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Distinguishing axion-like particles and additional Higgs bosons in $t\bar{t}$ final states at the LHC

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Why ALPs?

- Strong CP problem: no observation of CP violation in QCD although it would be allowed from first principles
- Solved by axions – BSM particles that exhibit U(1) shift symmetry
- In general: axion-like particles = particles with the same symmetry
  - Arise in many high-energy theories
  - Promising candidates for dark matter or dark matter mediators

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

CP-violating!
Obs.: $\theta < 10^{-10}$

↓

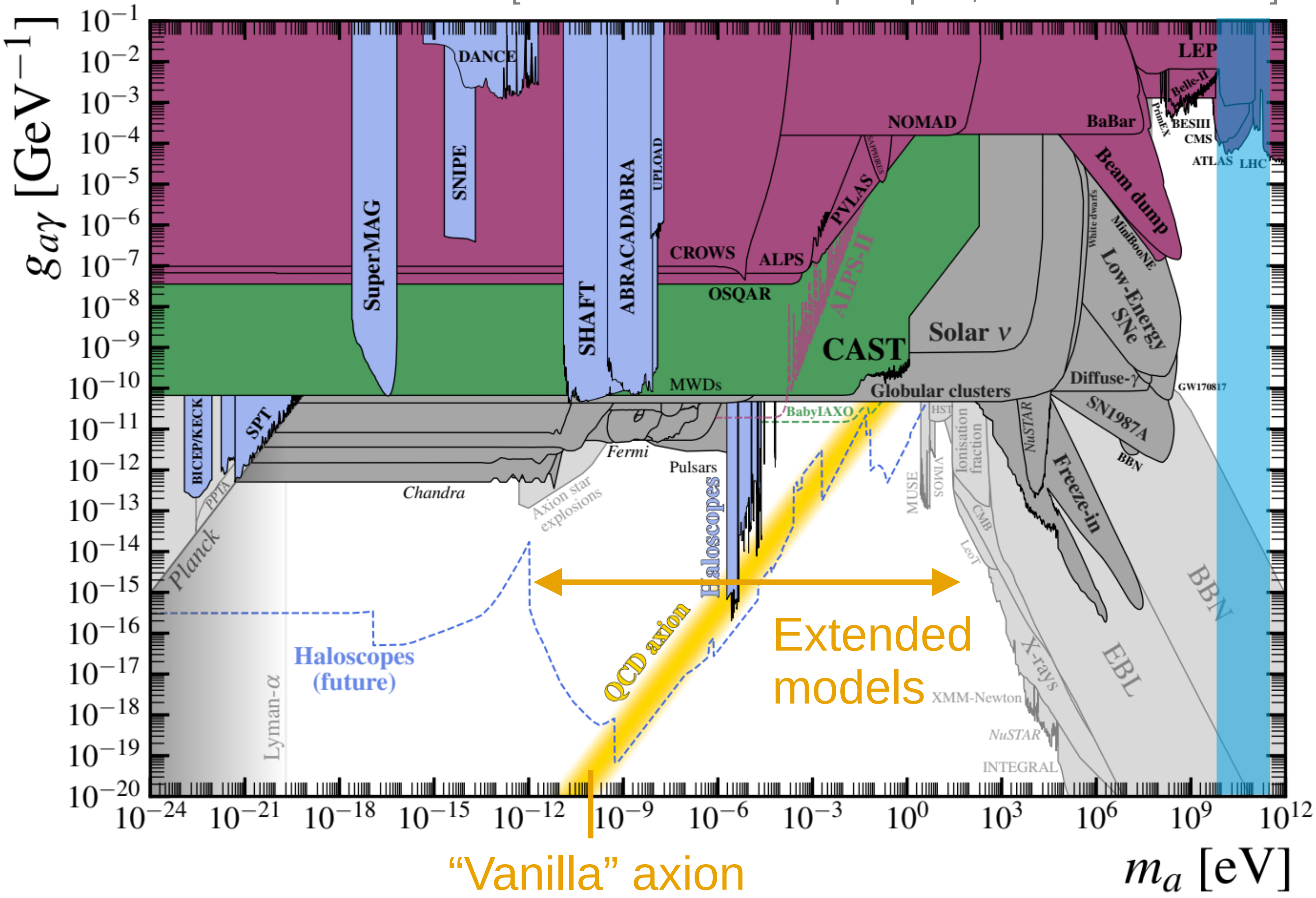
Promote to particle: $\theta \rightarrow a$
Absorb CP-violating term in

$$\mathcal{L}_{ax} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_G \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + \ldots$$

ALPs

- ALPs can have a large mass range!
- QCD axion is restricted to band
  - … but that can be different in extended models
- This work: focus on large masses O(0.1 – 1 TeV)

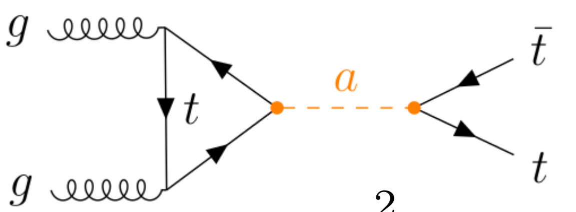
[FIPs 2022 Workshop Report, arXiv:2305.01715]



ALPs → $t\bar{t}$ at the LHC

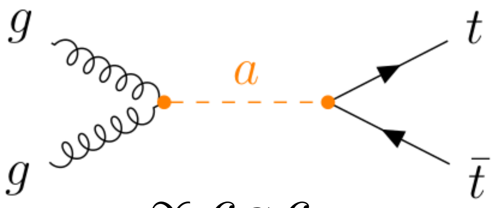
- ALP couplings: photons, EW bosons, gluons, massive fermions
  - usual models: Yukawa-like ~ m_f
- Produce at the LHC via gluon fusion
- If $m_a > 2m_t$: decay to top quarks → interferes with SM final state:

ALP



$\propto c_t^2$

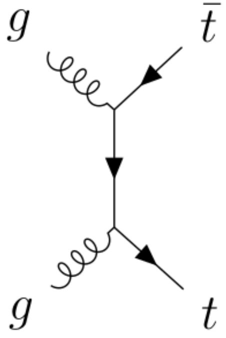
+



$\propto c_G\, c_t$

SM

+



+ ...

$\mathcal{O}(m_a) \approx m_t$
→ top quark loop explicitly considered

Explicit gluon coupling - physics at high scales integrated out

ALPs and additional Higgs bosons

- ALP coupling to top is similar to an additional pseudoscalar Higgs boson
  - e.g. 2HDM+a model, hMSSM, ...

ALP

top quark $\mathcal{L}_{ALP} = c_t \frac{\partial_\mu a}{f_a} (\bar{t}\gamma^\mu \gamma^5 t)$

gluons $+ c_G \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$

$+ \text{other fermions}$

$+ \text{EW bosons}$

Pseudoscalar Higgs

$\mathcal{L}_A = i g_{At\bar{t}} \frac{m_t}{v} (\bar{t}\gamma^5 t) A$ top quark

$+ \text{other fermions}$

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$+ \text{other fermions}$

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Pseudoscalar Higgs

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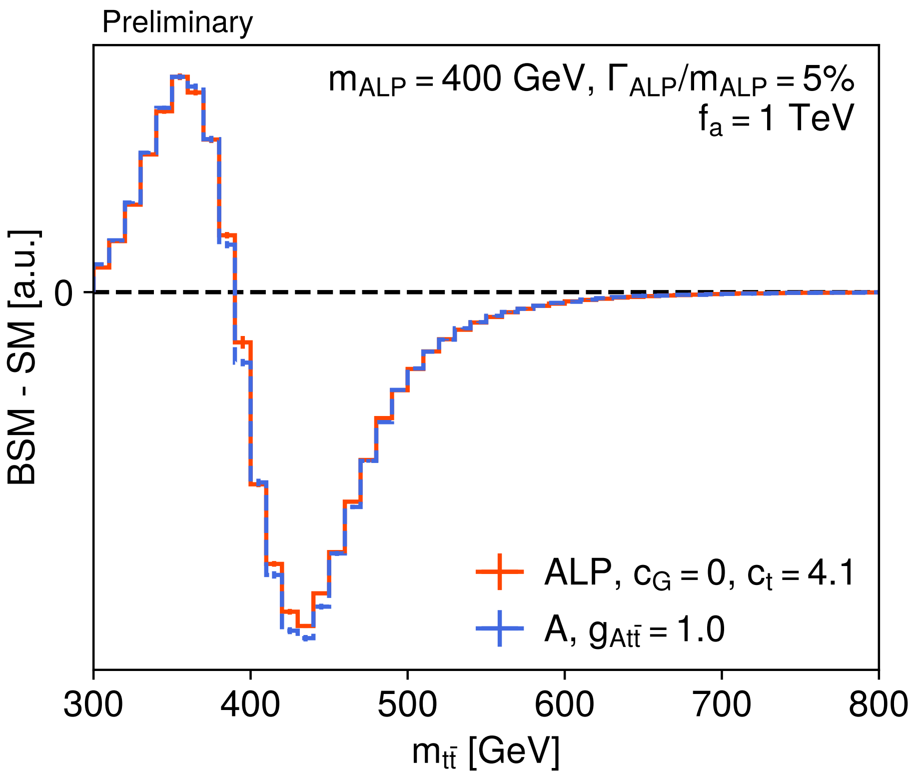
$+ \text{other fermions}$

Top quark coupling can be rewritten to be identical!

ALP vs $A \to t\bar{t}$

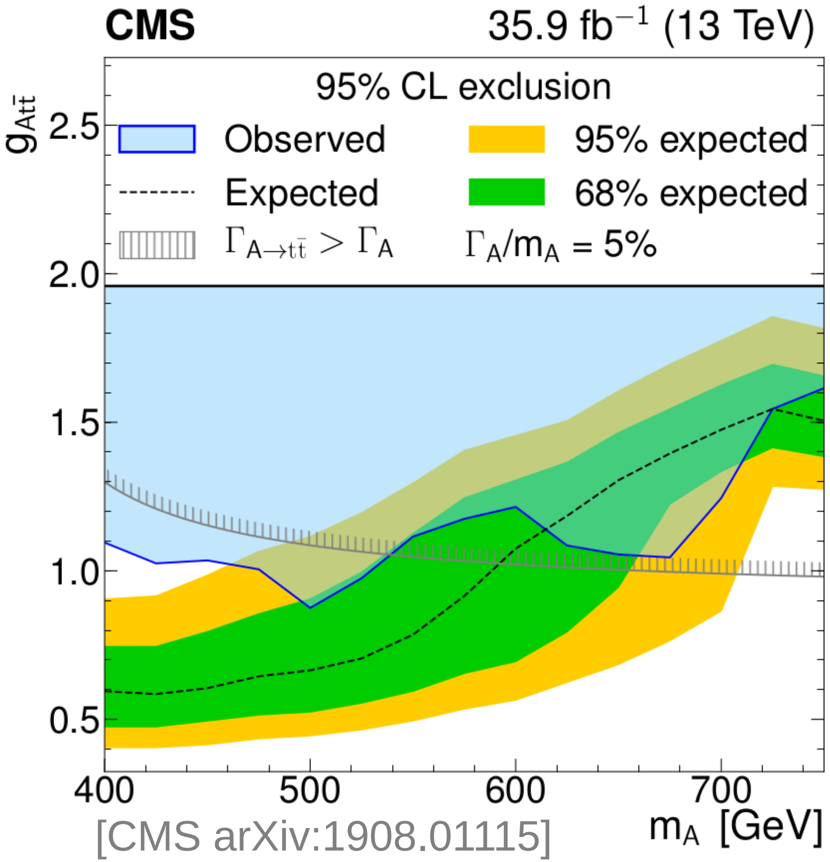
- Invariant $t\bar{t}$ mass distribution for ALP and pseudoscalar Higgs (A)
  - Dileptonic decay of $t\bar{t}$
  - Truth level top quark reconstruction
  - Gaussian smearing (σ = 7.5%) to model detector response
- For ALP with $c_G = 0$: identical to Higgs



➔ Translate experimental Higgs limits into ALP (assuming $c_G = 0$)

Search for additional Higgs bosons in $t\bar{t}$

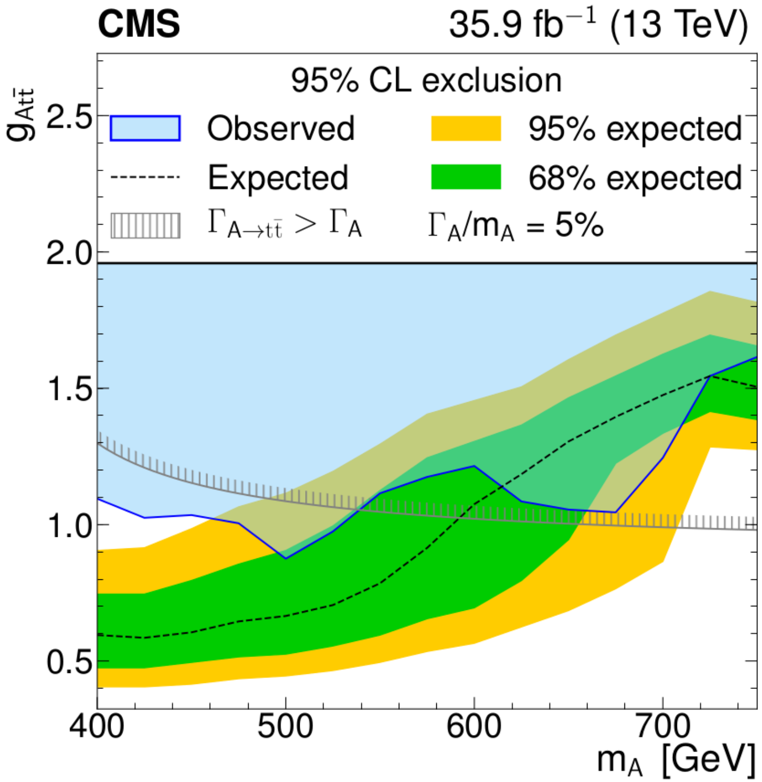
- CMS and ATLAS have published searches for additional Higgs bosons (including pseudoscalars) in $t\bar{t}$
  [CMS arXiv:1908.01115, ATLAS arXiv:1707.06025]
- Focus here on CMS: dilepton and lepton+jets final states
- CMS sees 3σ local (2σ global) excess at m_A = 400 GeV



[CMS arXiv:1908.01115]

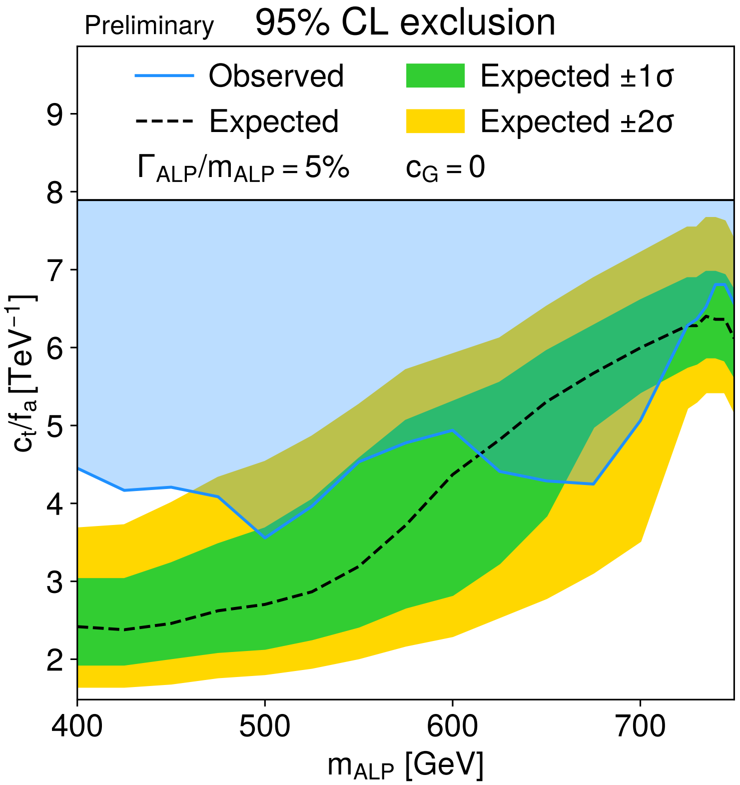
ALP limit for $c_G = 0$

Pseudoscalar Higgs
[CMS arXiv:1908.01115]



Factor $\frac{1}{\mathrm{vev}}$

Axion-Like Particle
with $c_G = 0$



ALPs and additional Higgs bosons

- ALP coupling to top is similar to an additional pseudoscalar Higgs boson
  - e.g. 2HDM+a model, hMSSM, ...

ALP

top quark
$$\mathcal{L}_{ALP} = c_t \frac{i m_t a}{f_a} (\bar{t}\gamma^5 t)$$

gluons
$$+ c_G \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

$$+ \text{other fermions}$$

$$+ \text{EW bosons}$$

Pseudoscalar Higgs

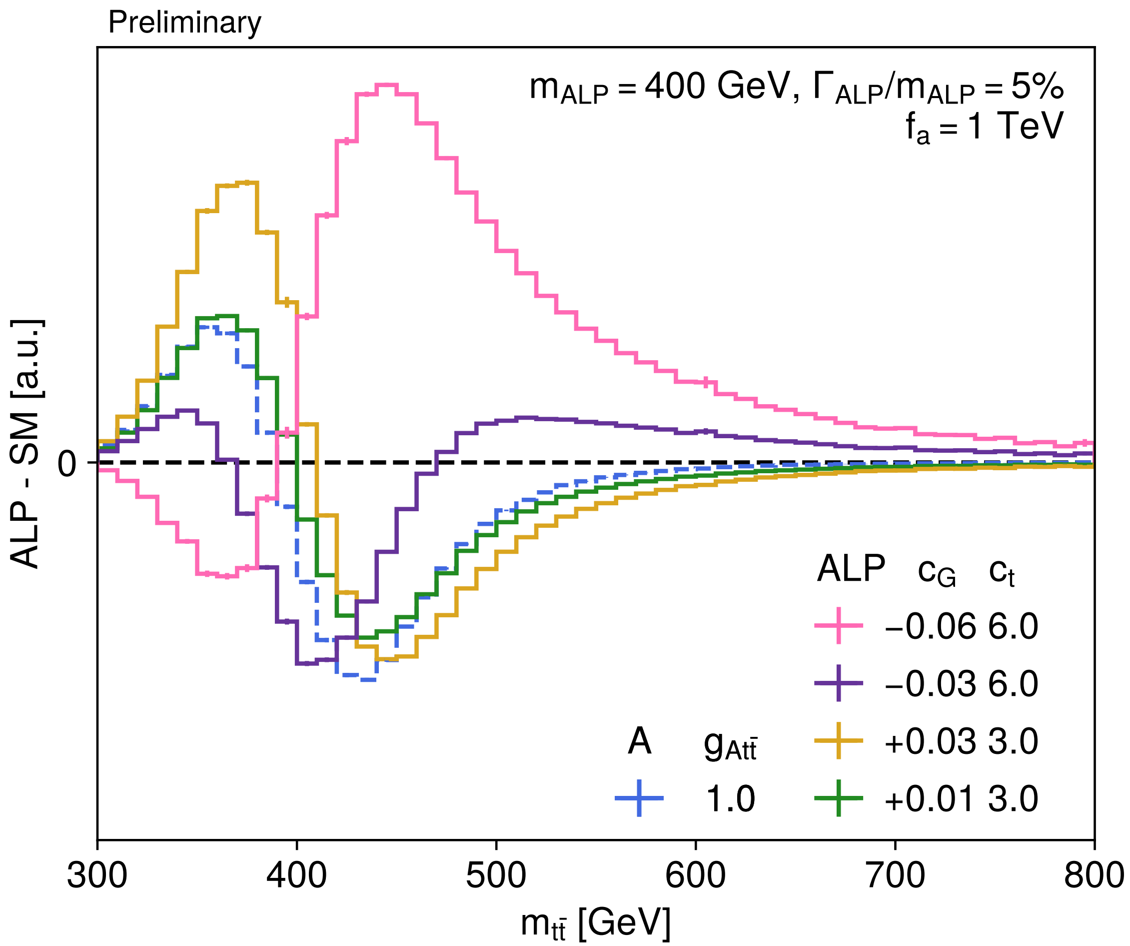
$$\mathcal{L}_A = i g_{At\bar{t}} \frac{m_t}{v} (\bar{t}\gamma^5 t) A$$
top quark

$$+ \text{other fermions}$$

Additional gluon coupling for the ALP!
$\rightarrow$ Effect?

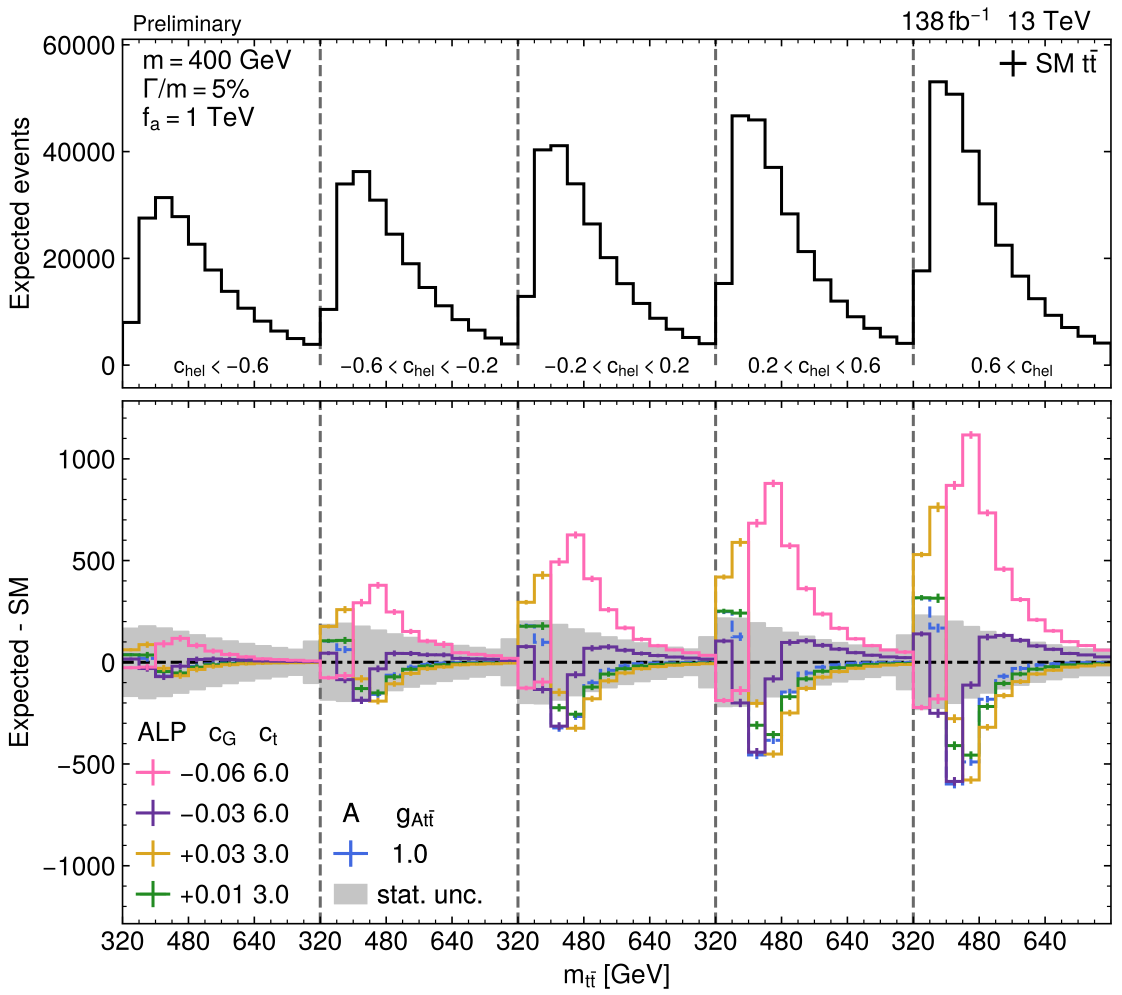
ALP with $c_G \neq 0$

- For $c_G \neq 0$, shapes in m_{tt} differ from pseudoscalar Higgs!
- Sensitive to relative sign of c_G and c_t:
  - Smaller “dip” for same sign
  - “dip-peak” for opposite sign
- Can we distinguish ALP and Higgs for $c_G \neq 0$?



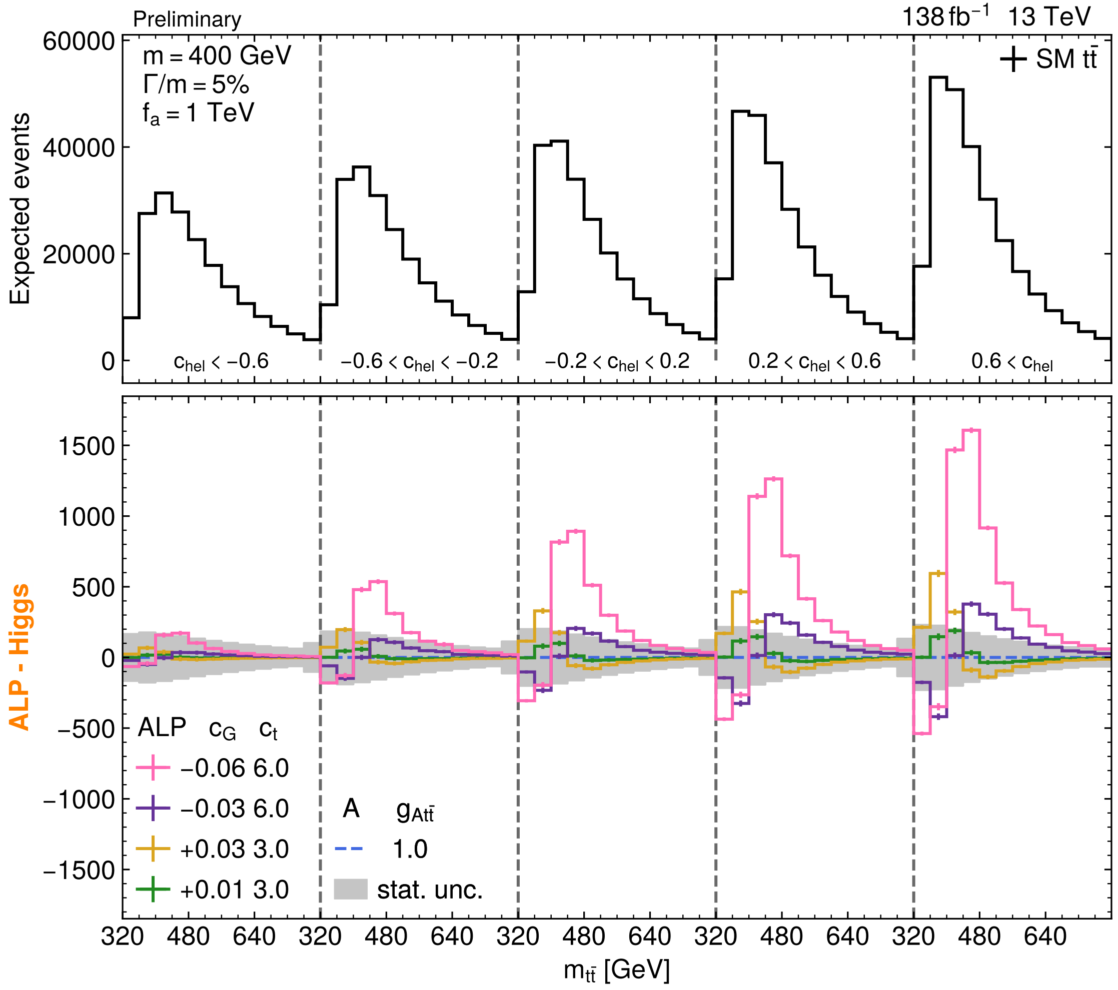
ALP with $c_G \neq 0$

- Use dileptonic variables & binning from CMS: m_{tt} x c_{hel}
  - c_{hel}: cosine of angle between leptons in their helicity frames → sensitive to parity of signal
- Acceptance taken from the CMS 2016 result
- Expected statistical uncertainty from LHC Run 2 (138 fb^{-1})



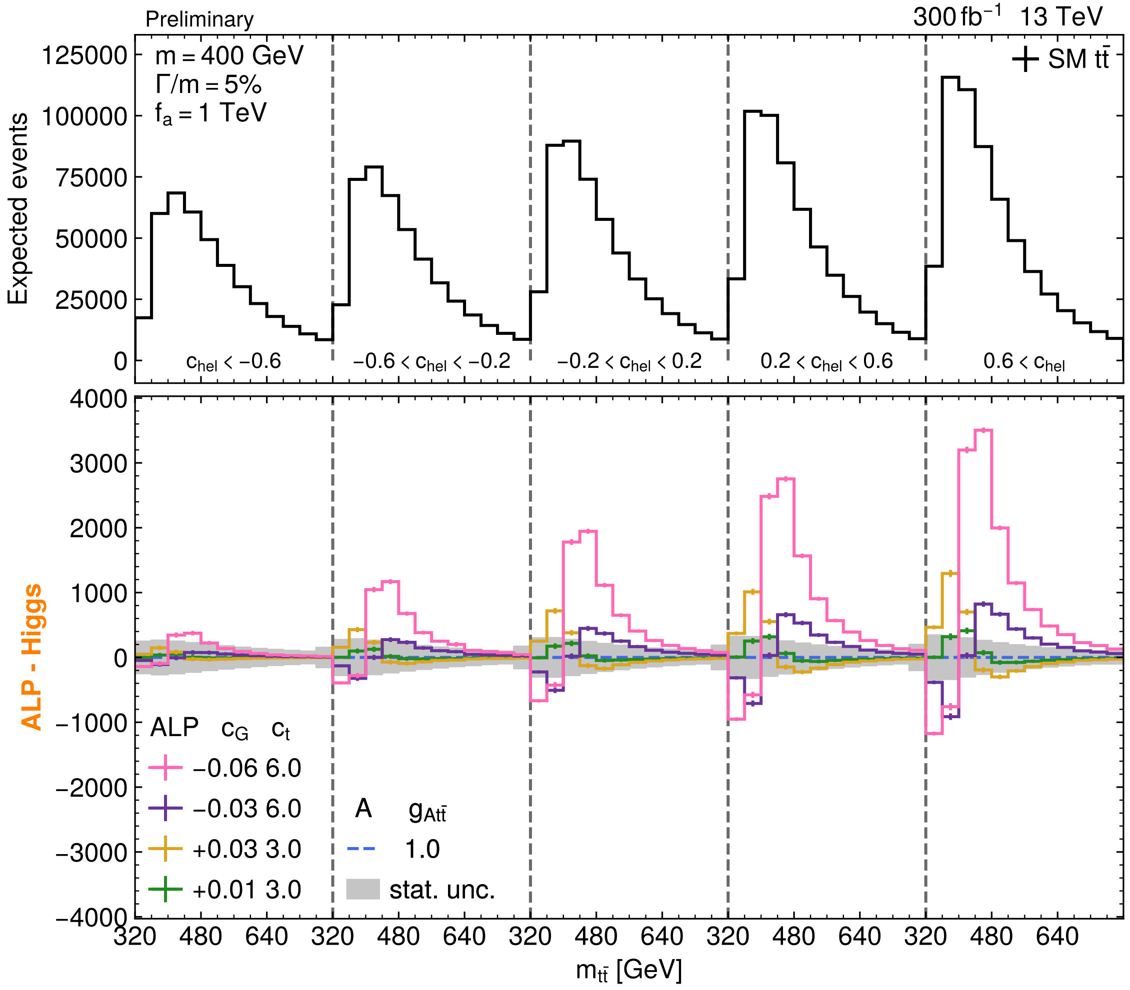
ALP with $c_G \neq 0$

- Difference of ALP with $c_G \neq 0$ and Higgs / ALP for $c_G = 0$
- For opposite signs of c_G and c_t, difference might already be observable with LHC Run 2!



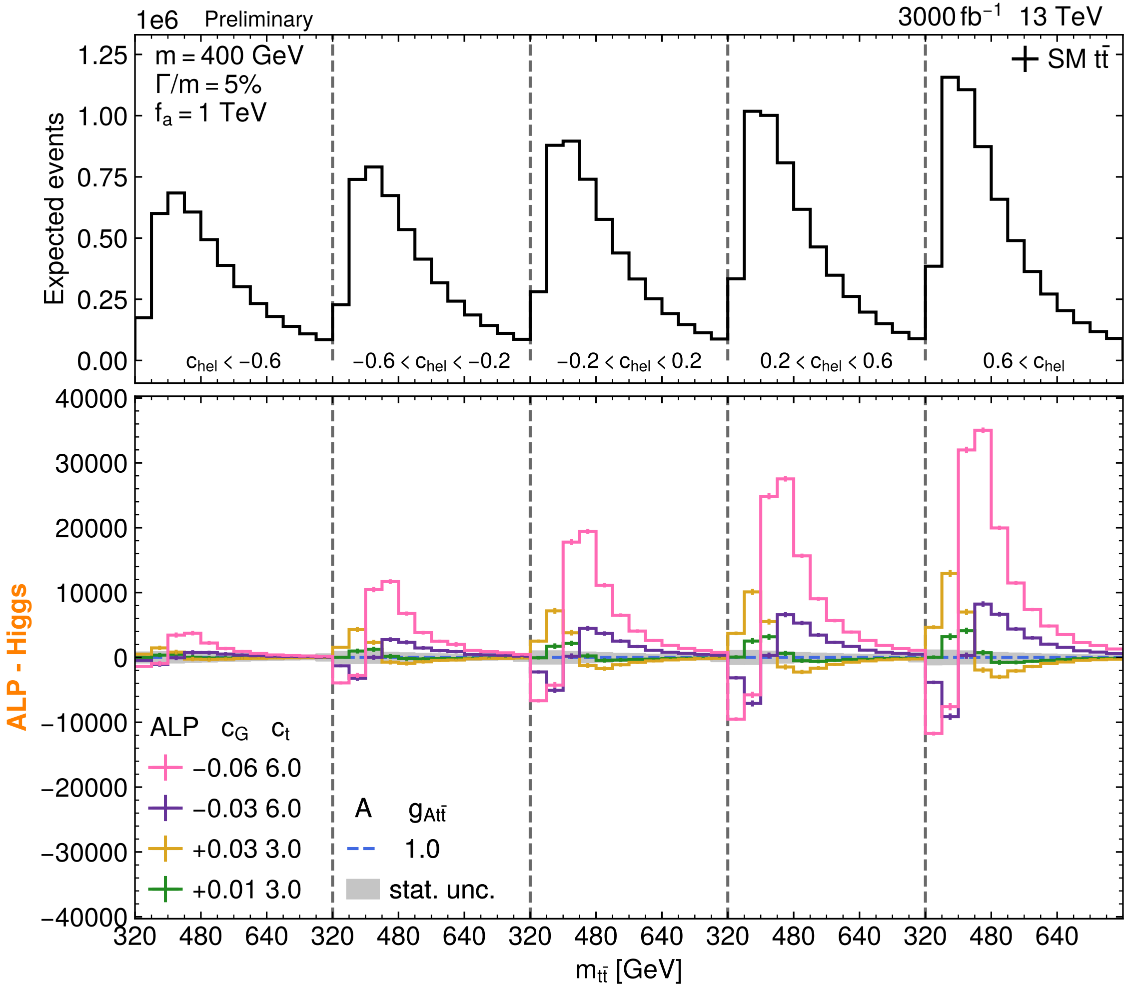
ALP with $c_G \neq 0$

- Projection to higher luminosity: LHC Run 2 + 3 ~ 300 fb^{-1}
- Inclusion of Run 3 data might also constrain c_G when c_G and c_t have same sign



ALP with $c_G \neq 0$

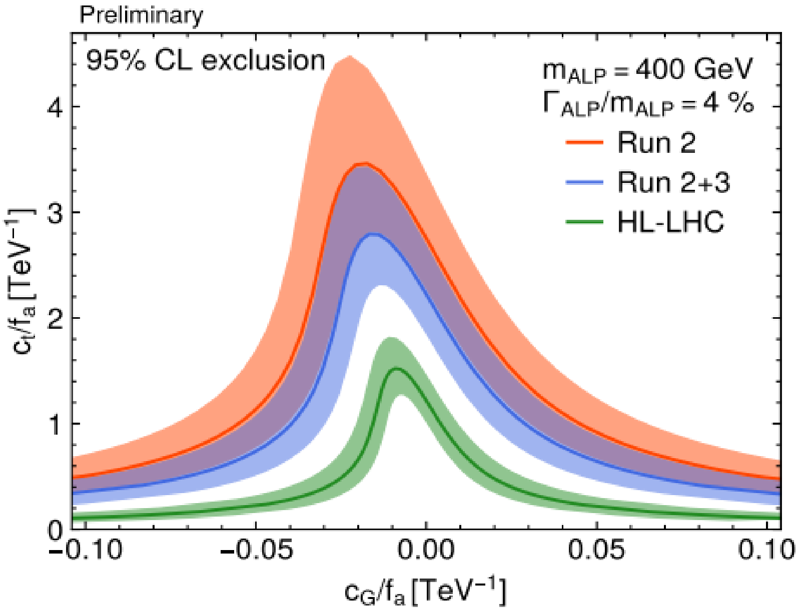
- Projection to higher luminosity: HL-LHC ~ 3 ab^{-1}
- Enough statistics expected for an explicit measurement of c_G!

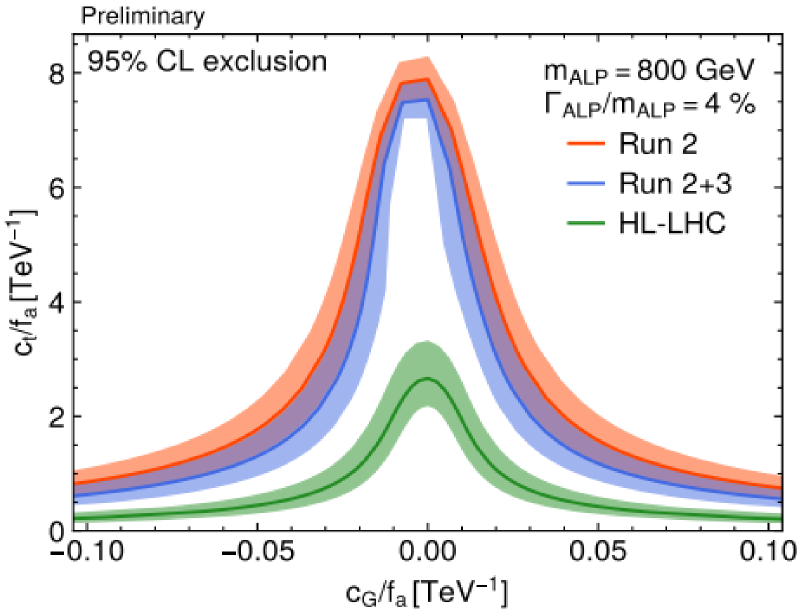


Projected ALP limits

- Maximum likelihood fits to expected data similar to the CMS setup
  - Including most important modeling uncertainties

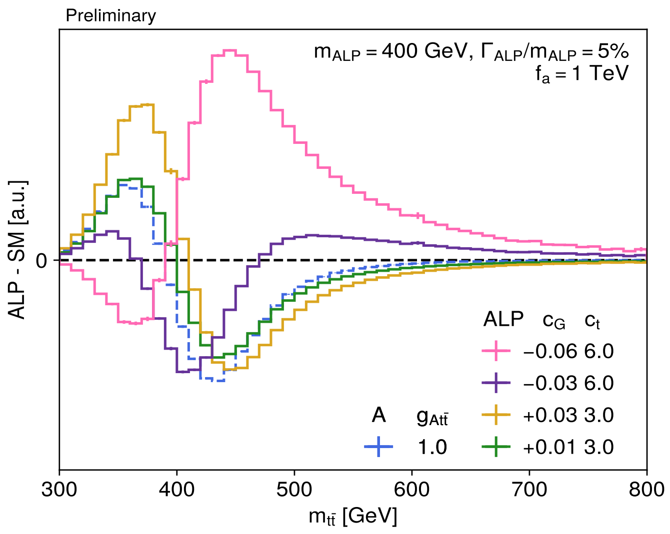
➔ Projected limits for ALPs in the c_t - c_G plane!

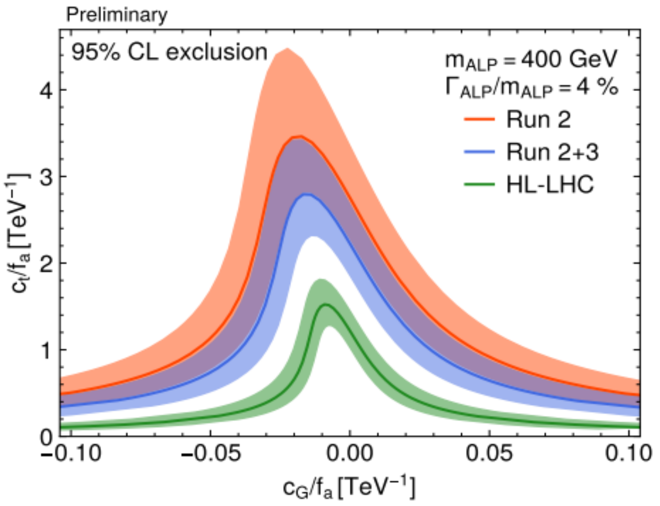




Summary & Outlook

- ALPs are candidates for dark matter mediators
- Heavy ALPs can be searched for in $t\bar{t}$ final states at the LHC
- Compared ALPs to an additional pseudoscalar Higgs boson:
  - For ALPs with $c_G = 0$: identical to Higgs
    ➔ Translate 2016 CMS limits!
  - For ALPs with $c_G \neq 0$: different m_{tt} distribution
    ➔ Can be distinguished!
- Projected ALP limits for the future of the LHC!

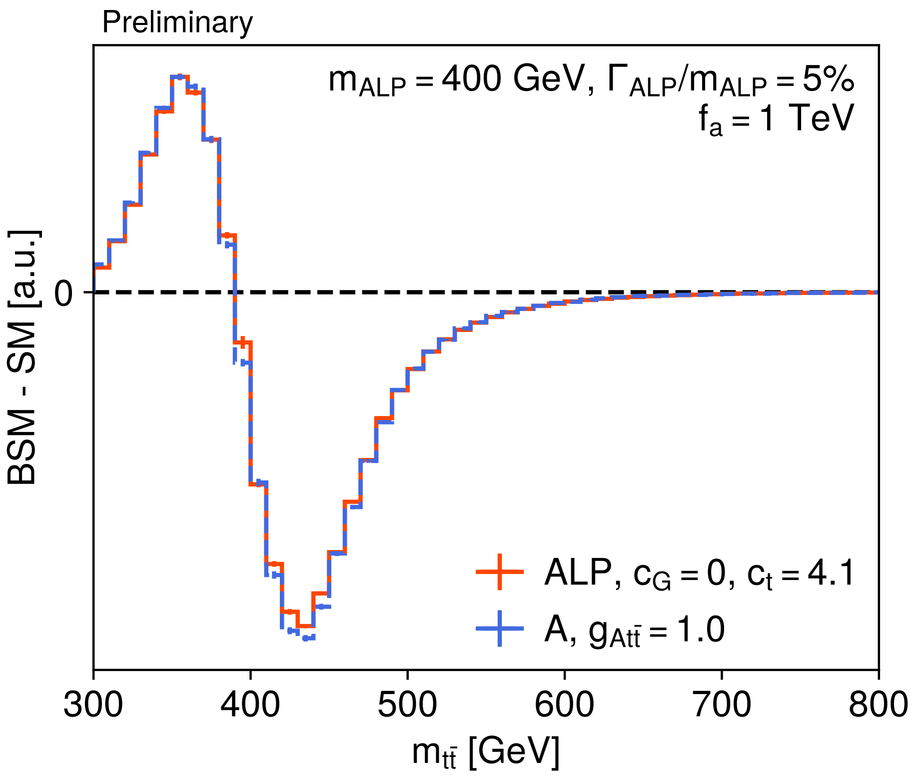




Backup

Technical details

- Generator: MadGraph 5 at LO, showered with Pythia 8
- Resonance and interference terms generated seperately
- Reconstruct top quarks at truth level
- Apply Gaussian smearing (σ = 7.5%) to model detector response in an experiment



Considered systematic uncertainties

- Systematics are implemented as nuisance parameters with shape effects in the likelihood fit
- Uncertainties on both signal and SM $t\bar{t}$ background:
  - Renormalization and factorization scales: varied by 0.5 / 2.0 independently
  - PDF: 100 replicas for the NNPDF 3.1 set
- Uncertainties on the SM $t\bar{t}$ background only:
  - Normalization: 4% uncertainty (taken from CMS)
  - Top mass: varied by 1 GeV up/down (central value 172.5 GeV)

Systematics

- Difference of ALP with $c_G \neq 0$ and Higgs / ALP for $c_G = 0$
- The error bands include the envelope of all systematic uncertainties except for the $t\bar{t}$ normalization
- Note that these are a large overestimate because the fit is sensitive to individual shapes, not just the envelope