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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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Welcome to the
ALP adventure!

Axion-Like Particles (ALPs)

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- ALPs appear as pseudo Goldstone bosons in many SM extensions with a spontaneous breaking of a global symmetry at scale f_a
- shift symmetry $a \to a + c$, couplings momentum dependent
- focus on ALP-fermion and ALP Higgs couplings in a large mass range
- ALP associated with a heavy new scale $f_a \gg v$
  $\Rightarrow$ Effective Field Theory approach
  $\rightarrow$ which EFT to use?

Linear ALP EFT

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- As in SMEFT, start from a linear realisation of EW symmetry, i.e. with a Higgs doublet H

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_a$$

- Expand in powers of a/f_a , NLO has one insertion

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

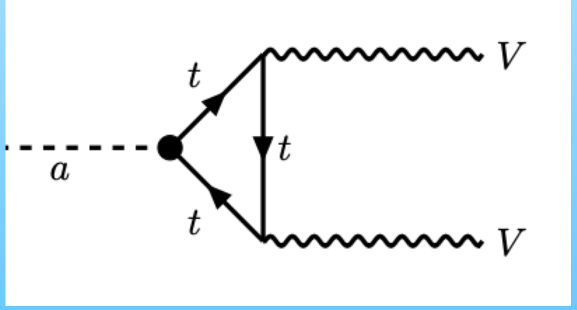
  - couplings to gauge bosons: $\mathcal{A}_{\tilde{X}} = -\frac{a}{f_a} X^a_{\mu\nu}\tilde{X}^{\mu\nu,a}$
  - couplings to fermions: $\mathcal{A}_f = \frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu f$
  - for top quark using EOM: $\mathcal{L} \supset -ic_t \frac{m_t a}{2f_a}\left(\bar{t}\gamma^5 t\right)$

- Couplings are proportional to the fermion mass!

  ⇒ 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]



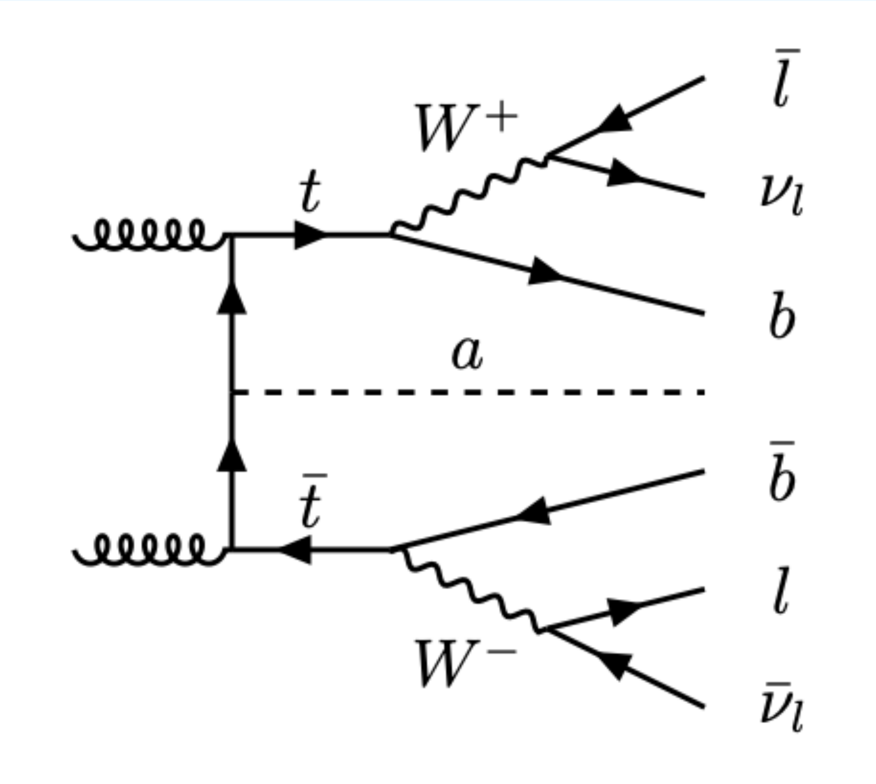
Direct constraints on c_t

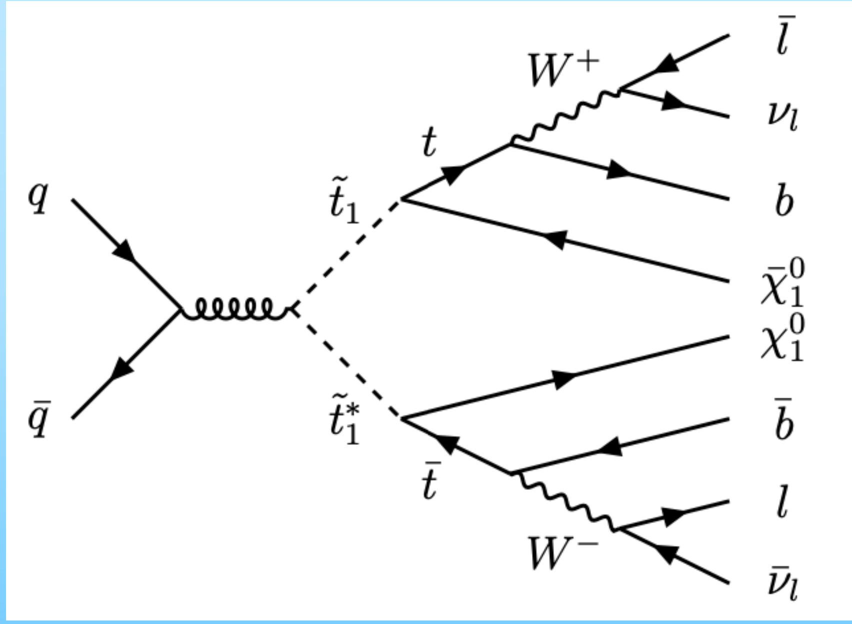
- signal process: $t\bar{t} + a$ production with leptonic top decay
- assume ALP collider stable, escapes the detector as missing transverse energy (MET)
- Reinterpret a Run II **ATLAS SUSY search for top squarks** in events with 2 leptons, 2 b-jets and MET [2102.134929]
- SUSY benchmark: pair production of stops with prompt decay into top quarks and neutralinos
- **same final state topology** $2l + 2j + MET$

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

- use ALP EFT UFO file and MadGraph5 to generate events

$$\boxed{\left|\frac{f_a}{c_t}\right| > 550 \text{ GeV at 95\% CL}}$$





Indirect constraints on c_t

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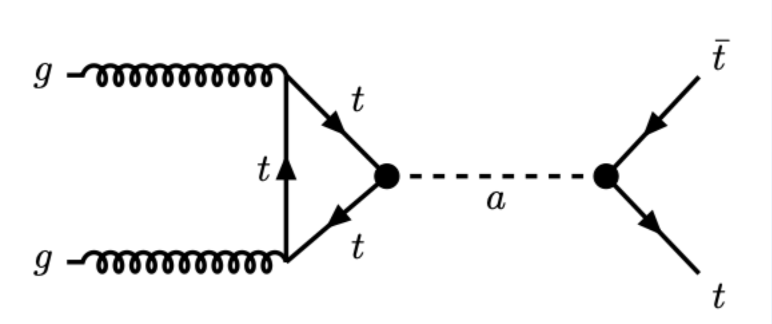
A. ALP mediated $t\bar{t}$ production:



light off-shell ALP contributing non-resonantly to $gg \to a \to t\bar{t}$,
calculate at tree-level with effective coupling $c_{agg}^{eff} = -\frac{\alpha_s}{8\pi} c_t$

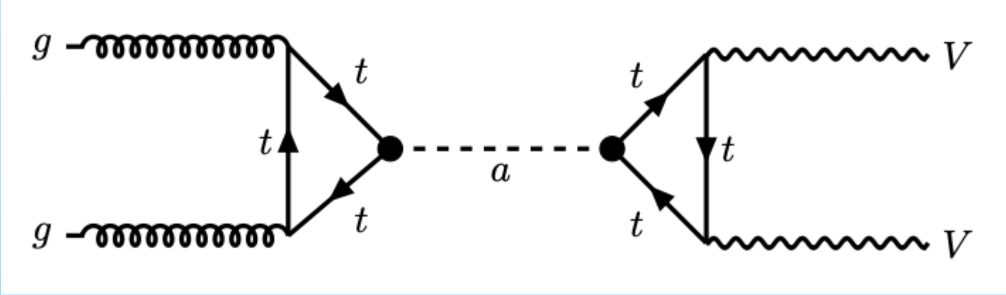
1. **CMS**: $m_{t\bar{t}}$ **distribution** in the lepton + jets channel, Run-II data [2108.02803]

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

2. **ATLAS:** p_T **spectrum** of the boosted hadronically decaying top-quark [2202.12134]

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

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

Chiral ALP EFT

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

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

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

- many more terms at NLO, all with arbitrary Higgs polynomial functions $\mathcal{F}_i(h) = 1 + a_i h/v + b_i (h/v)^2 + \ldots$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Chiral ALP EFT

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

$$\mathcal{A}_2(h) = \frac{i}{4\pi}\mathrm{Tr}[\tilde{W} \ldots$$

$$\mathcal{A}_3(h) = \frac{1}{4\pi} B_{\mu\nu} \ldots$$

$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2} \ldots$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2} \ldots$$

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

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

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

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

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

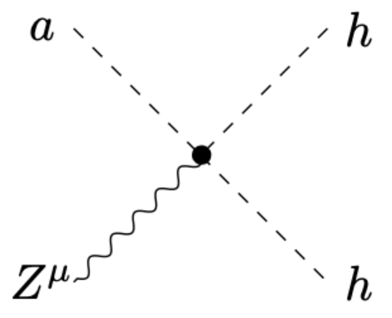
$$\mathcal{A}_{15}(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\partial_\nu \mathcal{F}_{15}(h)\partial^\nu \mathcal{F}'_{15}(h)$$

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

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

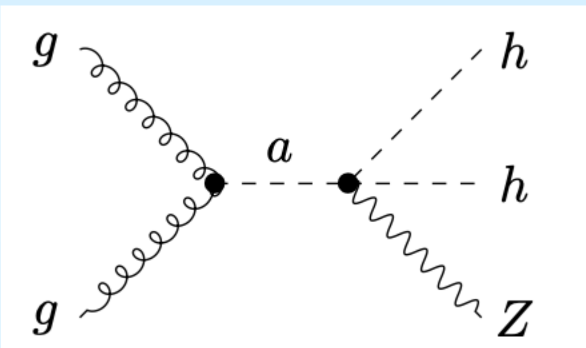
- More general description
- Many more terms at NLO than linear ALP EFT
- ALP-Higgs-Z couplings ah^nZ at NLO

ALP-Higgs couplings in chiral ALP EFT



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

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



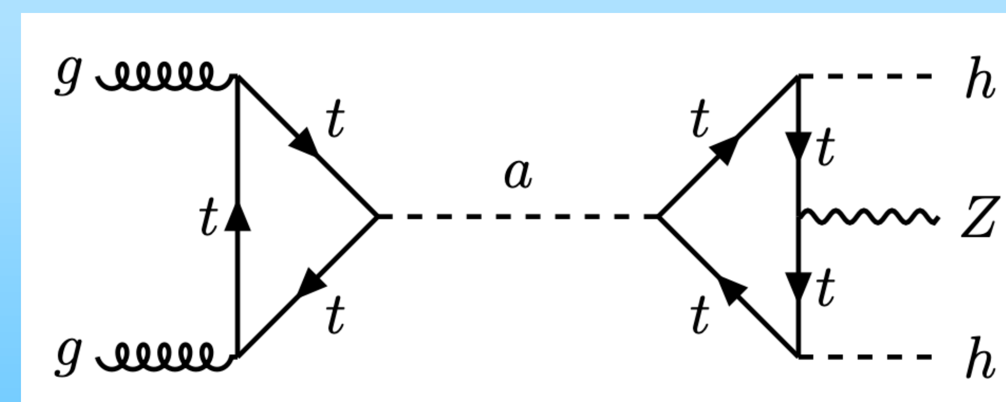
ALP-mediated Di-Higgs + Z production from gluon fusion is TREE LEVEL in chiral ALP EFT, effective coupling c

- Use ATLAS di-Higgs searches in the $b\bar{b}\gamma\gamma$ final state 2310.12301, no veto on MET ($Z \to \nu\nu$)
- simplest benchmark scenario: all $\tilde{a}_i$ and $\tilde{b}_i$ equal 1
- generate events in MadGraph, limits on f_a from χ^2 in high mass region:

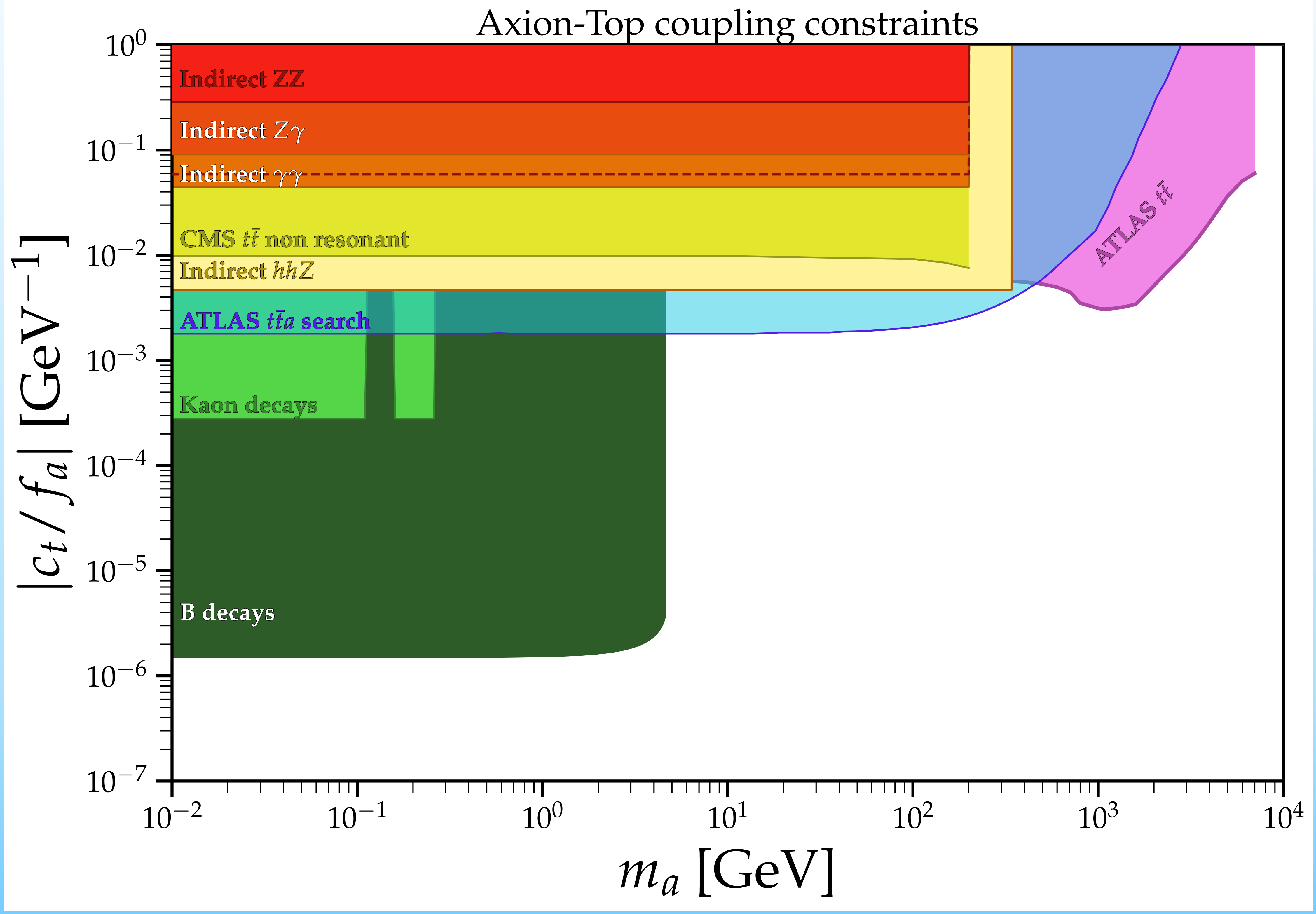
$$f_a > 0.53\sqrt{c}\ \mathrm{TeV}$$

- we can recast chiral ALP EFT limits into limits on c_t in the linear EFT using top loops

$$\frac{c}{f_a^2} \simeq \frac{\alpha_s}{8\pi c_W}\frac{c_t^2}{f_a^2}$$

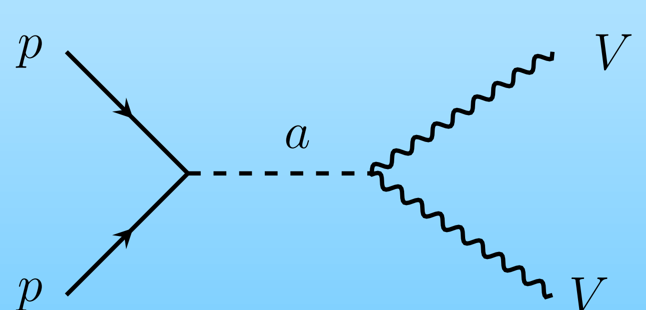


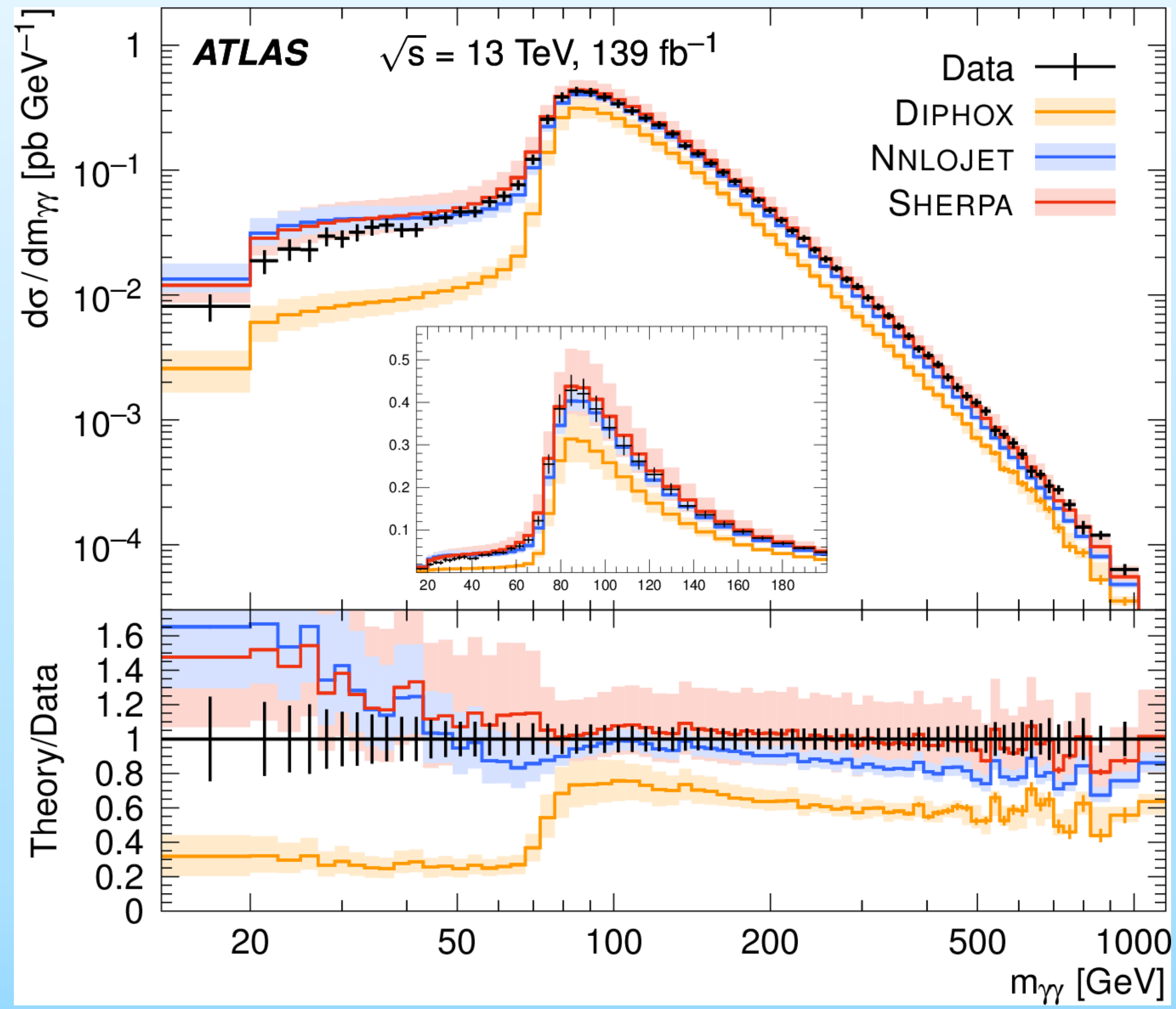
Summary


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

Global fit to multiboson final states, first in the linear ALP EFT (WIP)

vertex	Feynman Rule in linear ALP EFT
$a\gamma\gamma$	$-\frac{4i}{f_a}\left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 \mathbf{c}_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}(p_{\gamma 1})_\rho (p_{\gamma 2})_\sigma$
$a\gamma Z$	$\frac{2i}{f_a} s_{2\theta}\left(\mathbf{c}_{\tilde{B}} - \mathbf{c}_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}(p_Z)_\rho (p_\gamma)_\sigma$
aZZ	$-\frac{4i}{f_a}\left(s_\theta^2 \mathbf{c}_{\tilde{B}} + c_\theta^2 \mathbf{c}_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}(p_{Z1})_\rho (p_{Z2})_\sigma$
aW^+W^-	$-\frac{4i}{f_a}\mathbf{c}_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}(p_{W^+})_\rho (p_{W^-})_\sigma$
agg	$-\frac{4i}{f_a}\mathbf{c}_{\tilde{G}}\delta_{ab}\epsilon^{\mu\nu\rho\sigma}(p_{g1})_\rho (p_{g2})_\sigma$
$a\gamma W^+W^-$	$\frac{4ie}{f_a}\mathbf{c}_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}(p_{WW\gamma})_\sigma$
aZW^+W^-	$\frac{4ie}{f_a}\frac{c_\theta}{s_\theta}\mathbf{c}_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}(p_{WWZ})_\sigma$
$aggg$	$\frac{4}{f_a}g_s\mathbf{c}_{\tilde{G}}f_{abc}\epsilon^{\mu\nu\rho\sigma}(p_{ggg})_\sigma$



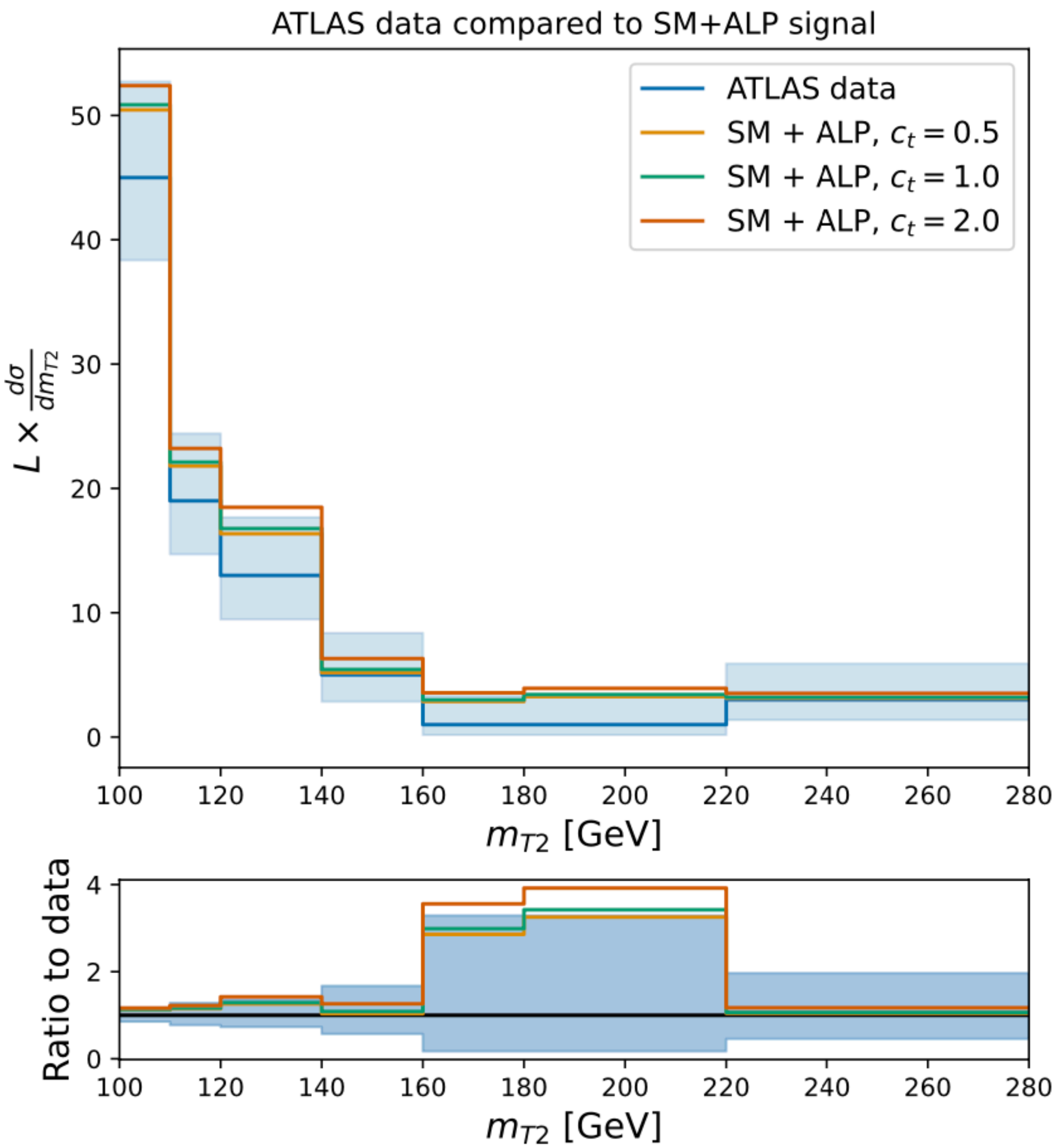


invariant mass distribution in the di-photon final state [2107.09330]


Thank you!

Back-up slides

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:

$$\left|\frac{f_a}{c_t}\right| > 550 \text{ GeV at 95\% CL}$$

Stransverse mass

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

leptons

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

neutrinos

with transverse mass of lepton-neutrino pairs

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

Summary of constraints from Run-II data

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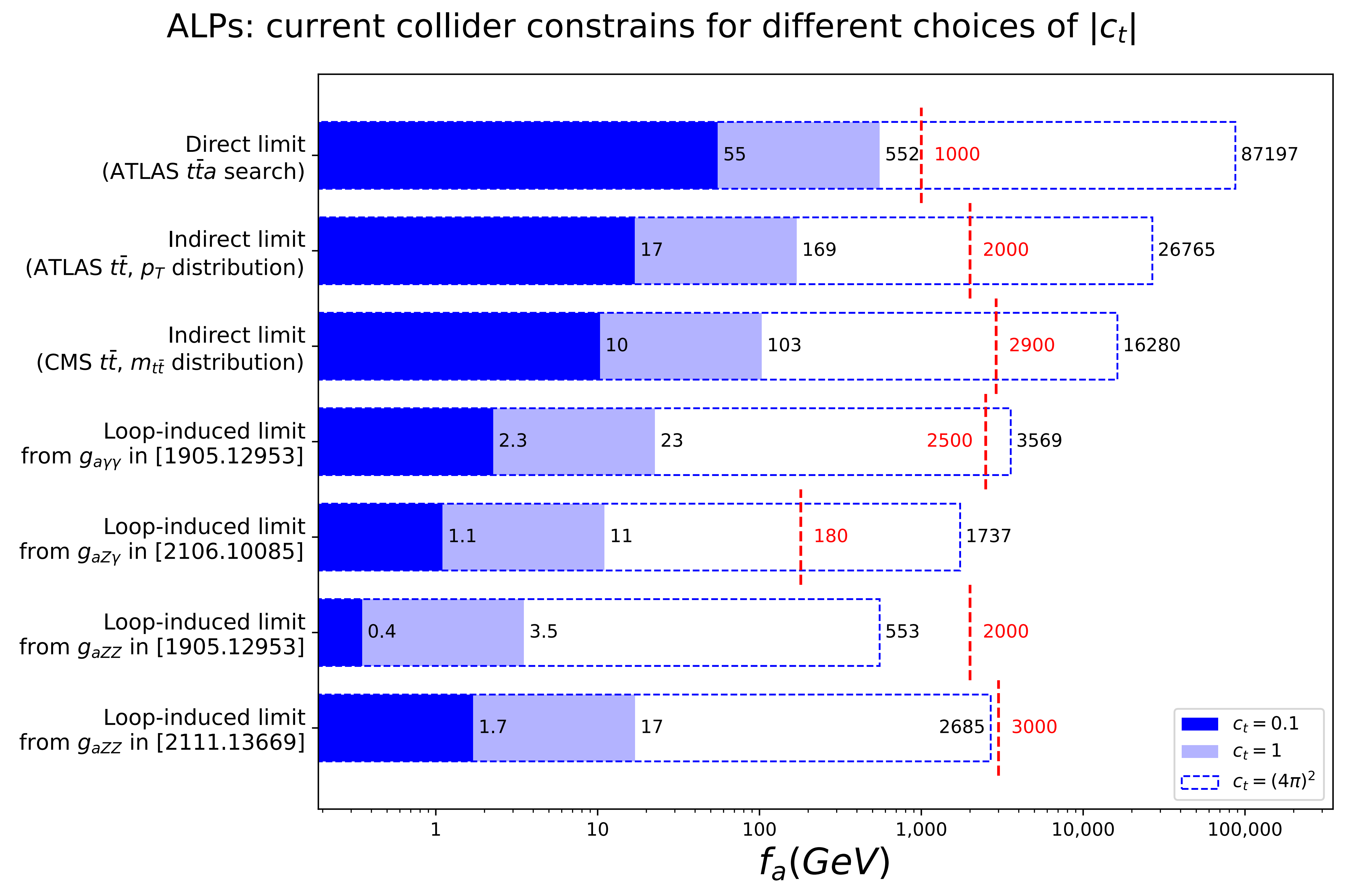

red dashed lines: EFT validity limits