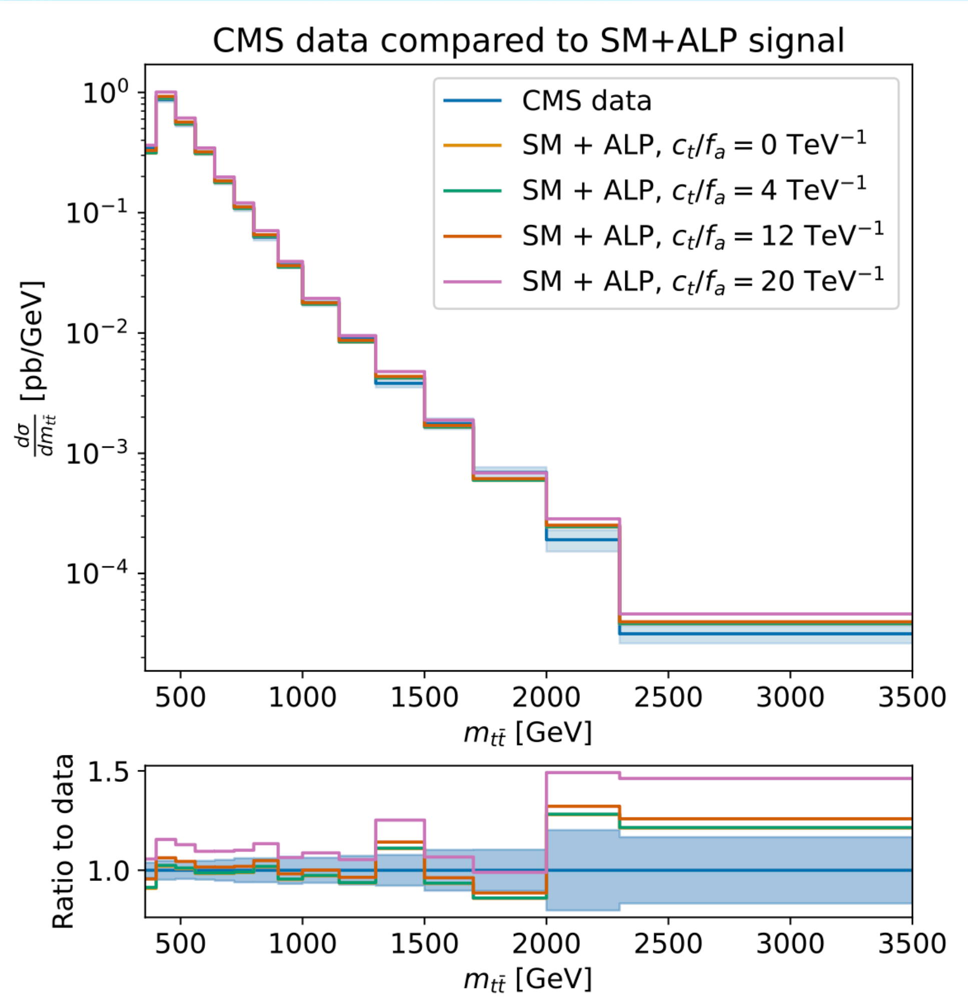
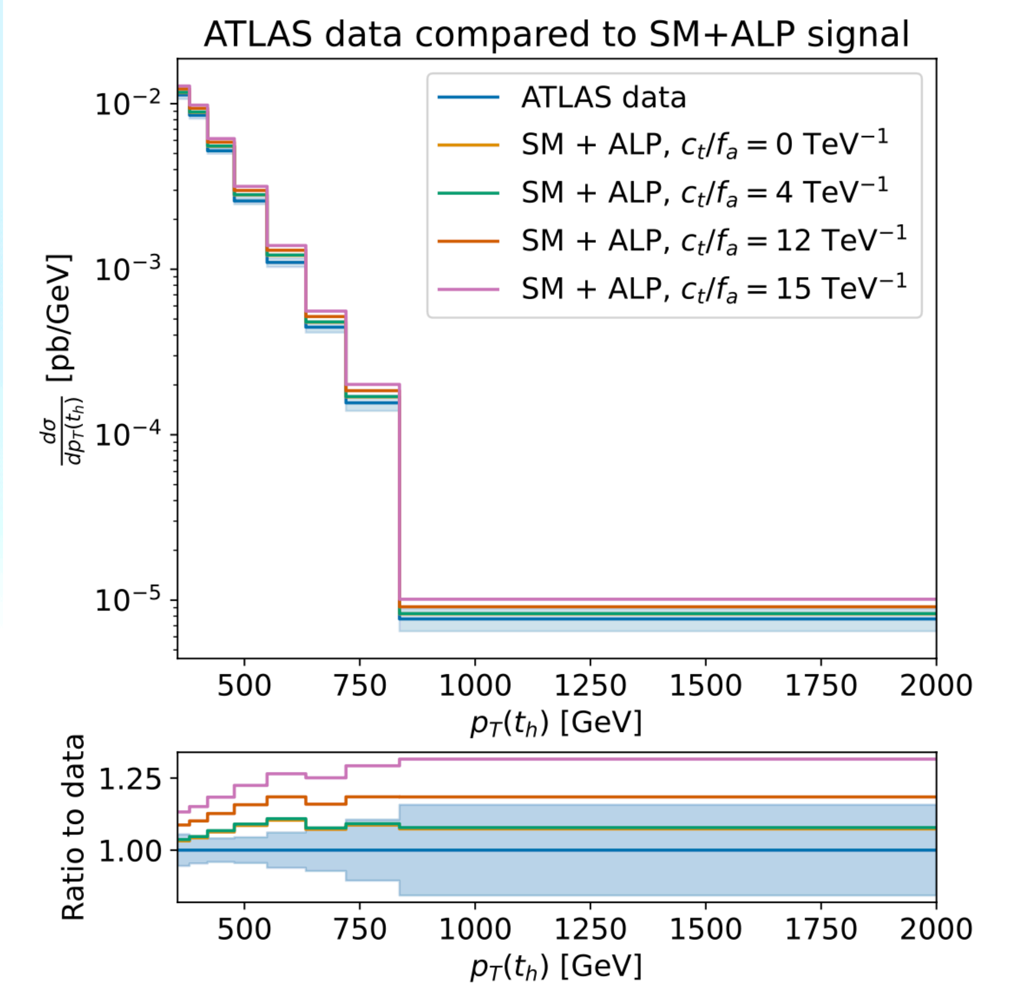




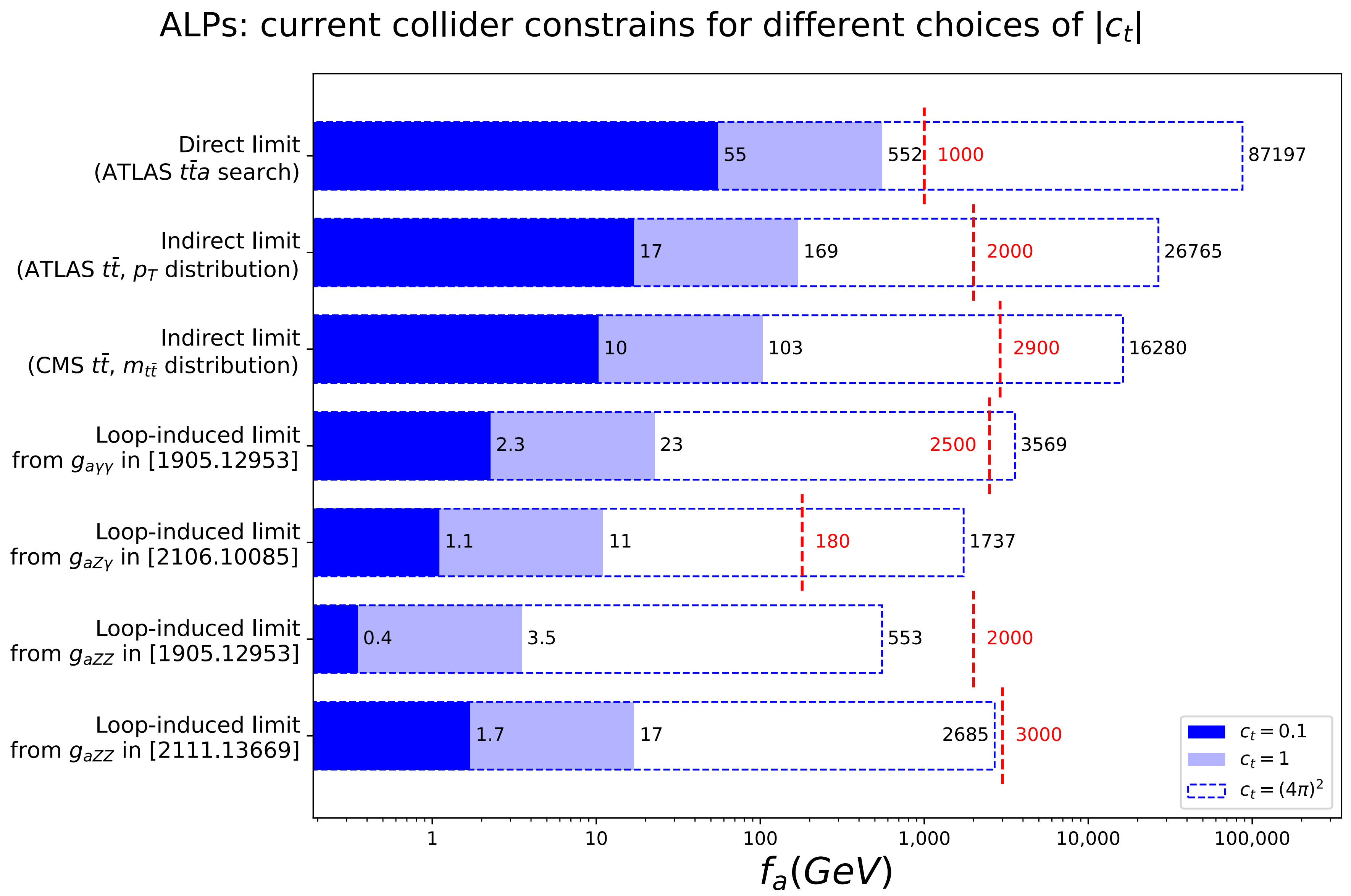
CMS: $\left|\frac{f_a}{c_t}\right| > 103.1$ GeV at 95% CL,

low $m_{t\bar{t}}$ bins and ALP-SM interference dominate

ATLAS: $\left|\frac{f_a}{c_t}\right| > 169.5$ GeV at 95% CL,

high p_T bins and pure ALP dominate

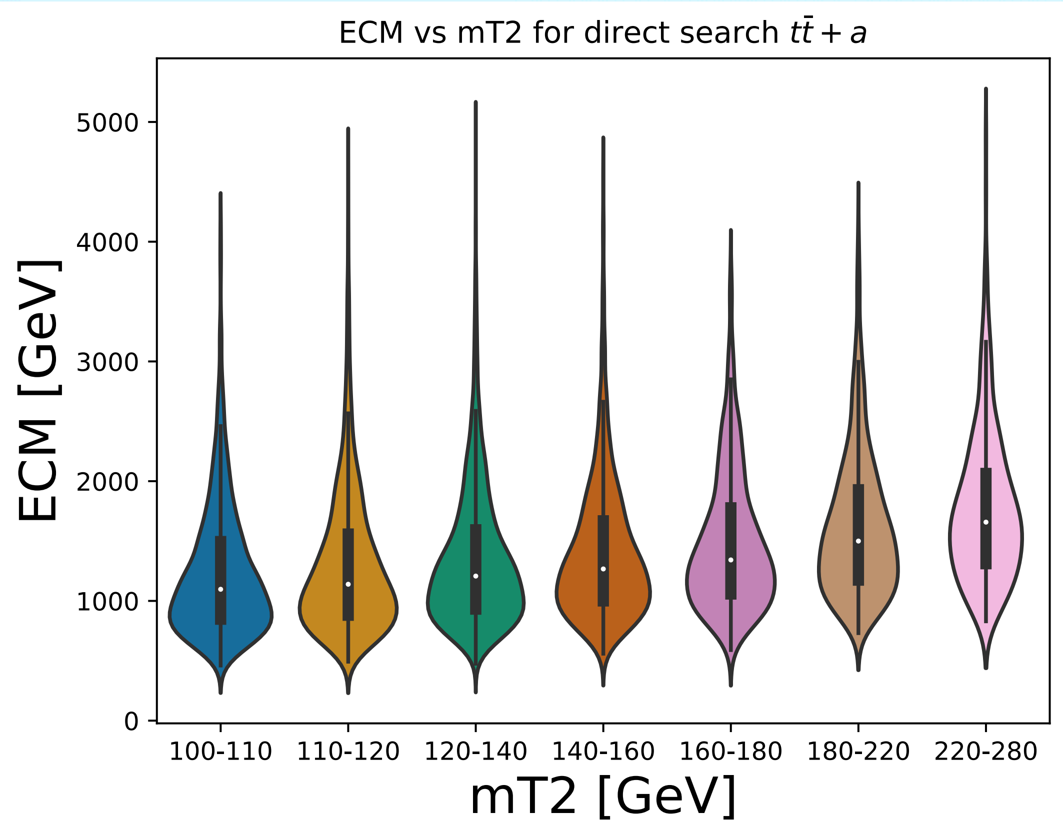
Summary of constraints from Run-II data



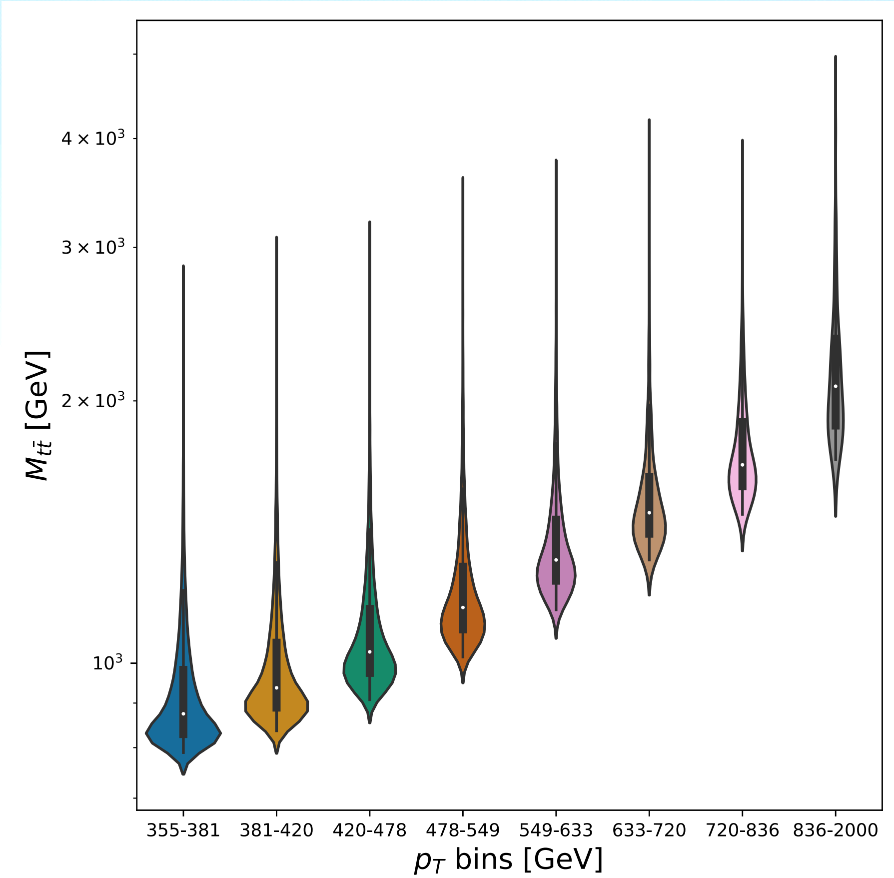
red dashed lines: EFT validity limits

EFT validity

- is the EFT adequate in the regime in which we obtain the limits?
- is the scale of the EFT expansion f_a larger than the typical p^2 of the process?
- “Is the limit on $|f_a/c_t|$ consistent with $f_a > \sqrt{\hat{s}}$?”

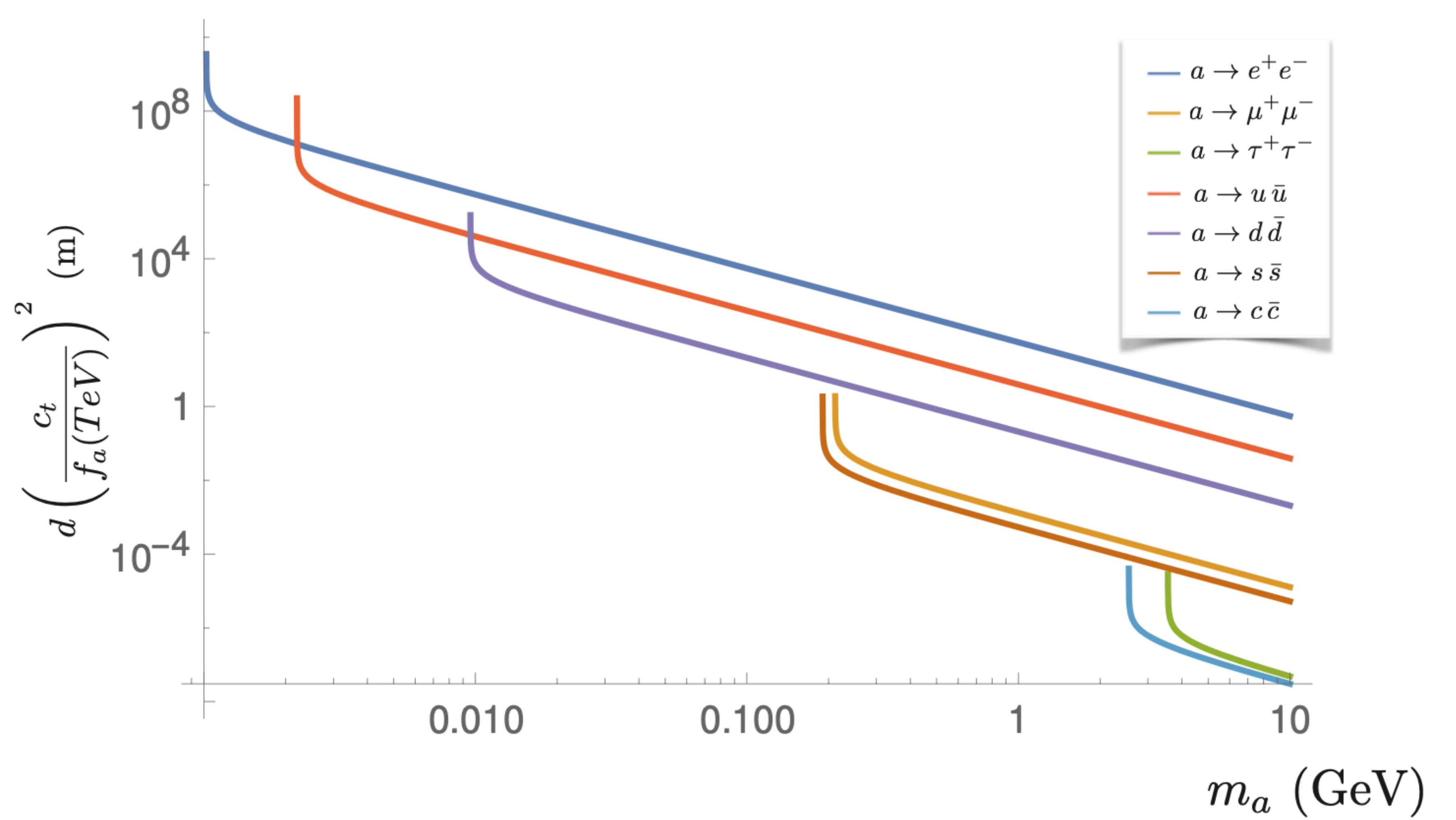


direct search $t\bar{t} + MET$



indirect ATLAS search $gg \to a \to t\bar{t}$

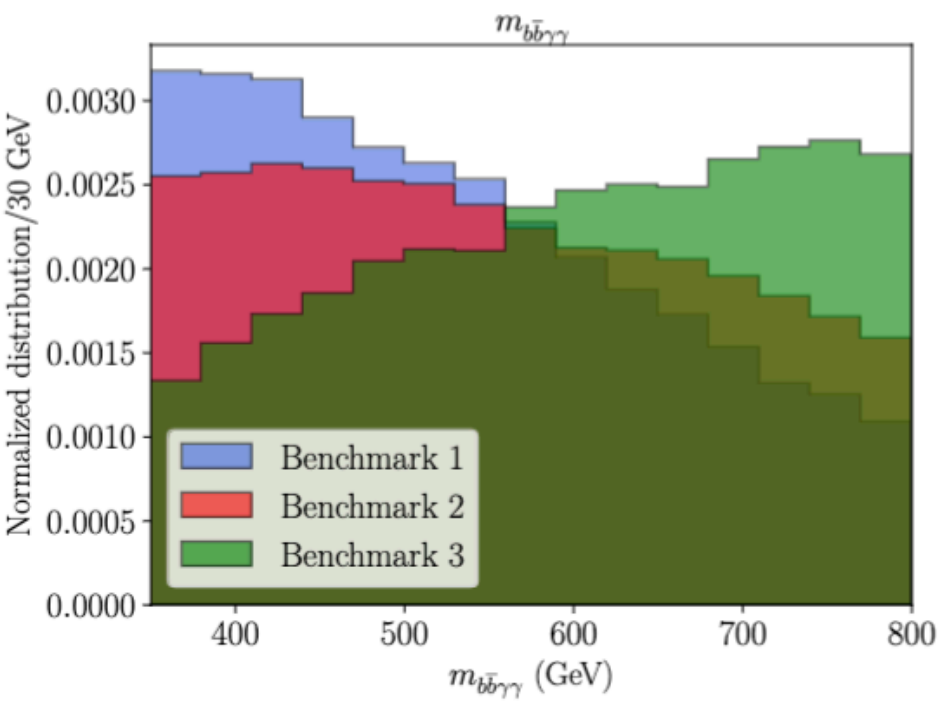
On the collider stability of the ALP

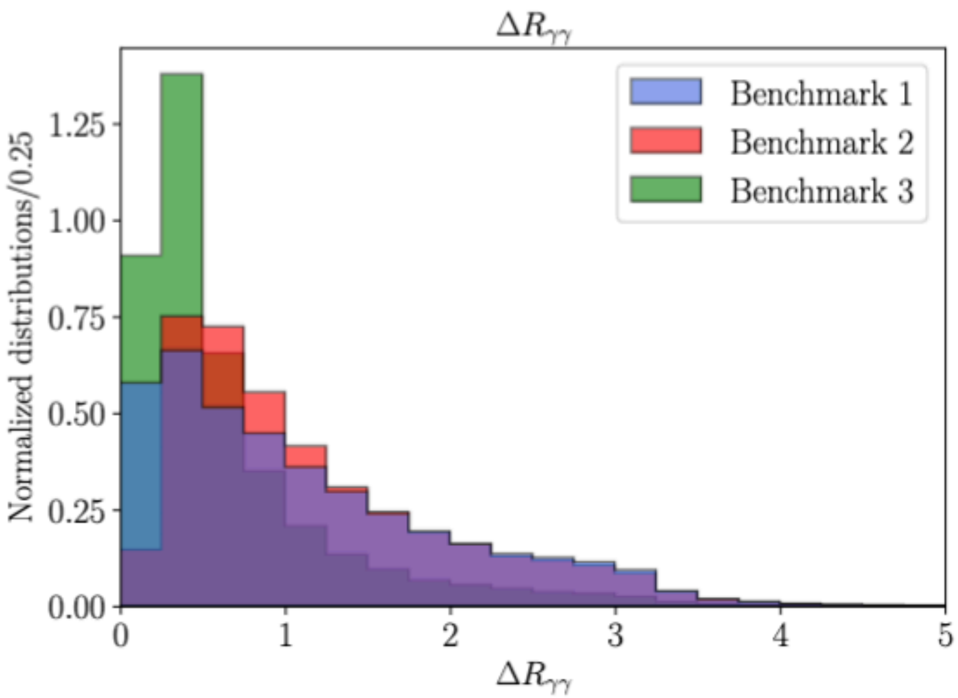


- is the distance the ALP travels before decaying larger than the typical detector size (~meters)?
- We find that for $|f_a/c_t| \sim 1$ TeV this holds up to $m_a < 200$ MeV, for larger values of $|f_a/c_t|$ even up to higher values of m_a

Differential distributions for Di-Higgs production

The ATLAS analysis has the differential distributions normalised to one.
The signal regions are defined by Boosted Decision Tree (classifiers), giving insufficient details to compare with the signal.





ALP induced processes are highly collimated!