On the coupling of axion-like particles to the top quark

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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 $a \to a + c$

  $\to$ restricts ALP couplings to SM particles

  $\to$ couplings momentum dependent

  $\Rightarrow$ energy scaling for processes involving ALPs differs from background processes

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)*

ALP EFT and ALP-top coupling

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

  ⇒ EFT approach $\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_a$

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

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

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

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

  ⇒ Couplings are proportional to the fermion mass!

  ⇒ Focus on **ALP-top coupling** c_t and **set all other couplings to zero**

Loop-induced ALP couplings to vector bosons

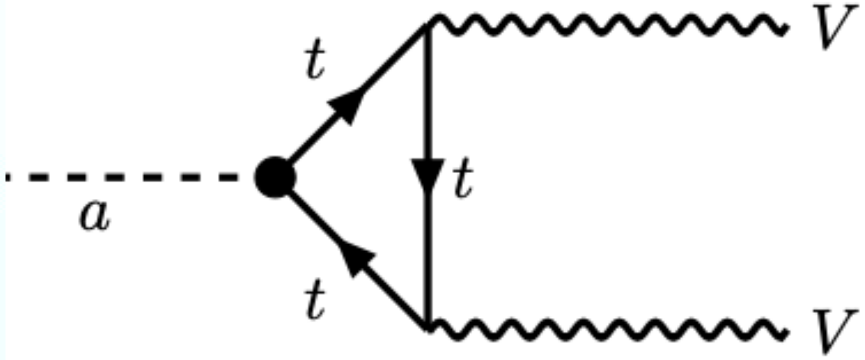
ALP-top coupling induces couplings to vector bosons at 1-loop, e.g. to $\gamma\gamma$:

$$\mathscr{L}^{1l} \supset -\frac{a}{f_a} c_{a\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \quad \text{with} \quad c_{a\gamma\gamma}^{eff} = -c_t Q_t^2 N_c B_1\left(\frac{4m_t^2}{p^2}\right)$$

[Bonilla, Brivio, Gavela, Sanz, 2021]

Asymptotic behaviour:

- $B_1 \to 1$ for high p^2
- $B_1 \to 0$ for low p^2



Regime	Expression
high-pT	$c_{a\gamma\gamma}^{\text{eff}} = -\frac{\alpha_{\text{em}}}{3\pi} c_t$
high-pT	$c_{a\gamma Z}^{\text{eff}} = \frac{2\alpha_{\text{em}} s_w}{3\pi c_w} c_t$
high-pT	$c_{aZZ}^{\text{eff}} = -\frac{\alpha_{\text{em}} s_w^2}{3\pi c_w^2} c_t$
high-pT	$c_{aW^+W^-}^{\text{eff}} = 0$
high-pT	$c_{agg}^{\text{eff}} = -\frac{\alpha_s}{8\pi} c_t$

→ probe c_t through ALP-vector boson couplings at the LHC!

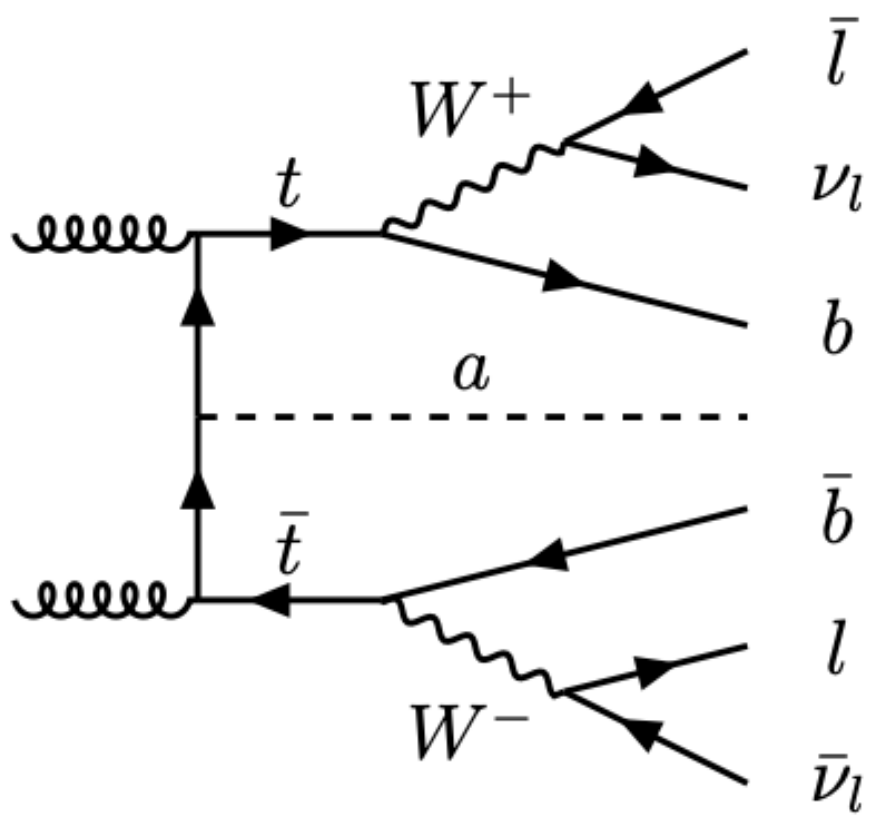
Constraining c_t

Motivate further collider searches to put constraints on the ALP-top coupling c_t

1. reinterpret a SUSY search in a final state with fully leptonic top pairs and missing transverse energy (**direct limits**)
2. **indirect limits** from
   A. ALP-top contributions to loop-induced $gg \to a \to t\bar{t}$ production
   B. recasting limits on loop-induced couplings to vector bosons

1. Direct constraints on c_t

- obtained from $pp \to t\bar{t} + a$ with subsequent leptonic decay of the tops
- assume ALP collider stable, escapes the detector as missing transverse energy (MET)



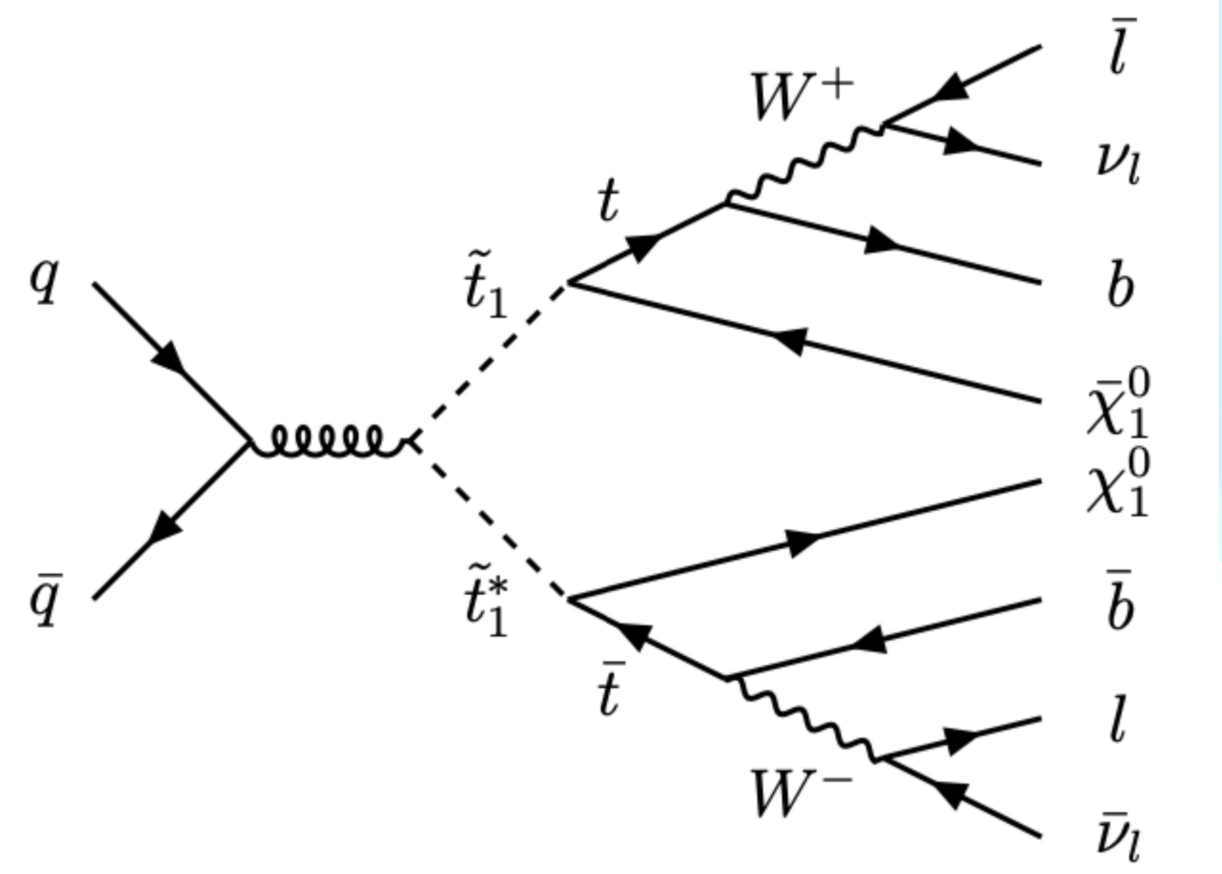
Reinterpret a Run II **ATLAS search for top squarks** in events with 2 leptons, 2 b-jets and MET at $\sqrt{s} = 13$ TeV, $\mathscr{L} = 139$ fb^{-1} [2102.134929]

Reinterpreting a SUSY top-squark search

- 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

$$2l + 2j + MET$$

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



We looked at p_T^{miss} and $\Delta\Phi_{boost}$ distributions:

The search is sensitive enough to distinguish ALP signal events from SM background and SUSY interpretations

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: $\vec{p}_{T1}$, $\vec{p}_{T2}$; neutrinos: $\vec{q}_{T1}$, $\vec{q}_{T2}$

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
$c_{a\Phi} = 1$

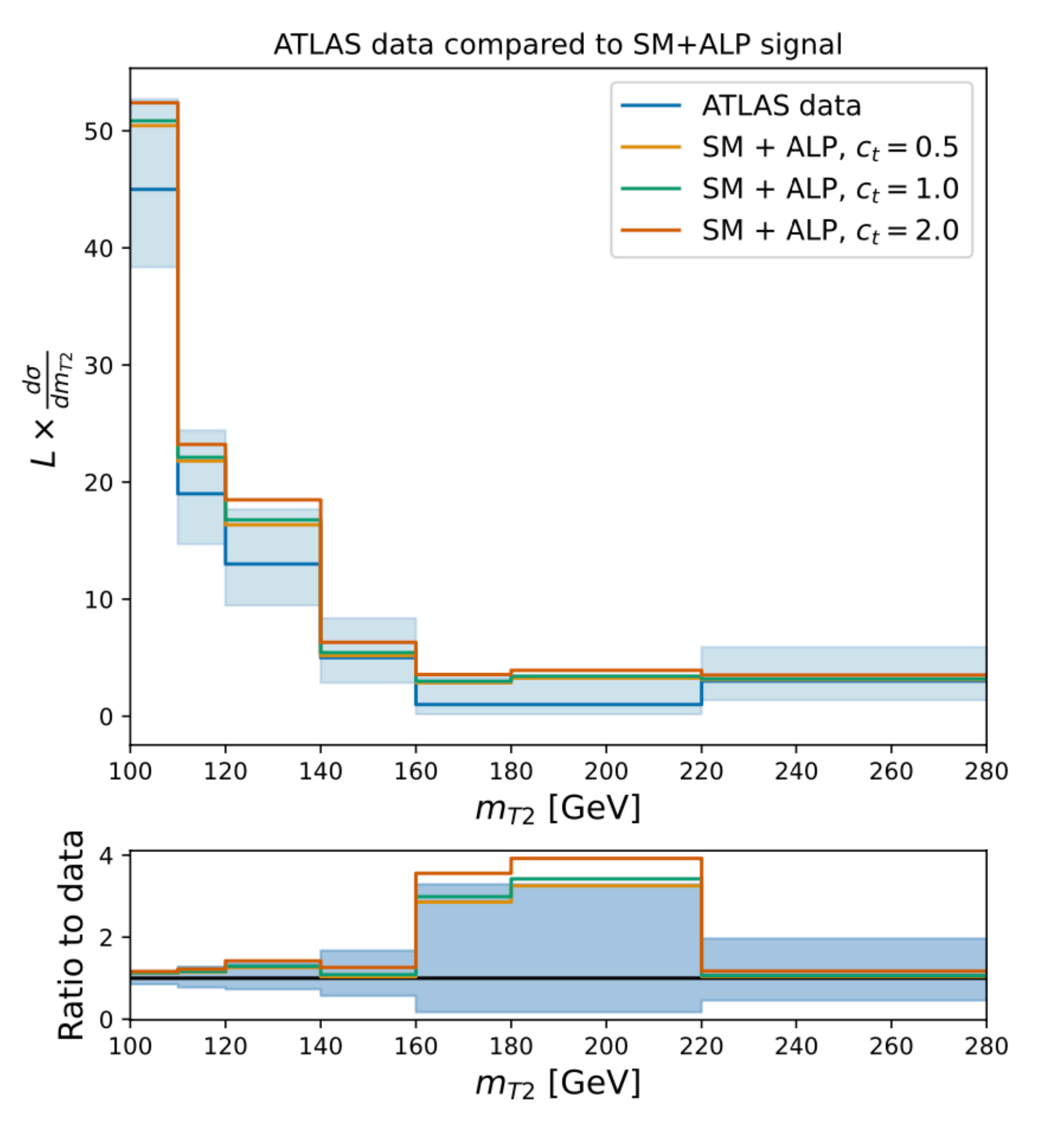
K-factor:

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

ALP signal



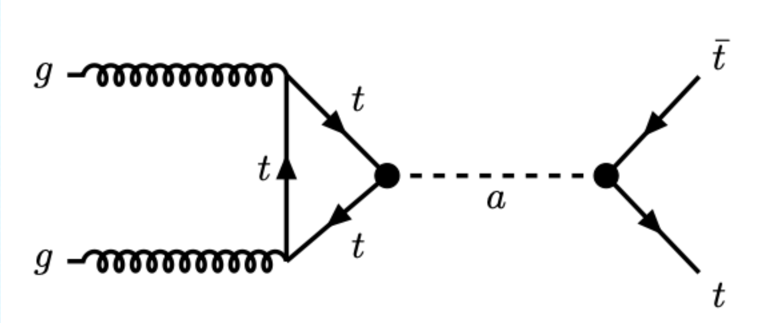
- compare ALP signal + SM background for different c_t to data
- show only experimental uncertainties, MadGraph and SM background uncertainties negligible
- $t\bar{t}a$ vertex proportional to c_t/f_a, global factor $\left(c_t/f_a\right)^2$ in the signal events
- Assume a Poisson likelihood

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

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

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

2A. 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 $c_{agg}^{eff} = -\frac{\alpha_s}{8\pi} c_t$

- Derivative couplings in $\mathcal{O}_{\tilde{G}}$ enhance the $\hat{s}$ dependence relative to the SM
- partonic ALP cross-section and ALP-SM interference:

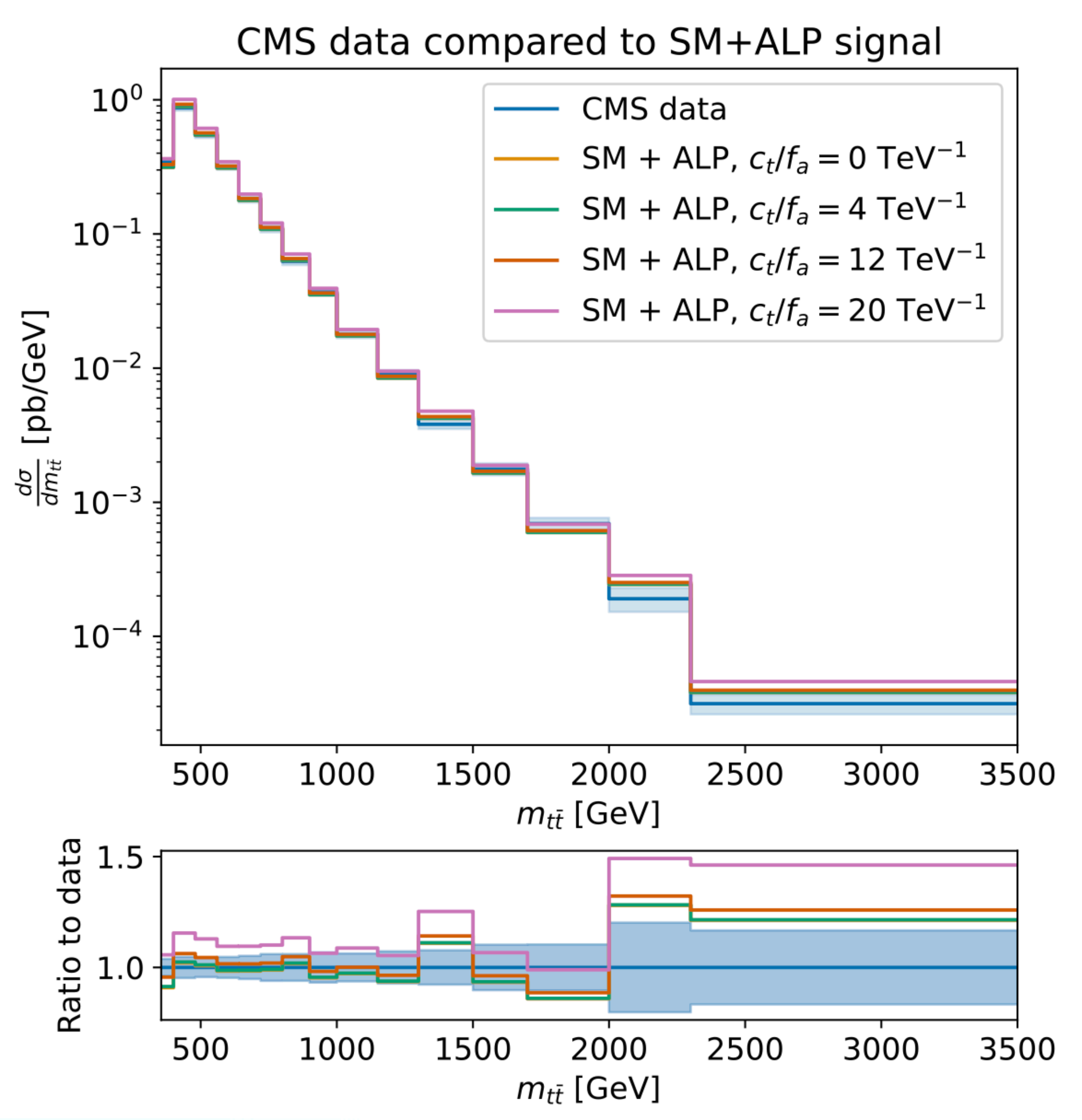
$$\hat{\sigma}_{ALP}(\hat{s}) \sim \frac{c_t^2 c_{\tilde{G}} m_t^2}{f_a^4} \left(1 - \frac{2m_t^2}{\hat{s}}\right) \qquad \hat{\sigma}(\hat{s})_{ALP-SM} \sim \frac{1}{\hat{s}} \log\left(\sqrt{\frac{\hat{s}}{m_t^2}}\right)$$

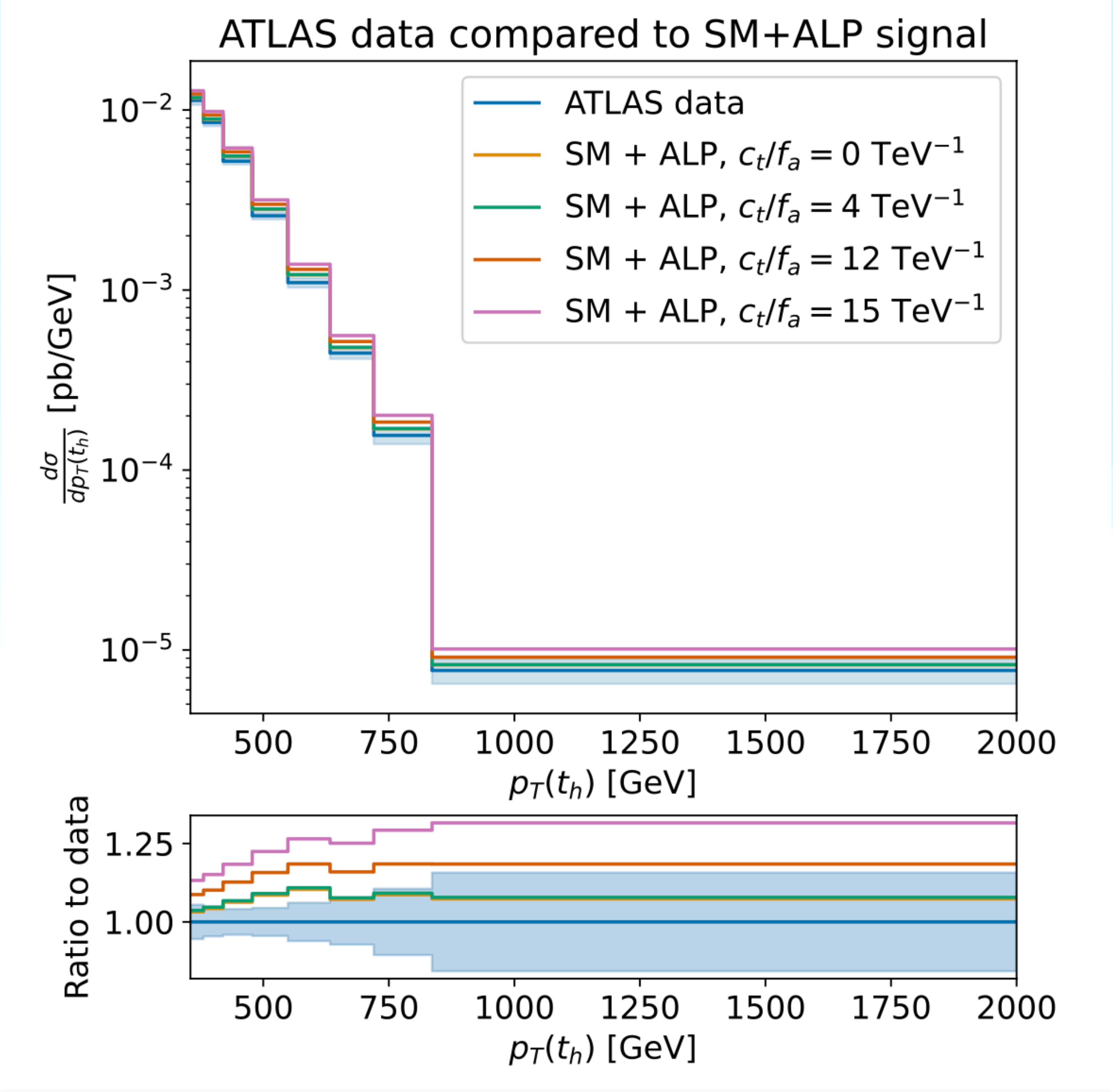
- SM-ALP interference can be suppressed by considering high-p_T top quarks (→ ATLAS) but will dominate for low $\hat{s}$

Study the impact of offshell-ALP signals on two measurements, use Gaussian likelihoods

1. **CMS**: $m_{t\bar{t}}$ **distribution** in the lepton + jets channel, Run-II data [2108.02803]
2. **ATLAS:** p_T **spectrum** of the boosted hadronically decaying top-quark [2202.12134]

ALP mediated $t\bar{t}$ production





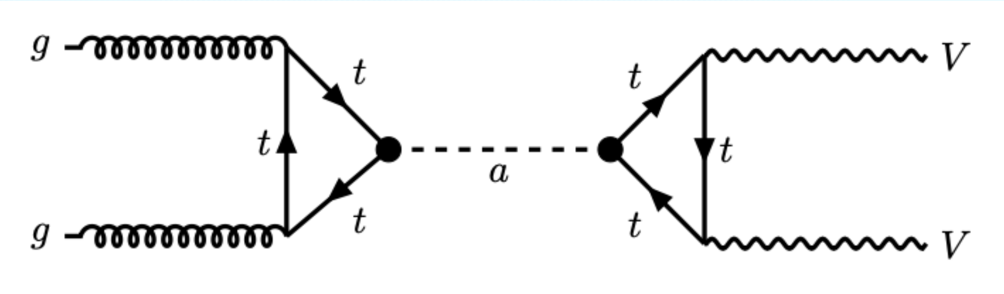
CMS: $\left|\frac{f_a}{c_t}\right| > 103.1$ GeV at 95% CL,

(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)

2B. ALP mediated diboson production



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

constrain 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]

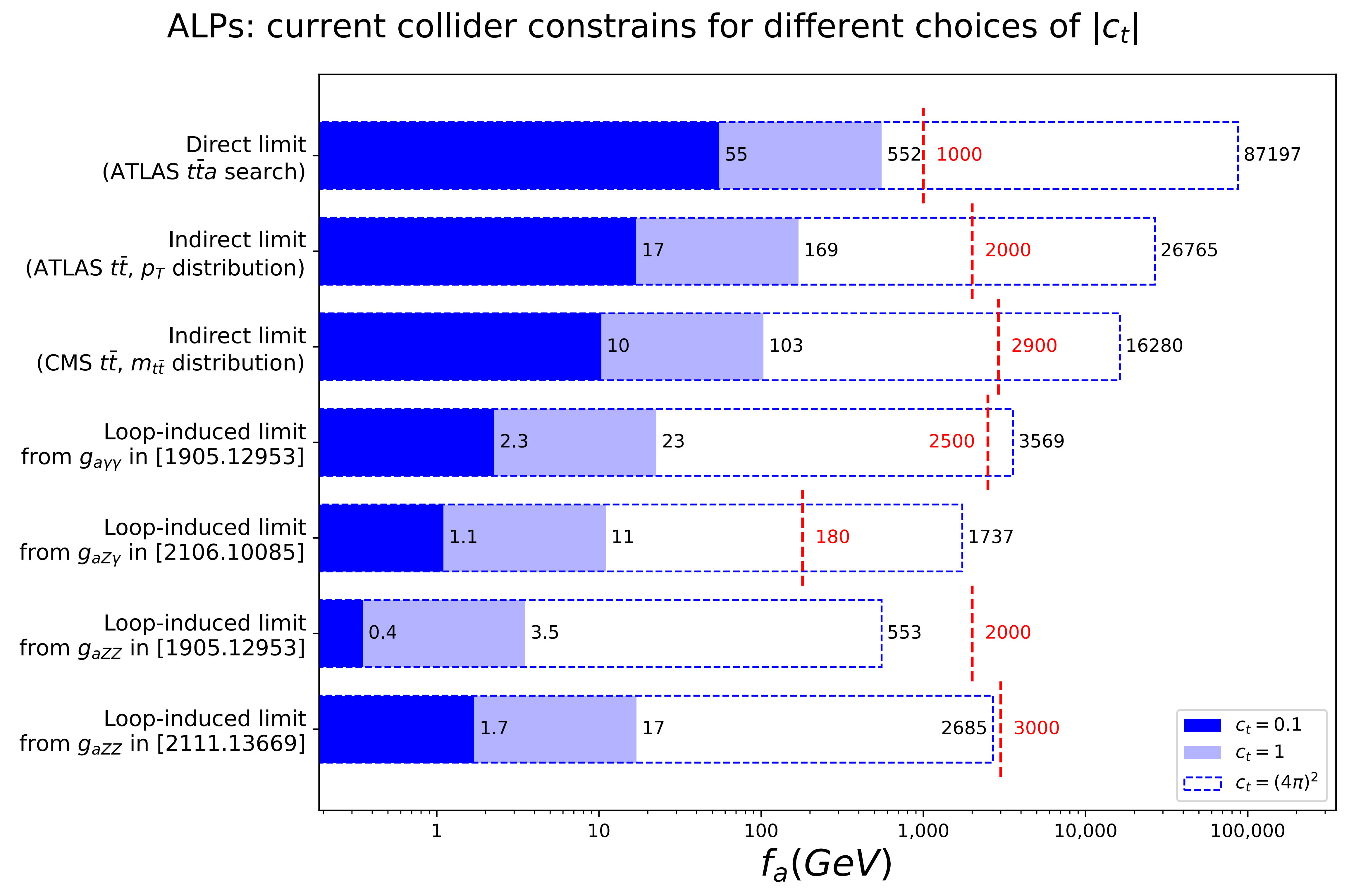
here: use loop-induced couplings g_{aVV}^{eff} to recast these limits into limits on c_t

$$\left| g_{agg} g_{aZZ} \right| < 1 \text{ TeV}^{-2} \quad \Rightarrow \quad \left| \frac{f_a}{c_t} \right| > 3.5 \text{ GeV}$$

$$\left| g_{agg} g_{a\gamma\gamma} \right| < 0.08 \text{ TeV}^{-2} \quad \Rightarrow \quad \left| \frac{f_a}{c_t} \right| > 22.5 \text{ GeV}$$

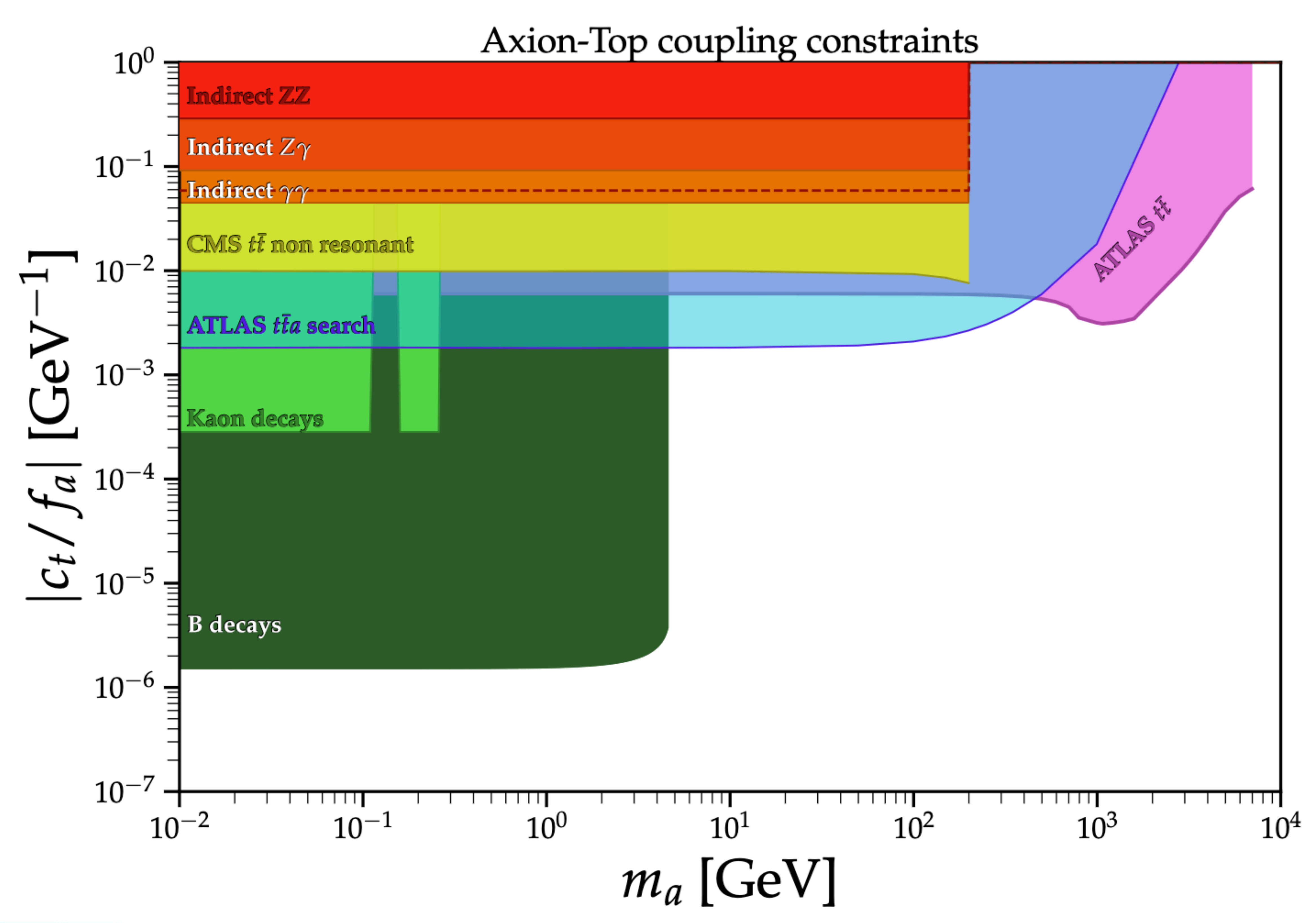
$$\left| g_{agg} g_{aZ\gamma} \right| < 0.37 \text{ TeV}^{-2} \quad \Rightarrow \quad \left| \frac{f_a}{c_t} \right| > 11.0 \text{ GeV}$$

Summary of constraints from Run-II data



red dashed lines: EFT validity limits

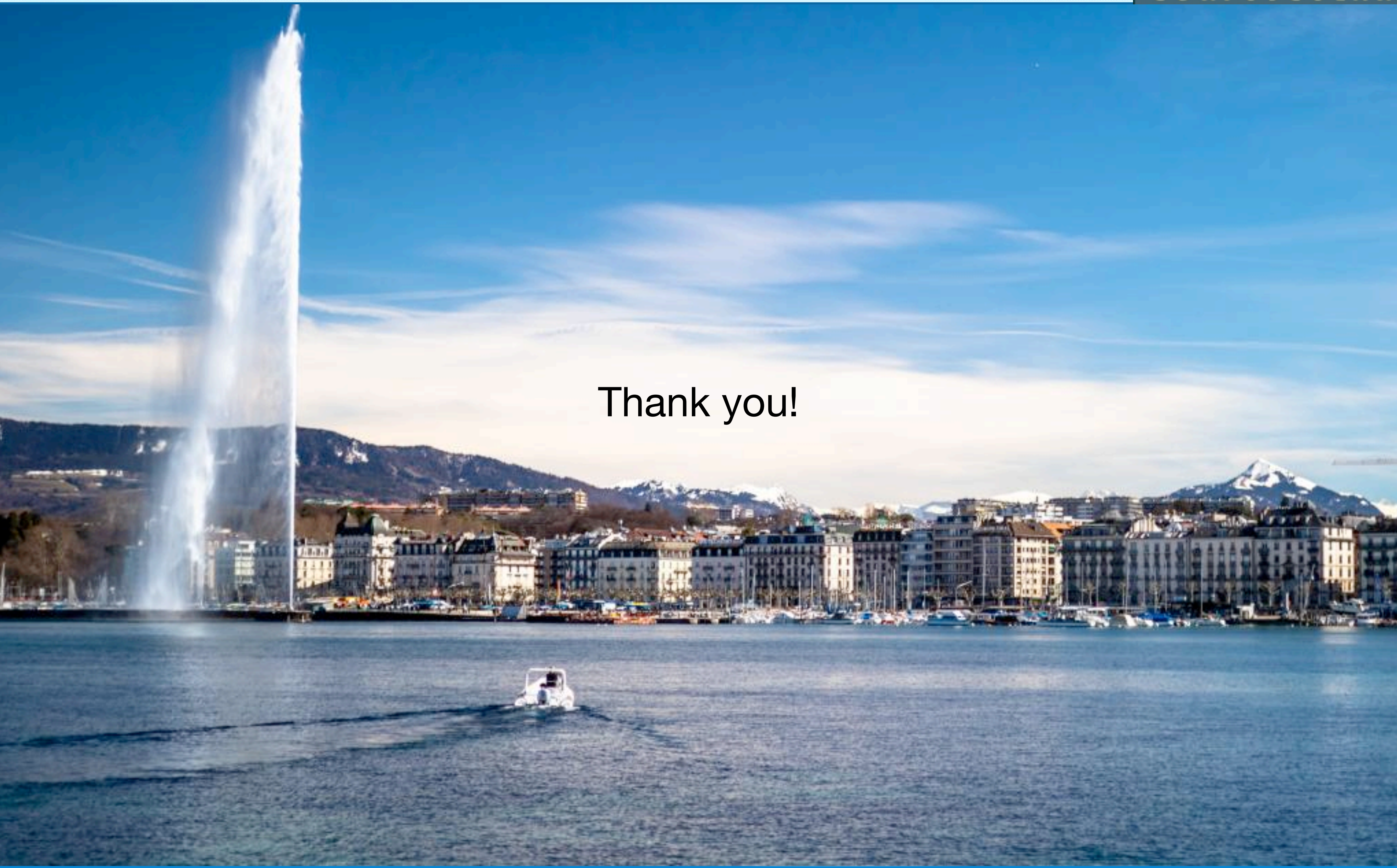
Summary



Axion-Top coupling constraints
Indirect ZZ
Indirect $Z\gamma$
Indirect $\gamma\gamma$
CMS $t\bar{t}$ non resonant
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

- ALP EFT with focus on the ALP-top coupling motivated by the proportionality to the fermion mass
- we studied the current sensitivity of the LHC to a light ALP coupled to top-pairs, interesting interplay between
  - → reinterpretation of a SUSY search for stops ($t\bar{t} + MET$)
  - → reinterpretation of SM measurements of $t\bar{t}$ production at high invariant mass
  - → recasting limits on ALP to vector boson couplings
- for collider stable ALPs: the direct limits are currently stronger
  - → however, the scaling with luminosity is different, in the future the high $m_{t\bar{t}}$ could become more sensitive than the $t\bar{t} + MET$ search
- dedicated ALP-specific experimental analyses would be interesting:
  - → reinterpret Top-SMEFT studies as ALP searches (long tails)
  - → ALP in proton PDF
  - → study of decaying ALPs and LLPs

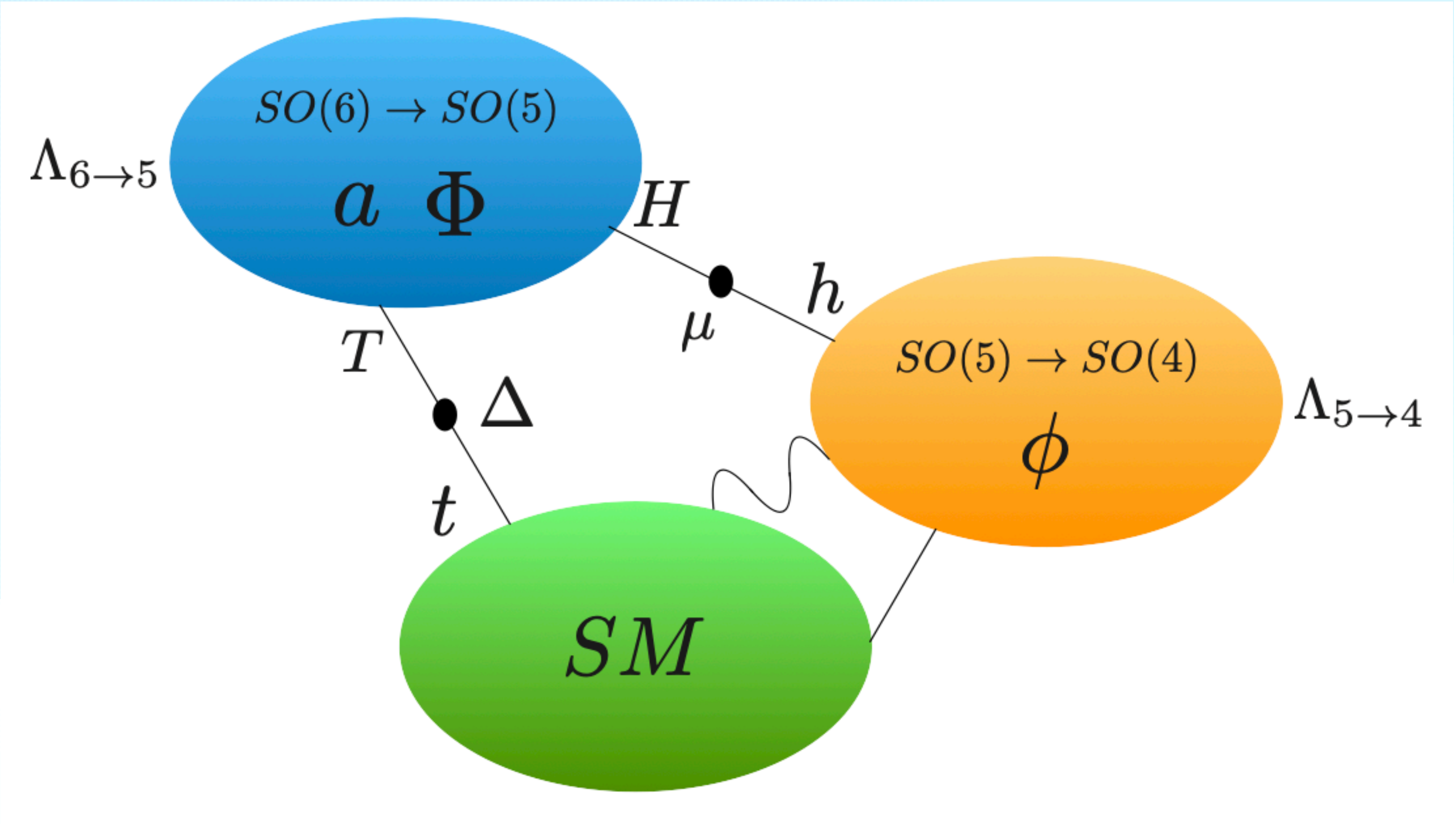


Thank you!

Back-up slides

c_t from model building

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



- 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

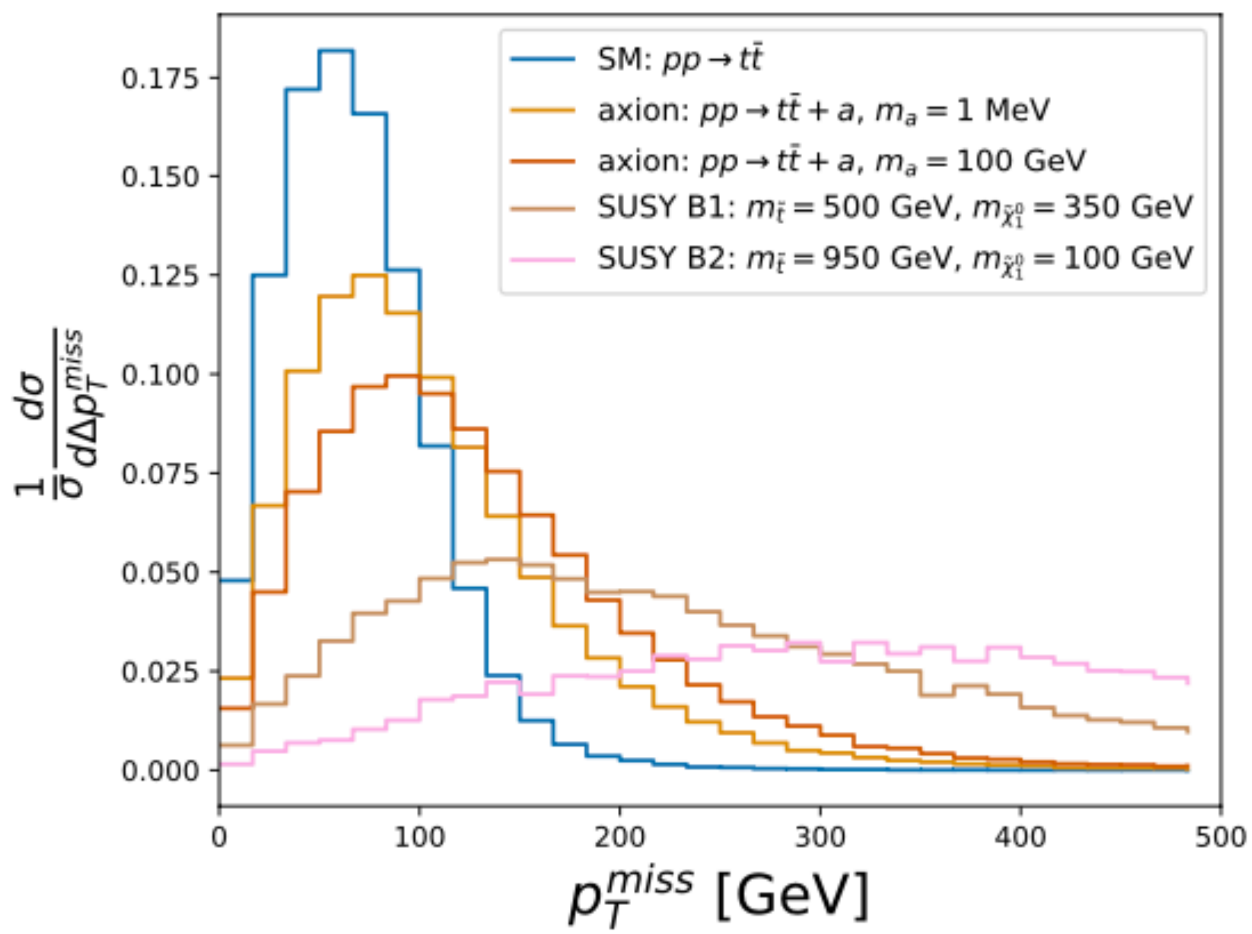
$$\mathscr{L} \supset -c_T \frac{\partial_\mu a}{\Lambda_{6\to5}}(\bar{T}\gamma^\mu T)$$

- T mixes with top quarks through mass mixing $-\Delta \bar{t}_R T + h.c.$

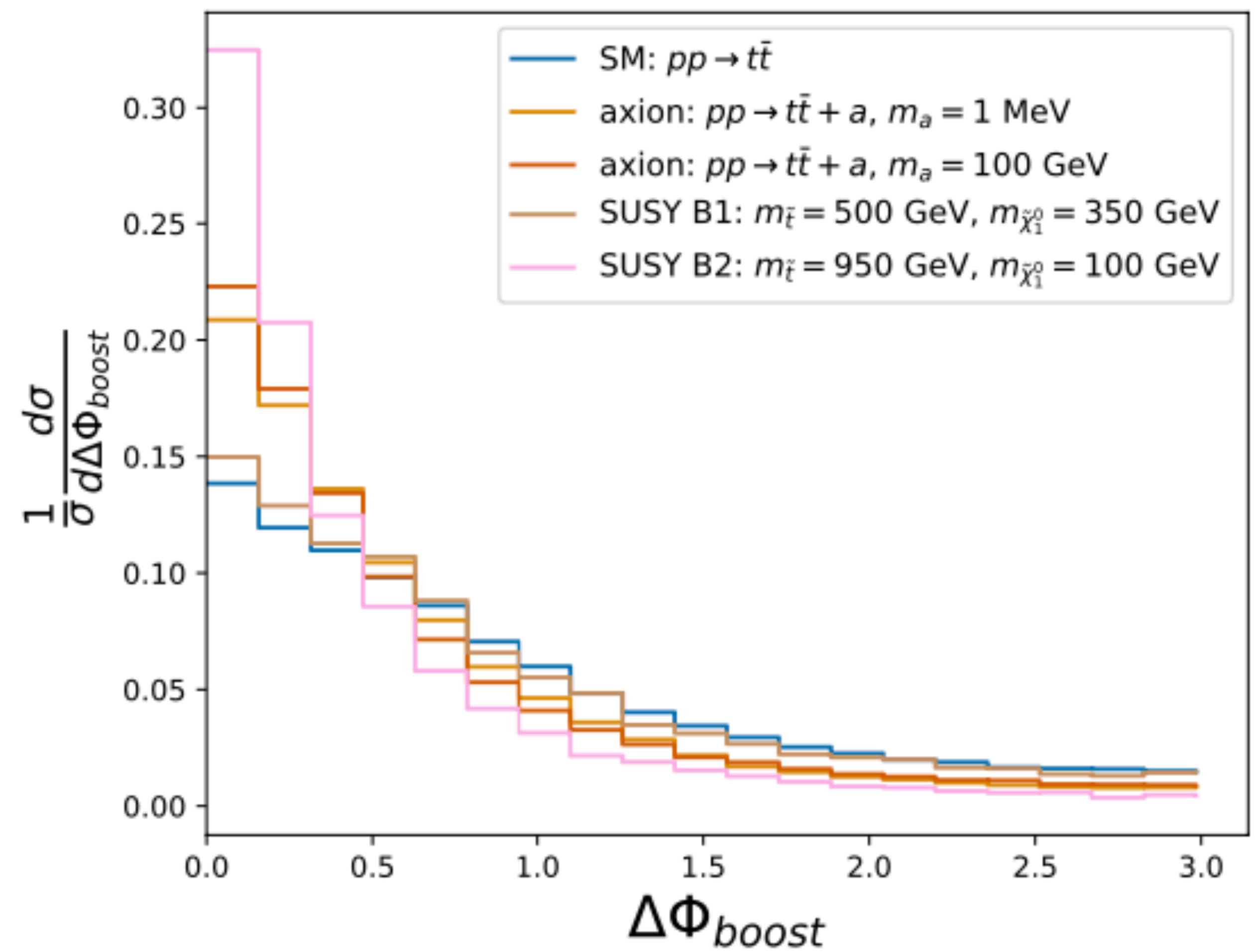
→ induces an ALP top coupling $c_t \propto c_T \frac{\Delta^2}{m_T^2}$

Kinematics of $t\bar{t} + a$ production

- compare the distributions of 2 kinematic variables for SM background, ALP models with different masses and 2 benchmark SUSY models:



(a) total missing transverse momentum $\vec{p}_T^{miss}$



(b) "boost angle" $\Delta\Phi_{boost}$: azimuthal angle between the sum of the boosted momenta $\vec{p}^{boost}$ and the missing momentum $\vec{p}^{miss}$

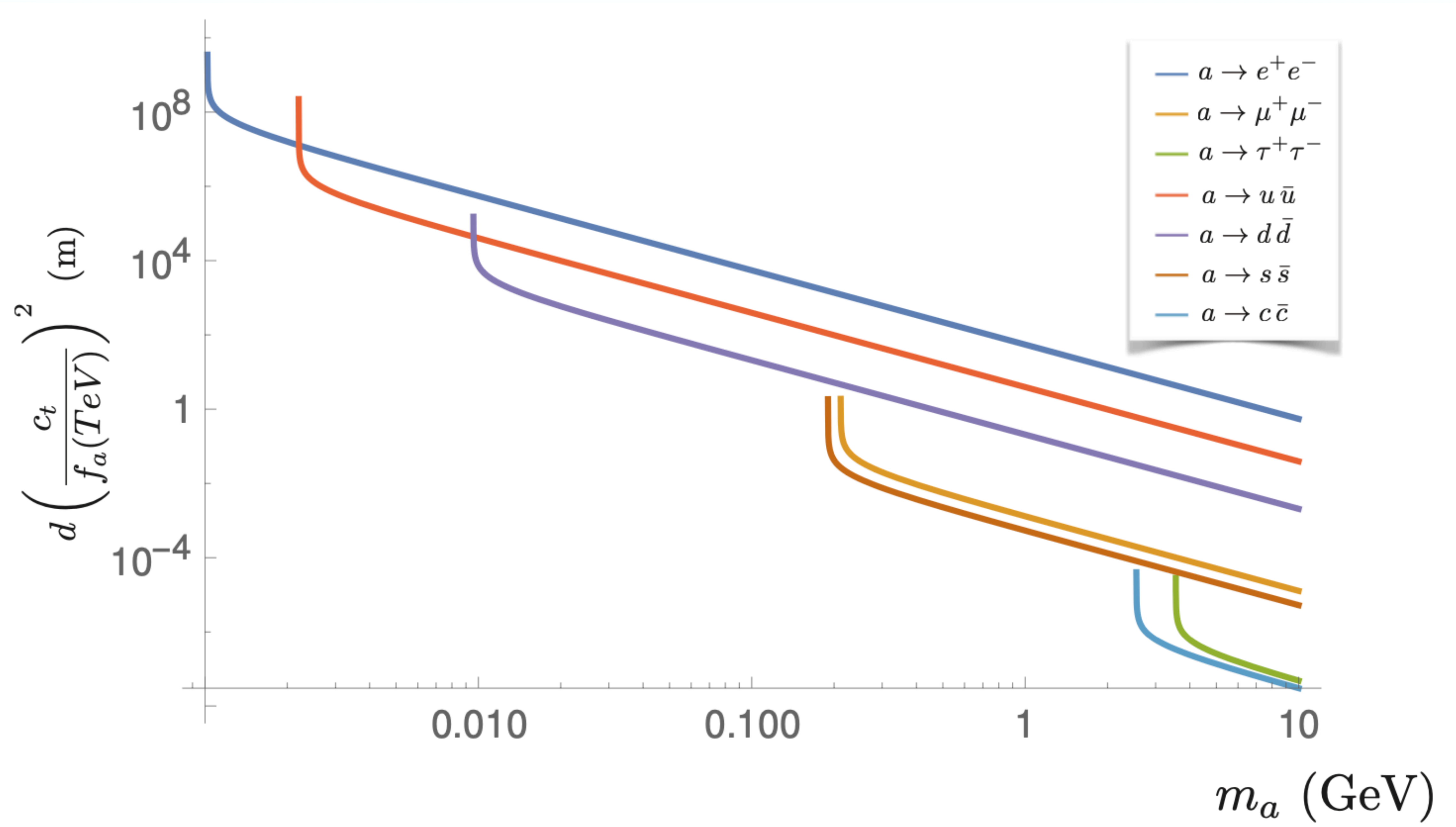
$\Rightarrow$ Search well-suited to distinguish ALP signals from SM background and SUSY

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
$\|m_Z - m_{ll}\|$	> 20 GeV
$n_{\text{b-jets}}$	≥ 1
$\Delta\Phi_{\text{boost}}$	< 1.5 rad

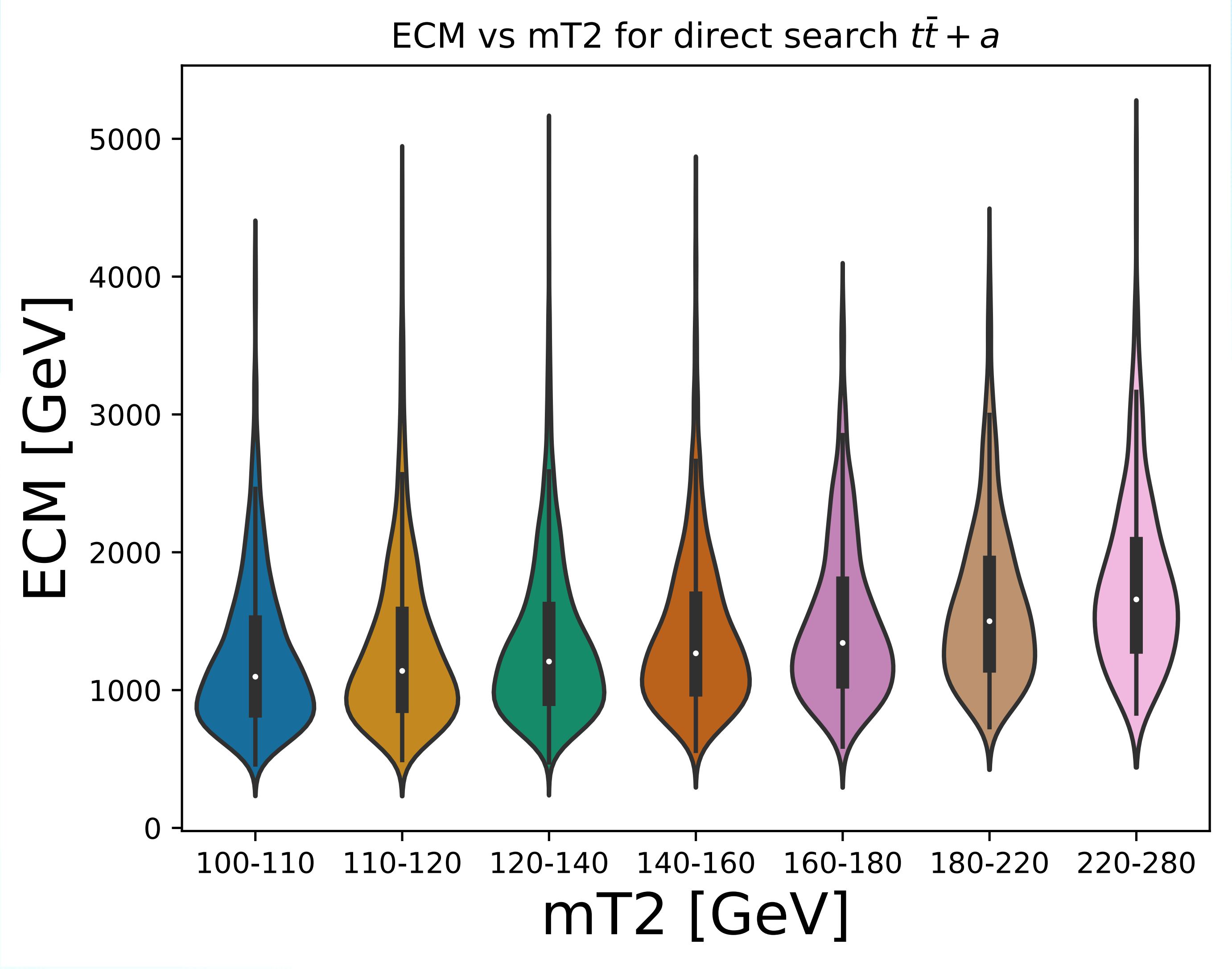
On the collider stability of the ALP



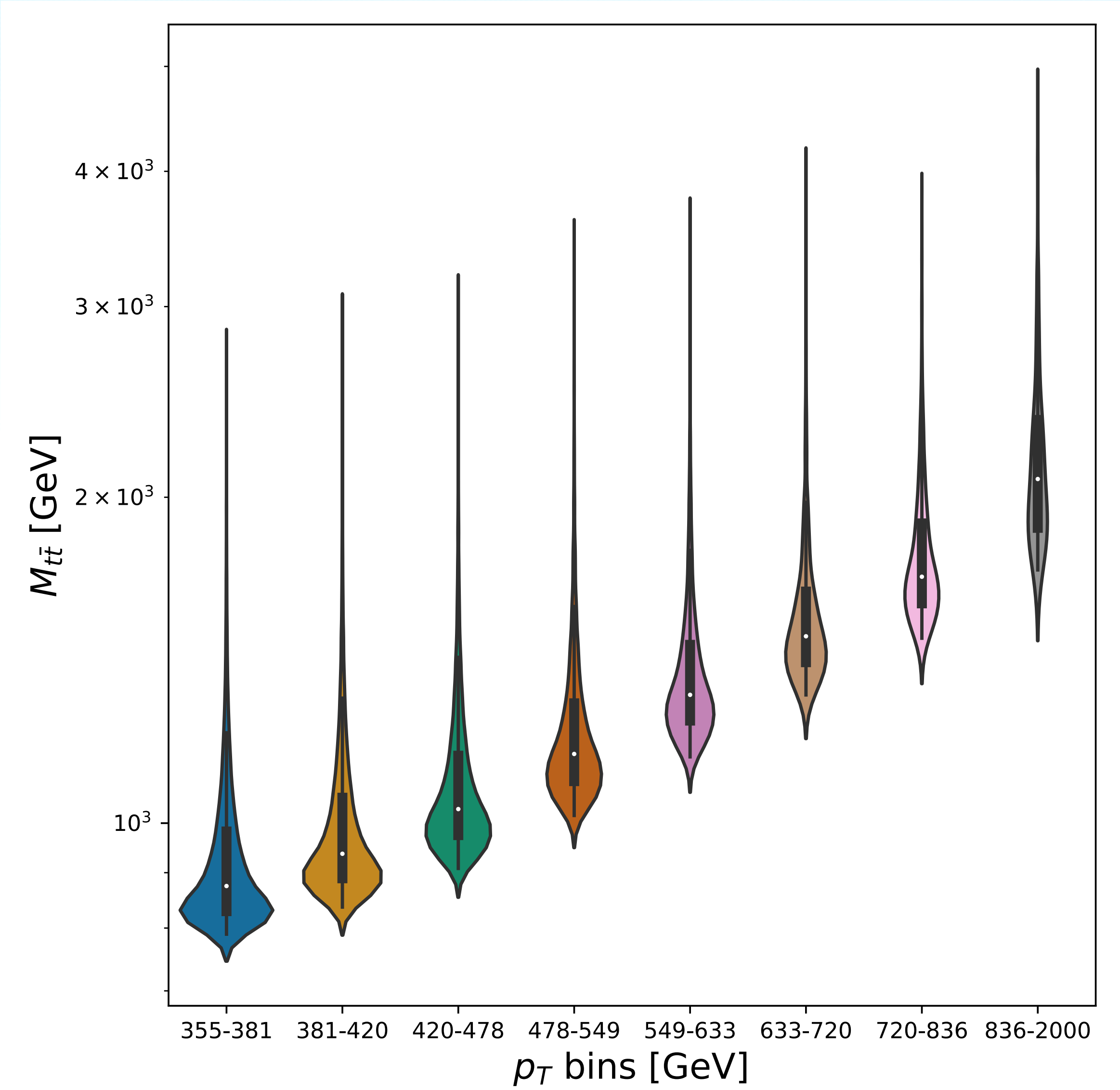
- is the distance the ALP travels before decaying larger than the typical detector size (~meters)?
- We find that for $|f_a/c_t| \sim 1$ TeV this holds up to $m_a < 200$ MeV, for larger values of $|f_a/c_t|$ even up to higher values of m_a

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 $gg \to a \to t\bar{t}$