Distinguishing axion-like particles and extended Higgs sector pseudocalars in $t\bar{t}$ final states at the LHC

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RESEARCH FOR GRAND CHALLENGES

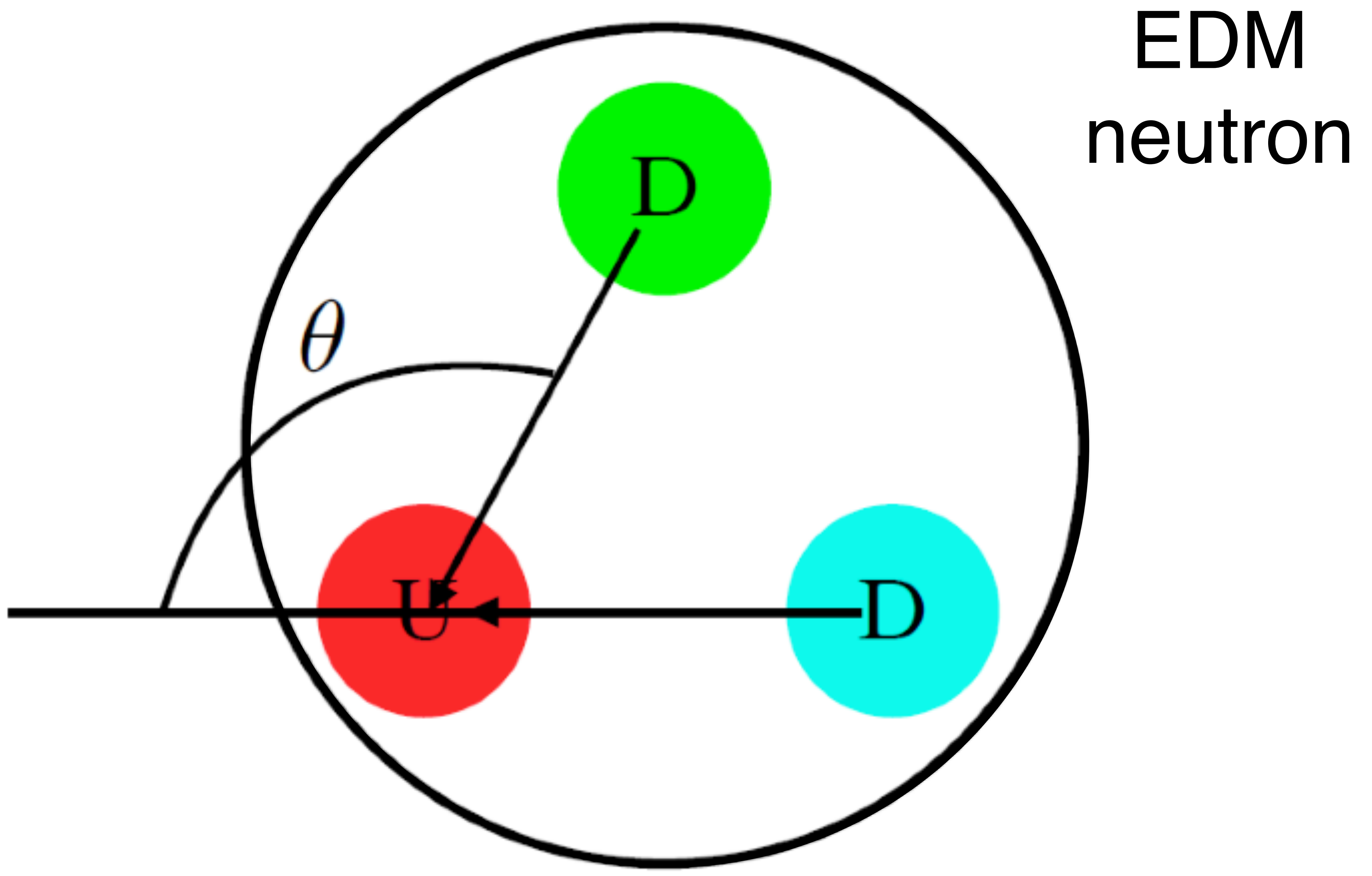
LHC Top Working Group Open Meeting
Top-philic Axion Festival
30 November, 2022

Why axions?

- Strong CP problem: no observation of CP violation in QCD although it would be allowed from first principles

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

CP-violating!



https://arxiv.org/abs/1812.02669

SM: $d_n = \theta \times 3\times10^{-16}$ e×cm

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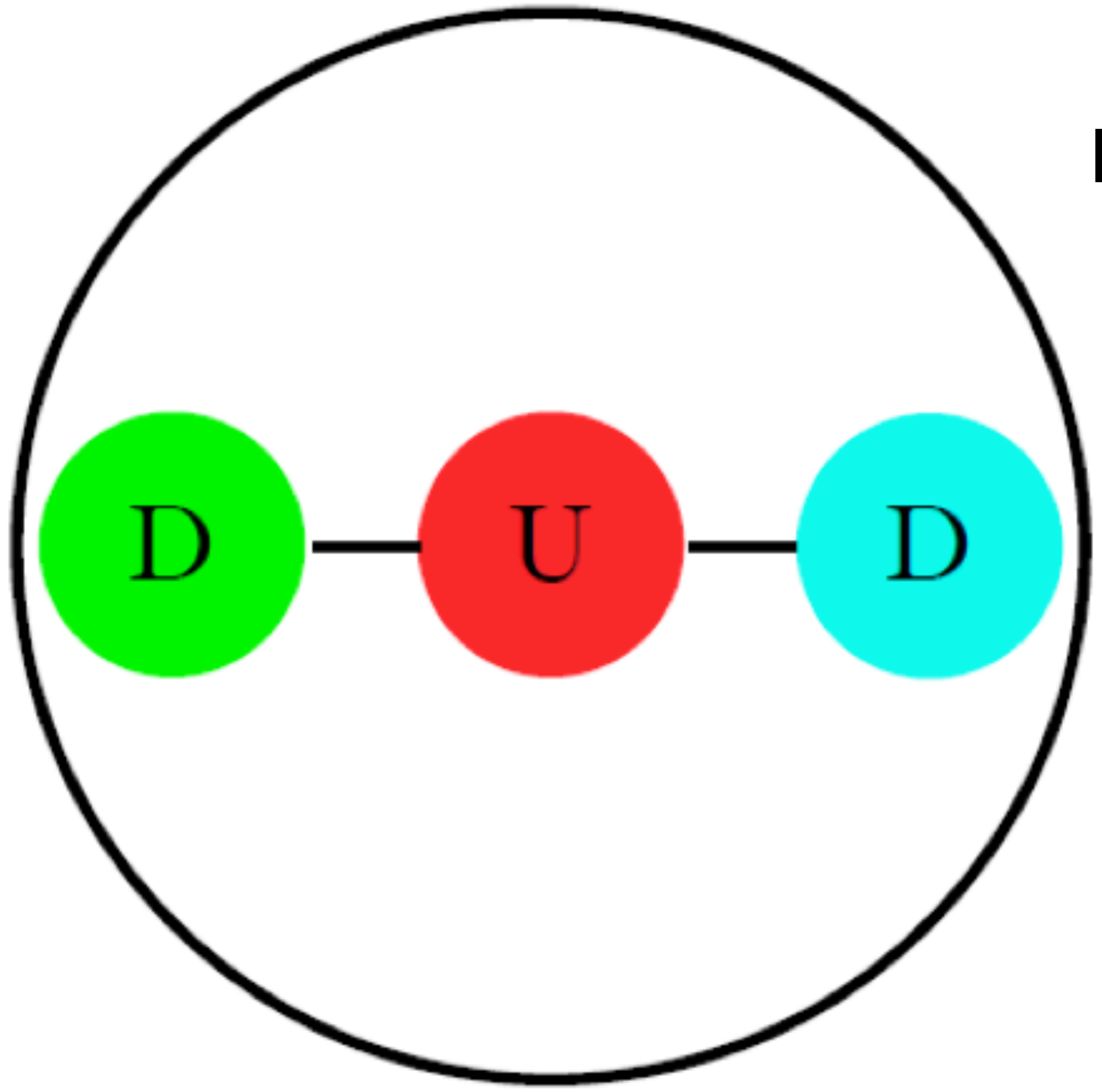
EDM neutron



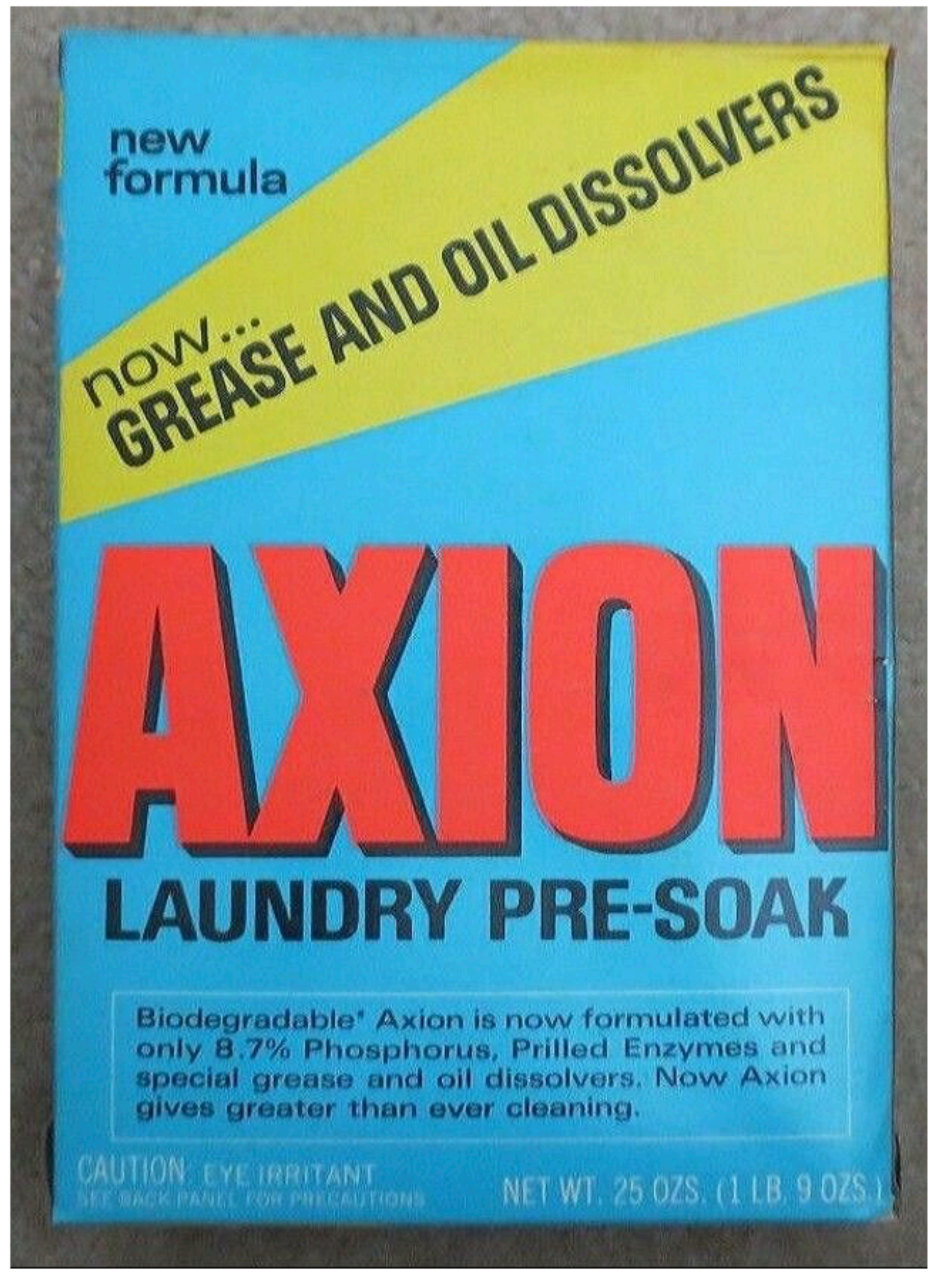
https://arxiv.org/abs/1812.02669

experiment: $d_n < 3\times10^{-26}$ e×cm

$\theta < 10^{-10}$

Why axions?

- 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



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

CP-violating!

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

Promote to particle: $\theta \rightarrow a$

Absorb CP-violating term in

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

Why axions?

- 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 = pseudoscalar pseudo-Nambu-Goldstone bosons arising from approximate Abelian global symmetries beyond the SM which are broken spontaneously at a scale f_a much greater than the electroweak scale

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

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

↓

Promote to particle: $\theta \to a$
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could also be dark matter particle or dark matter mediator…

Axion "band"

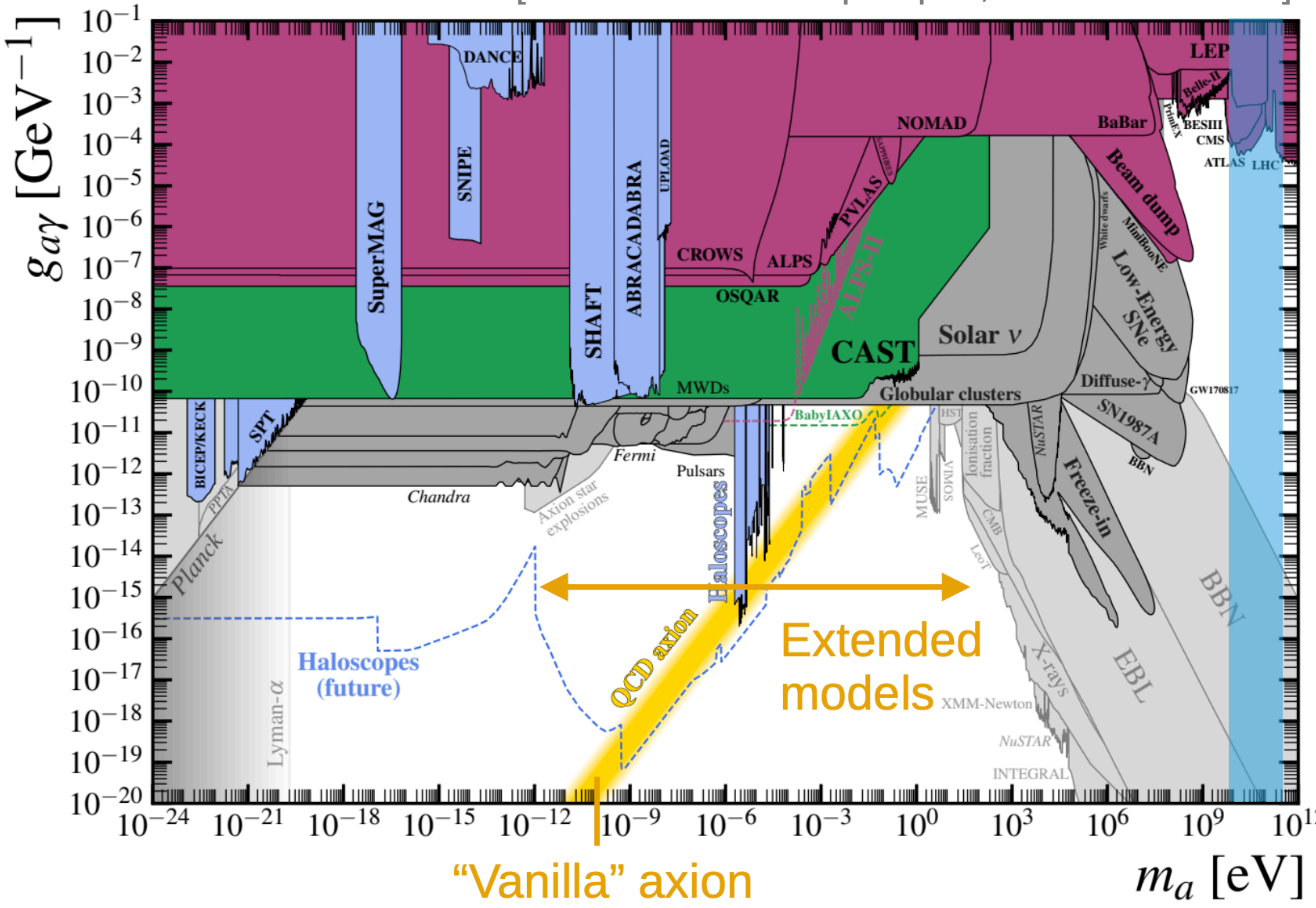
The axion bands can be alternatively changed enlarging the confining sector beyond QCD. New contributions of topologically non-trivial gauge field fluctuations give then additional contributions to the axion mass

- right of the canonical axion band are heavy axion models that solve the strong CP problem at low scales (e.g. $f_a \sim \mathrm{TeV}$)

[Rubakov, 97; Berezhiani et al. 01; Fukuda et al, 01;...]

- This work: focus on large masses O(0.1 – 1 TeV)

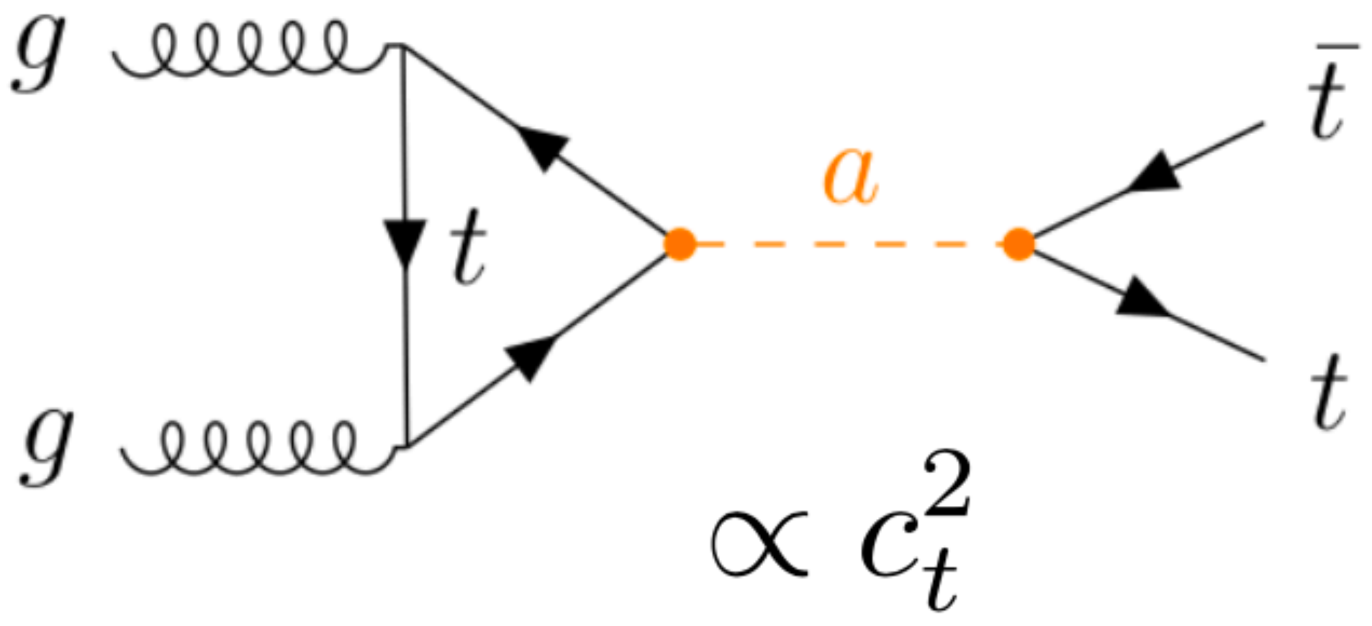
[FIPs 2022 Workshop Report, arXiv:2305.01715]



Search for ALPs in top pair production

- 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



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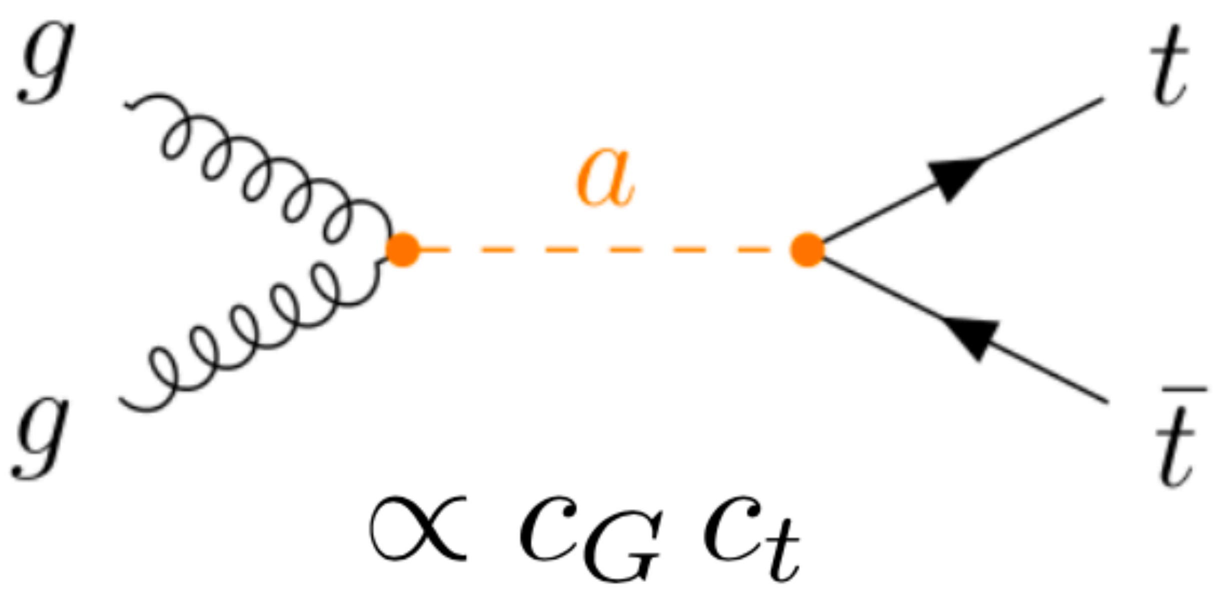
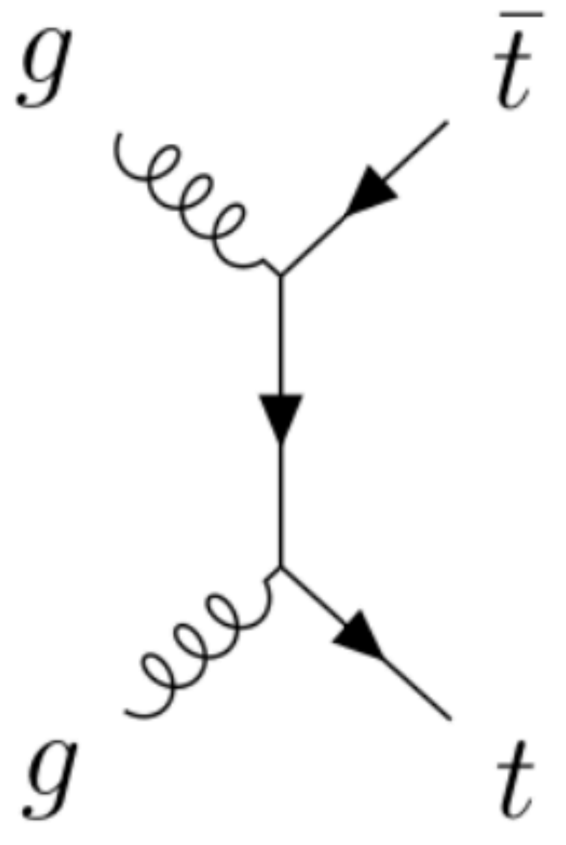


SM

+



+ ...

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

Explicit gluon coupling - physics at high scales integrated out

ALPs vs pseudoscalar Higgs bosons

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

ALP

top quark
$$\mathcal{L}_{ALP} = \frac{\partial_\mu a}{f_a} \sum_{\psi = Q_L, Q_R,} \bar{\psi}\gamma_\mu X_\psi \psi$$

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

$$+ \text{other fermions}$$

$$+ \text{EW bosons}$$

Pseudoscalar Higgs (e.g. 2HDM)

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

$$+ \text{other fermions}$$

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ALP

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

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

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Pseudoscalar Higgs (e.g. 2HDM)

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

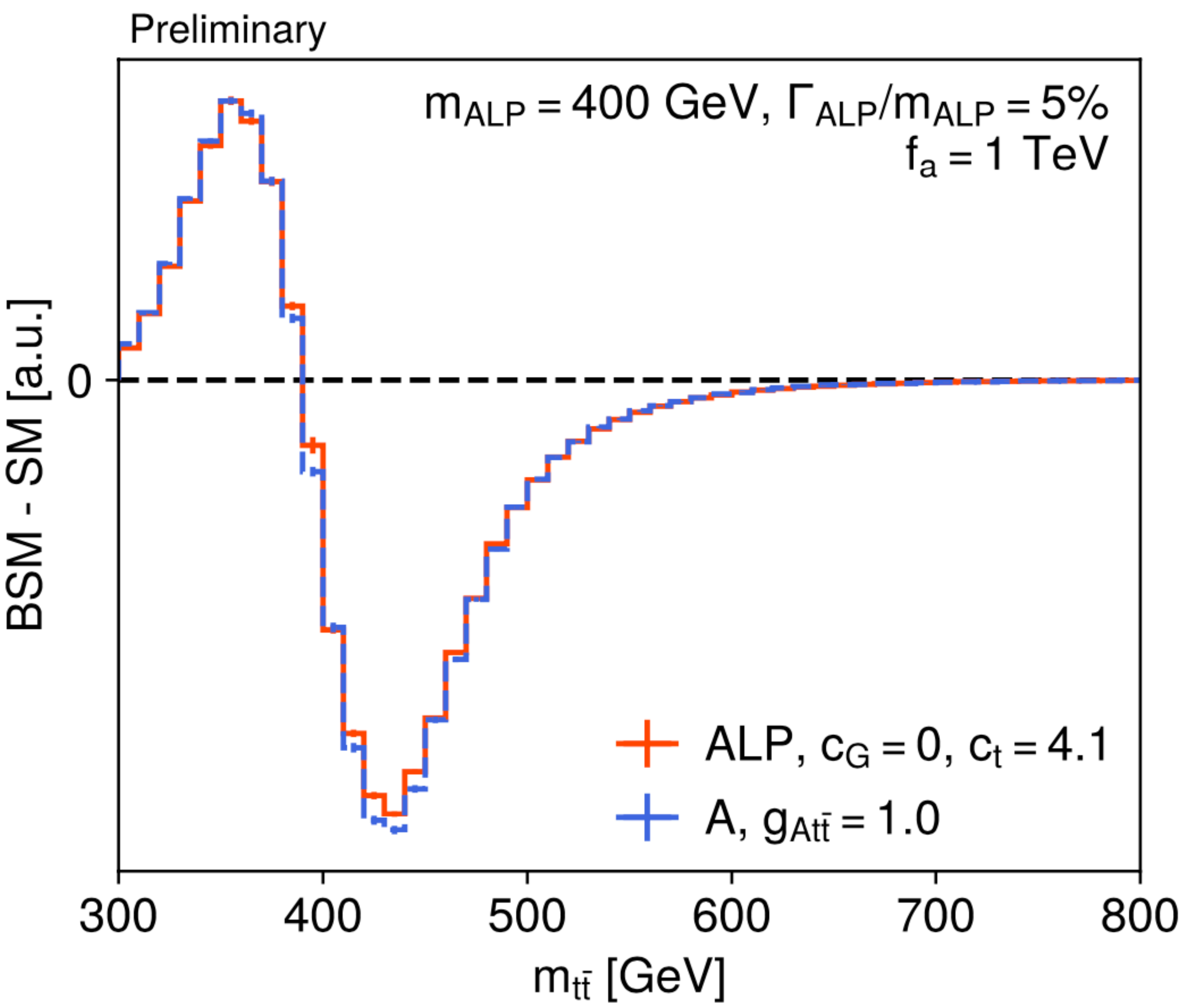
$$+ \text{other fermions}$$

Top quark coupling can be rewritten to be identical!

Search for ALPs without gluon coupling

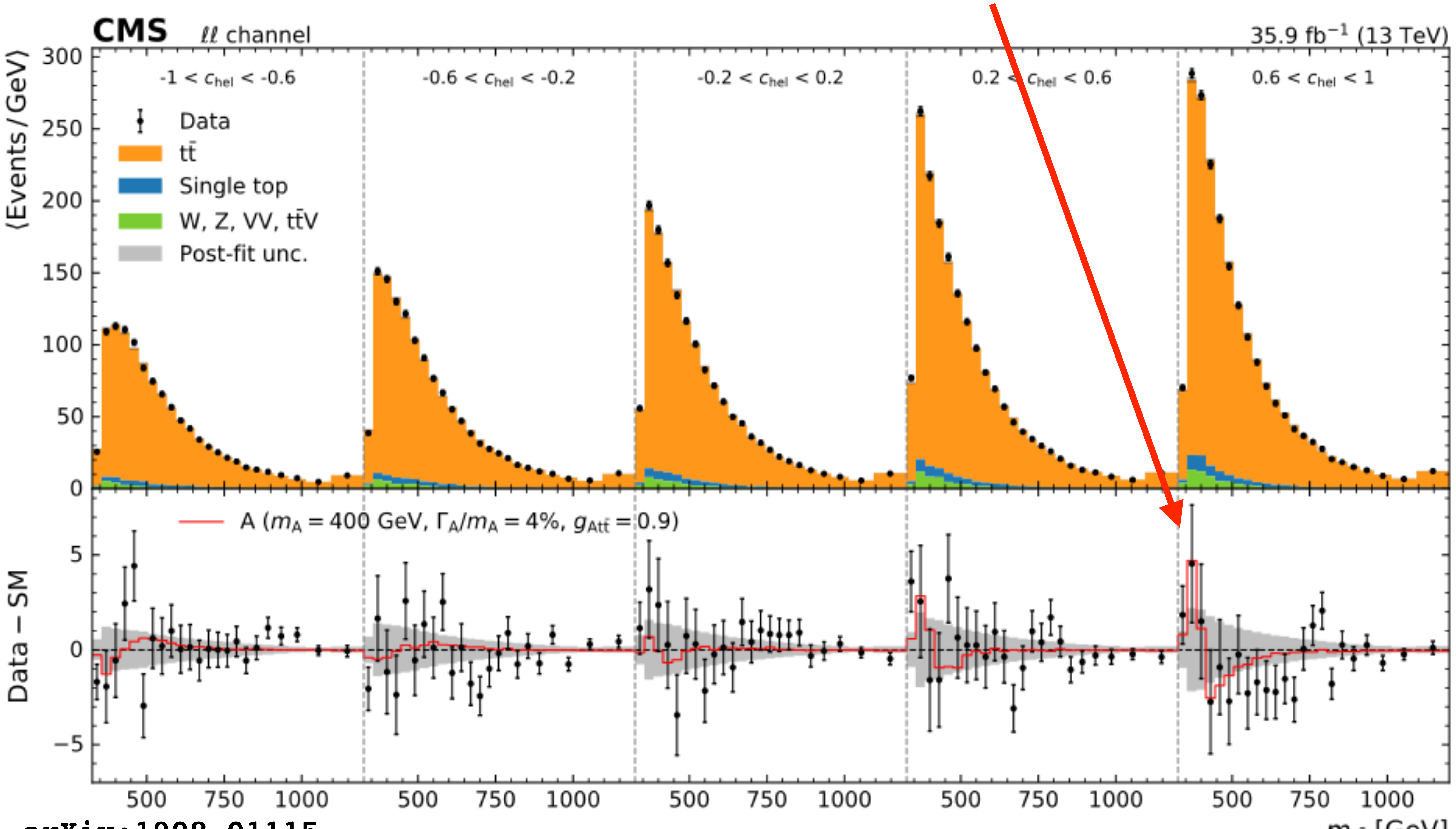
- Invariant $t\bar{t}$ mass distribution for ALP and pseudoscalar Higgs (A)
  - Dileptonic decay of $t\bar{t}$
  - Truth level top quark reconstruction
  - Gaussian smearing (σ = 7.5%) to model detector response
- For ALP with $c_G = 0$: identical to Higgs

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



Search for heavy pseudoscalar Higgs bosons

pseudoscalar, m_A=400 GeV, $\Gamma_A=0.04 \cdot m_A$

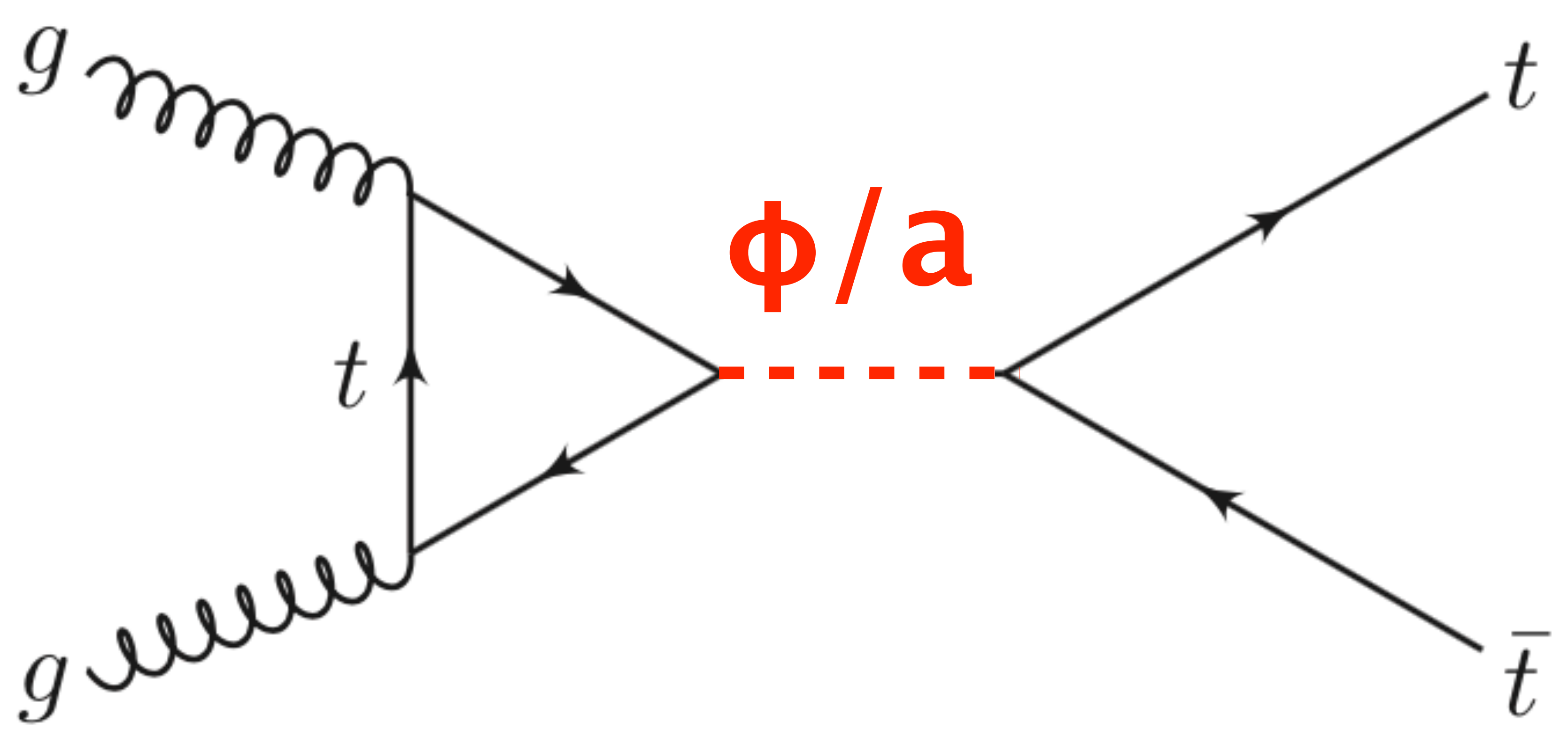


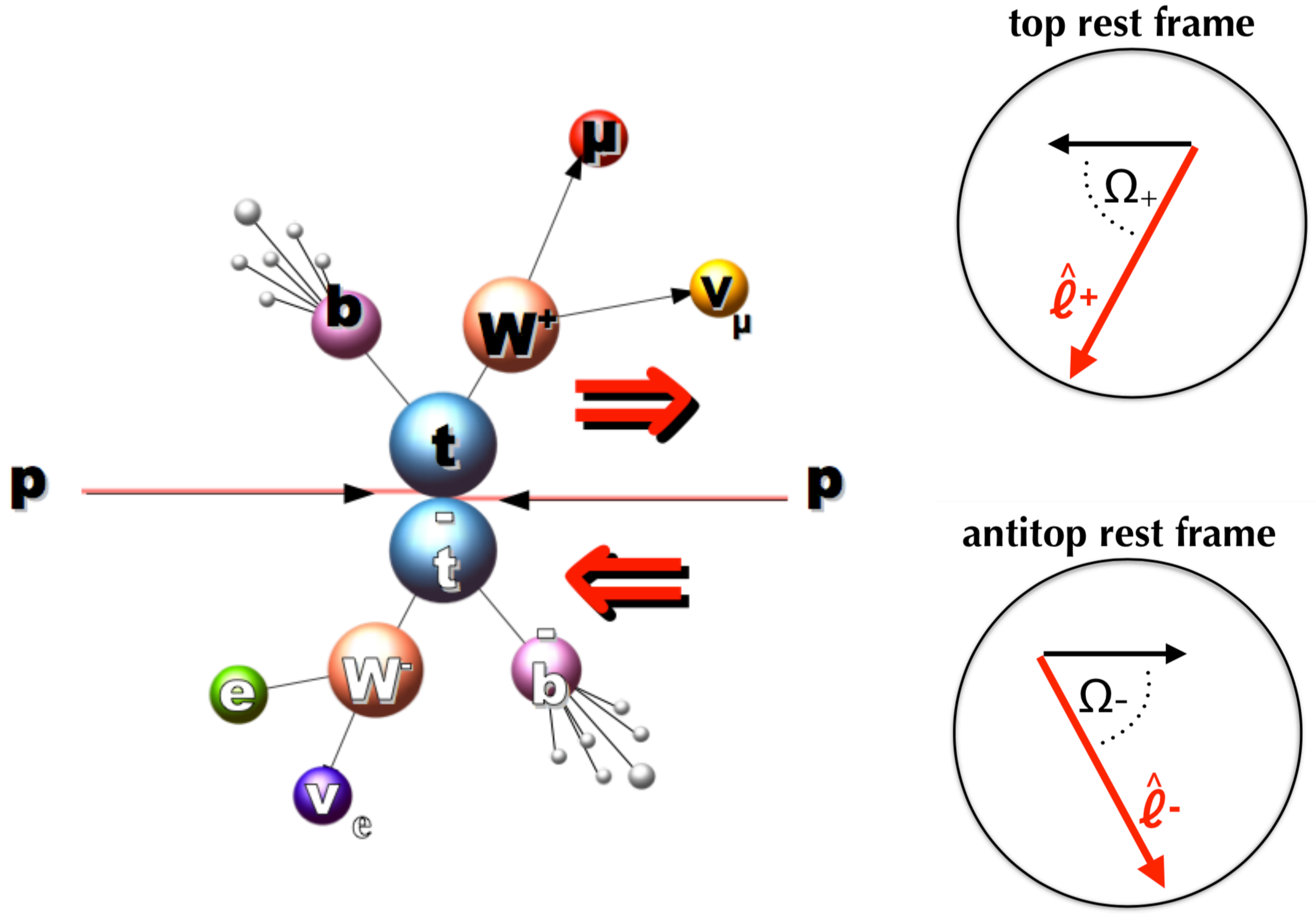
arXiv:1908.01115

$$c_{\text{hel}} = \cos\varphi = \hat{\ell}^{+} \cdot \hat{\ell}^{-}$$

→ **increased sensitivity of up to 30%**

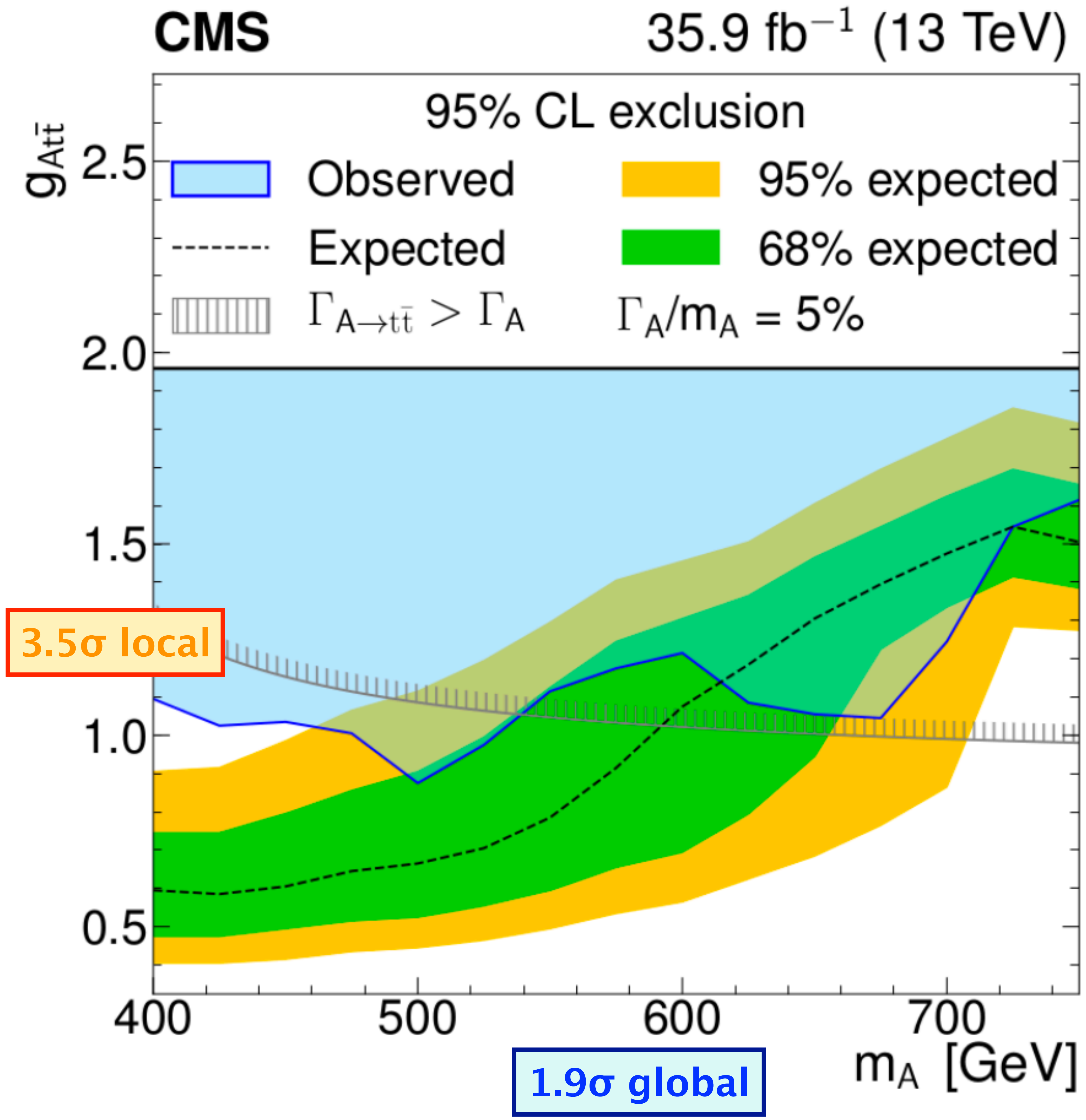
Dark Matter mediator production





Search for a heavy pseudoscalars

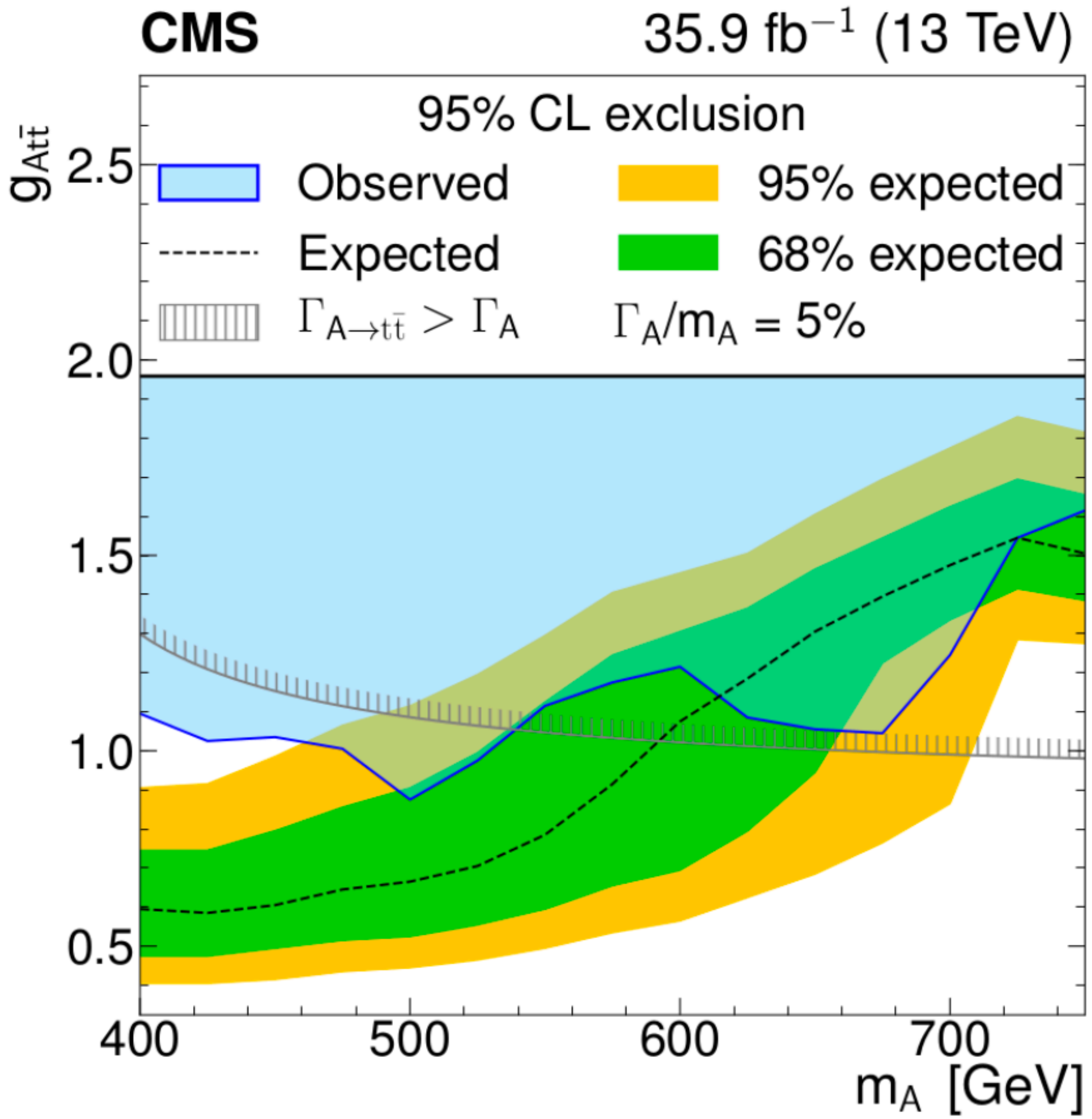
Pseudoscalar Higgs
[CMS arXiv:1908.01115]



- 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 3.5σ local (1.9σ global) excess at m_A = 400 GeV and 4% width

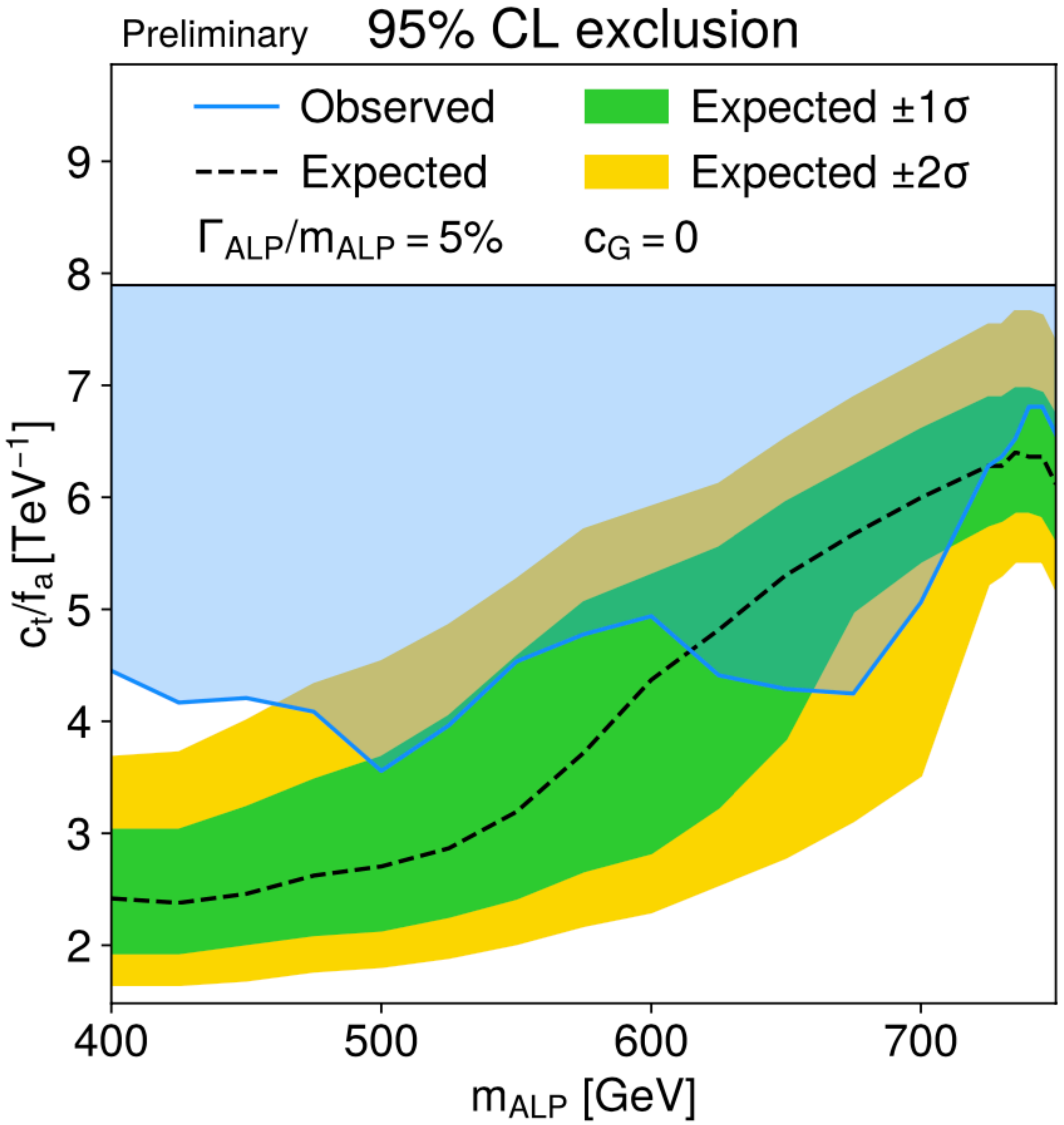
Limits on ALPs without gluon coupling

Pseudoscalar Higgs
[CMS arXiv:1908.01115]



Translation factor $\frac{1}{\text{vev}}$

Axion-Like Particle
with $c_G = 0$



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

$$+ \text{other fermions}$$

$$+ \text{EW bosons}$$

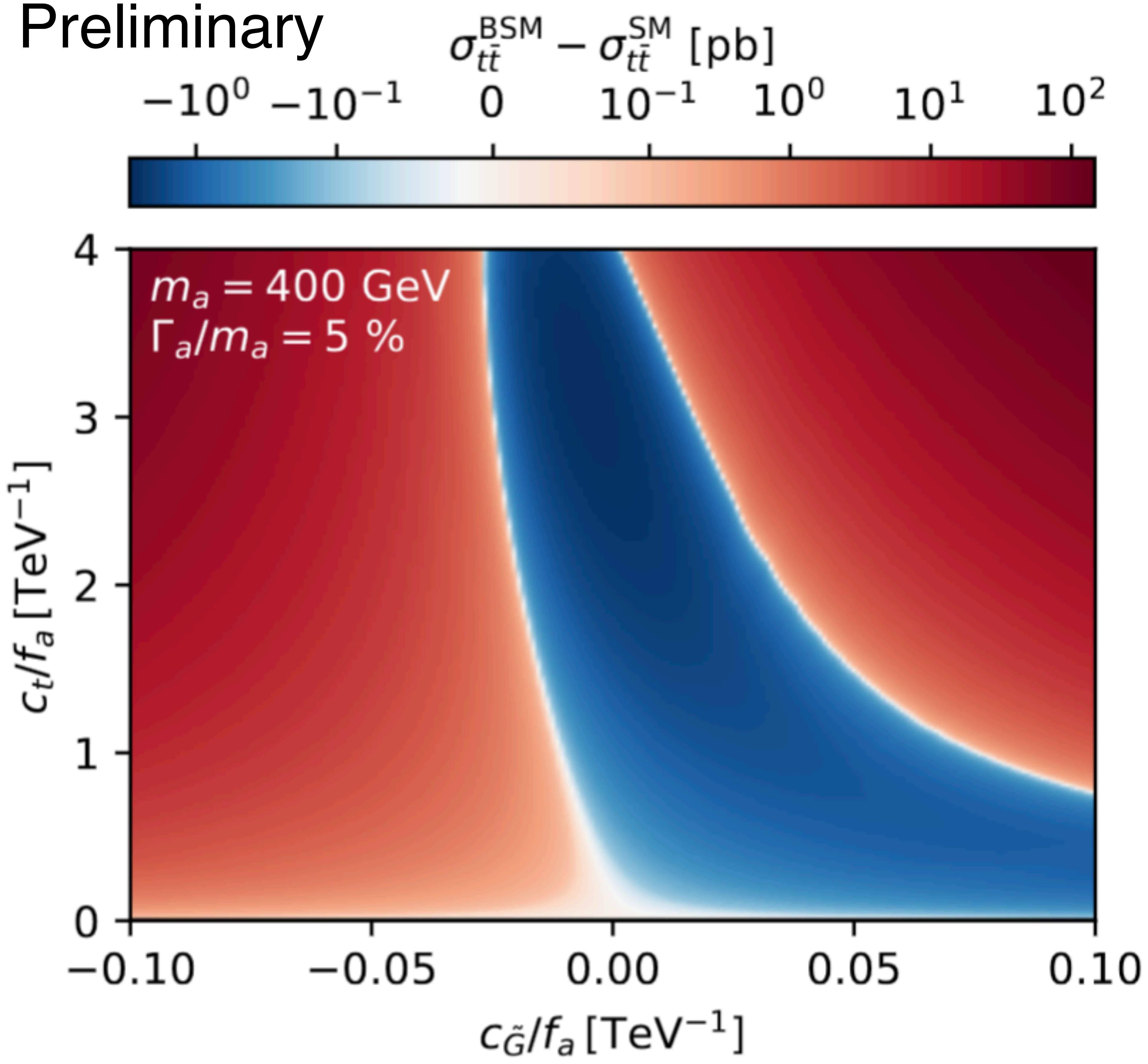
Pseudoscalar Higgs (e.g. 2HDM)

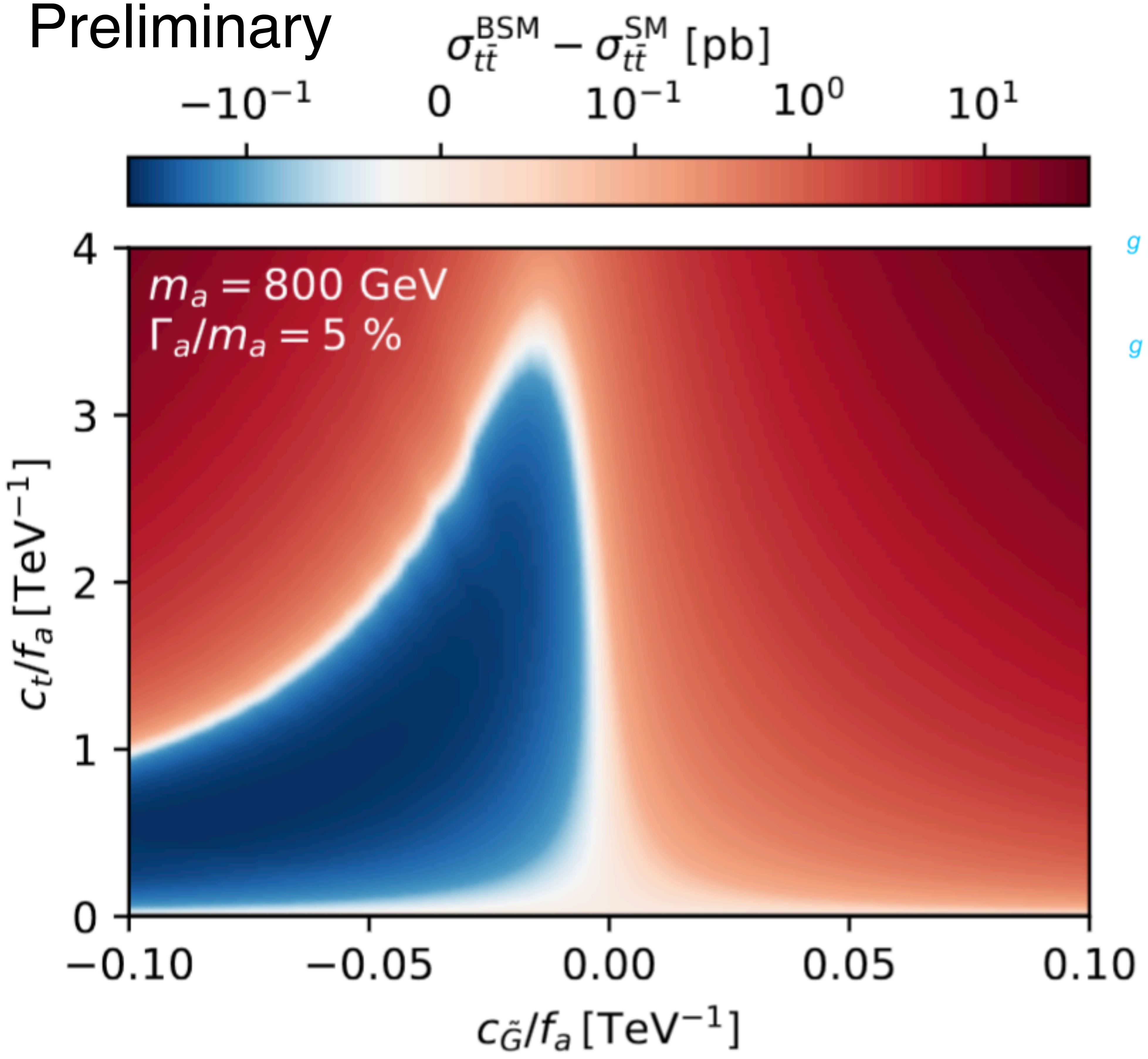
$$\mathcal{L}_A = i g_{At\bar{t}} \frac{m_t}{v}(\bar{t}\gamma^5 t) A$$ top quark

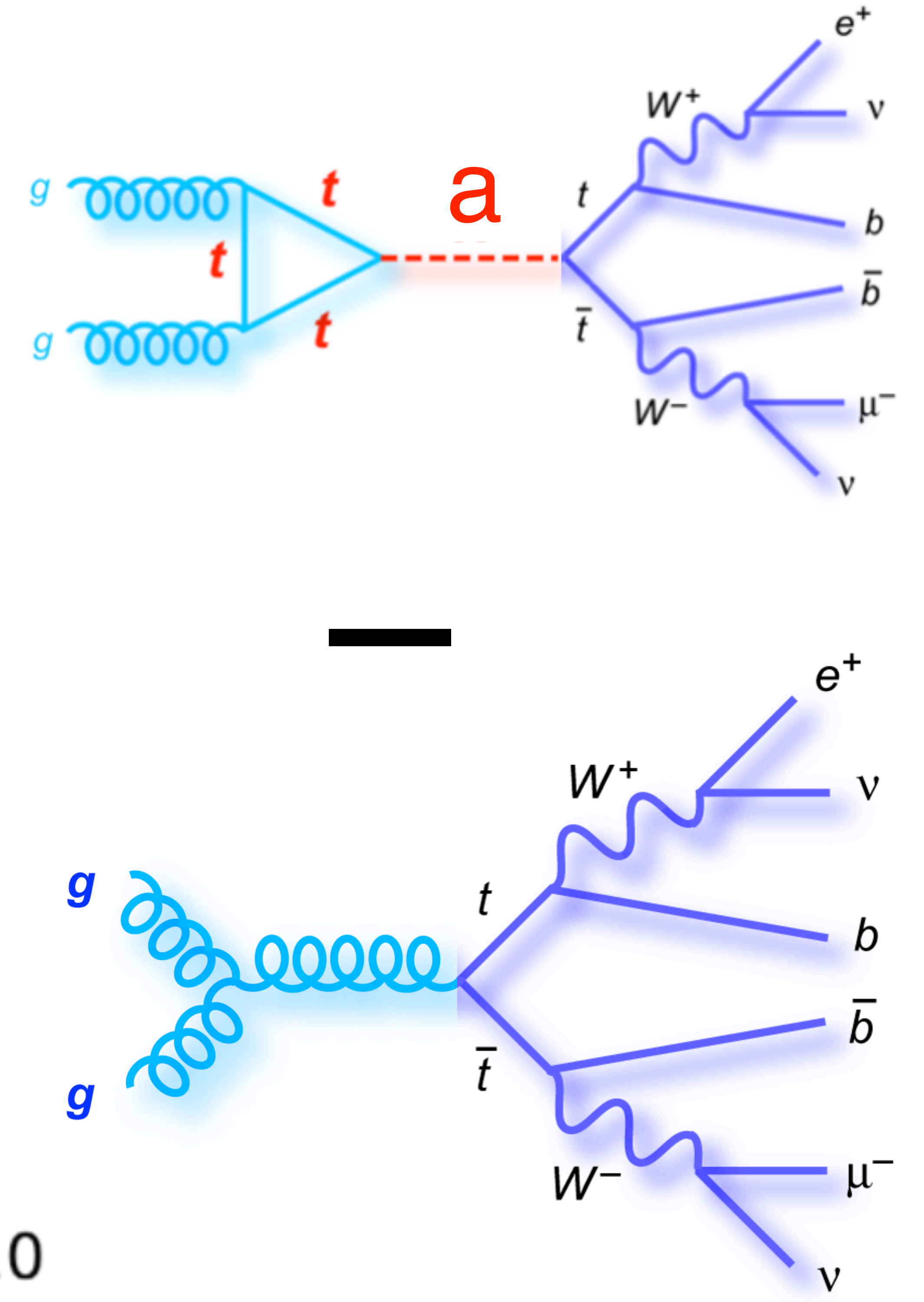
$$+ \text{other fermions}$$

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

Cross section for ALPs with gluon and top couplings



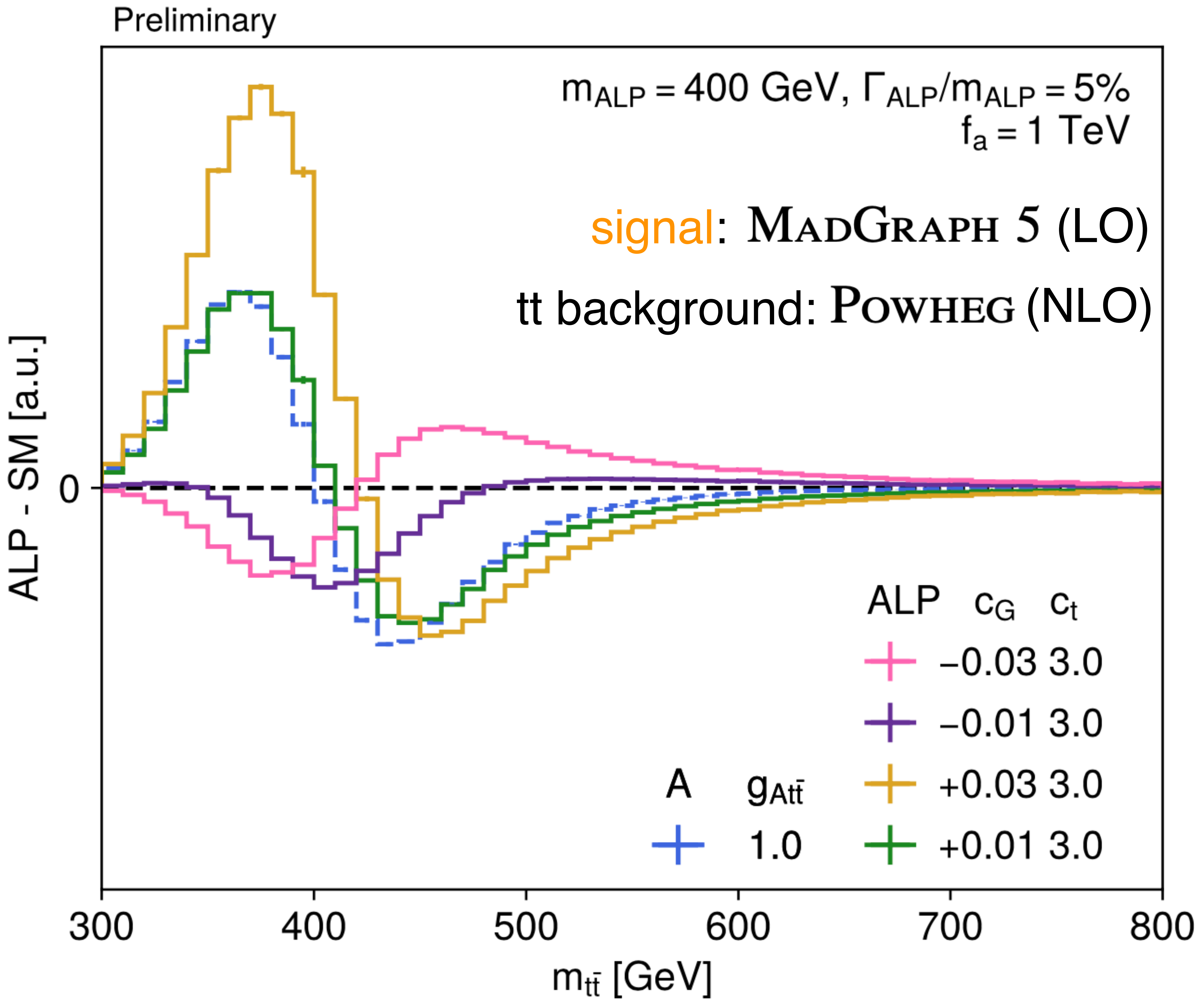




difference in the dileptonic pp → $t\bar{t}$ cross section between the ALP model (including resonance and interference) and the SM

Search for ALPs with gluon and top couplings

- For $c_G \neq 0$, shapes in m_{tt} differ from simple pseudoscalar!
- Sensitive to relative sign of c_G and c_t:
  - For same sign: different form of "peak"
  - For opposite sign: "dip-peak" or pure "dip"
- Can we distinguish ALP and e.g. 2HDM Higgs for $c_G \neq 0$?

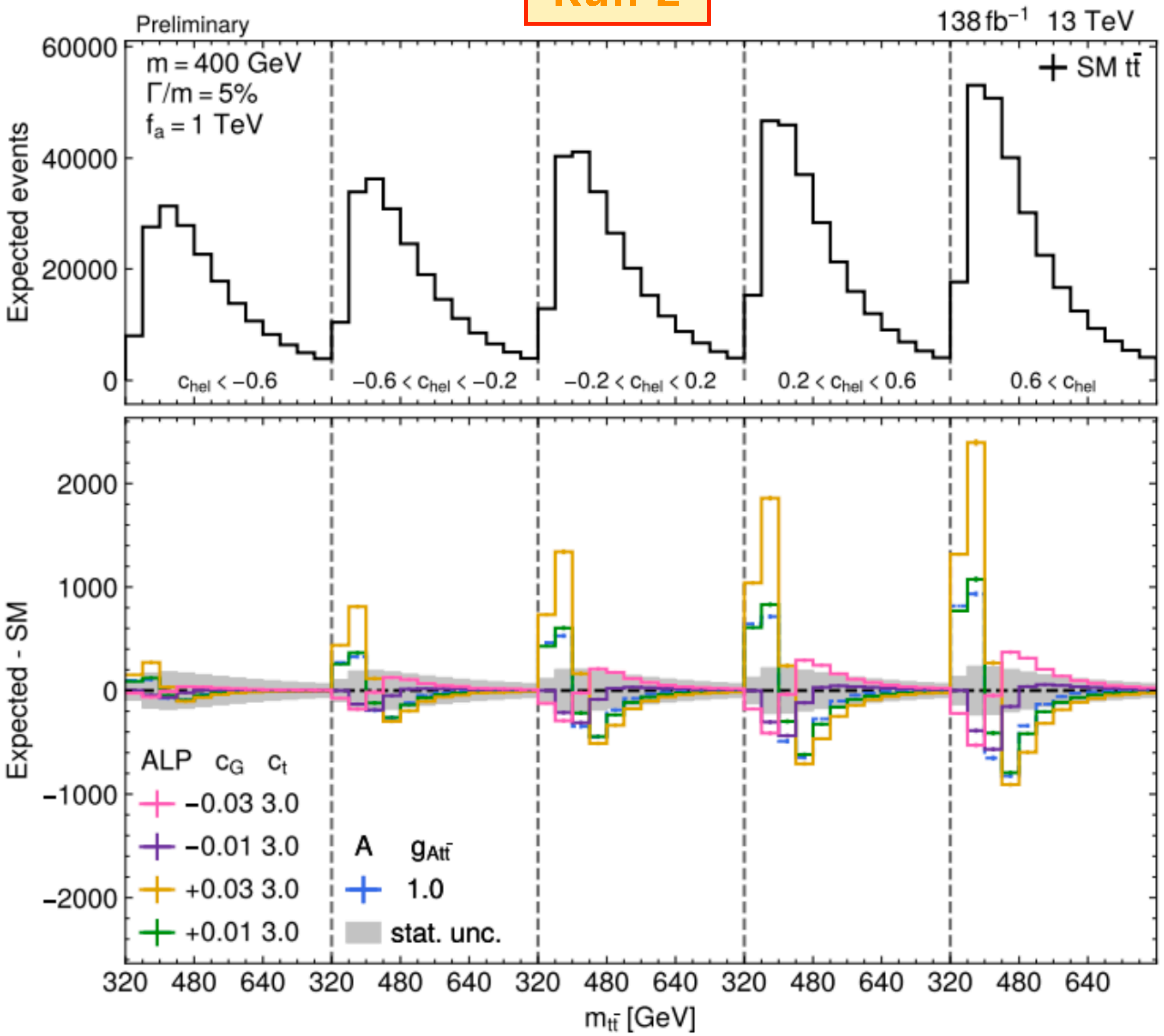


Distinguishing ALPs from pseudoscalar Higgs

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})

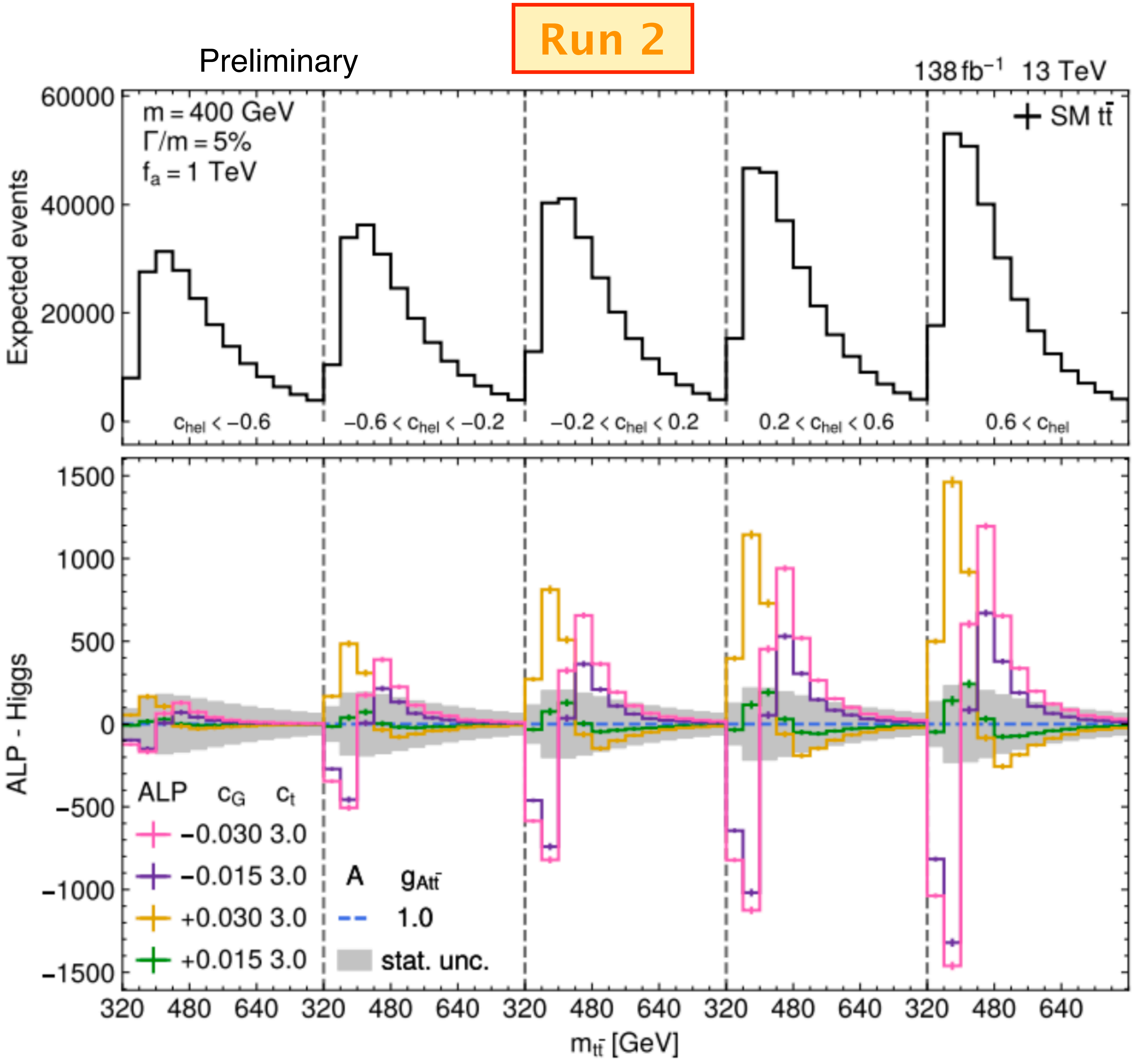
Run 2



Distinguishing ALPs from pseudoscalar Higgs

ALP with $c_G \neq 0$

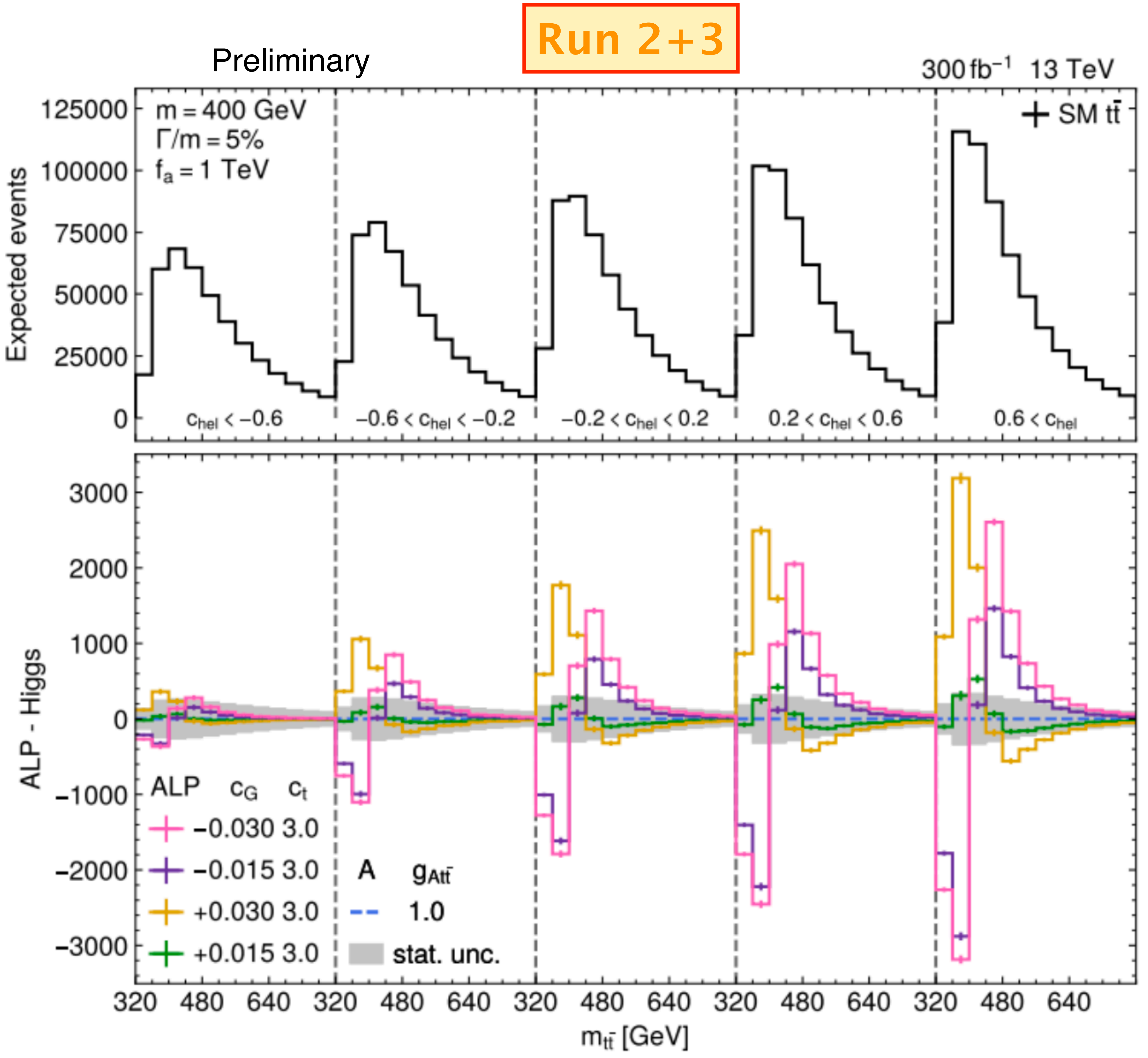
- Difference of ALP with $c_G \neq 0$ and Higgs / ALP for $c_G = 0$
- E.g. opposite signs of c_G and c_t difference might already be observable with LHC Run 2!



Distinguishing ALPs from pseudoscalar Higgs

ALP with $c_G \neq 0$

- Projection to higher luminosity: LHC Run 2 + 3 ~ 300 fb^{-1}

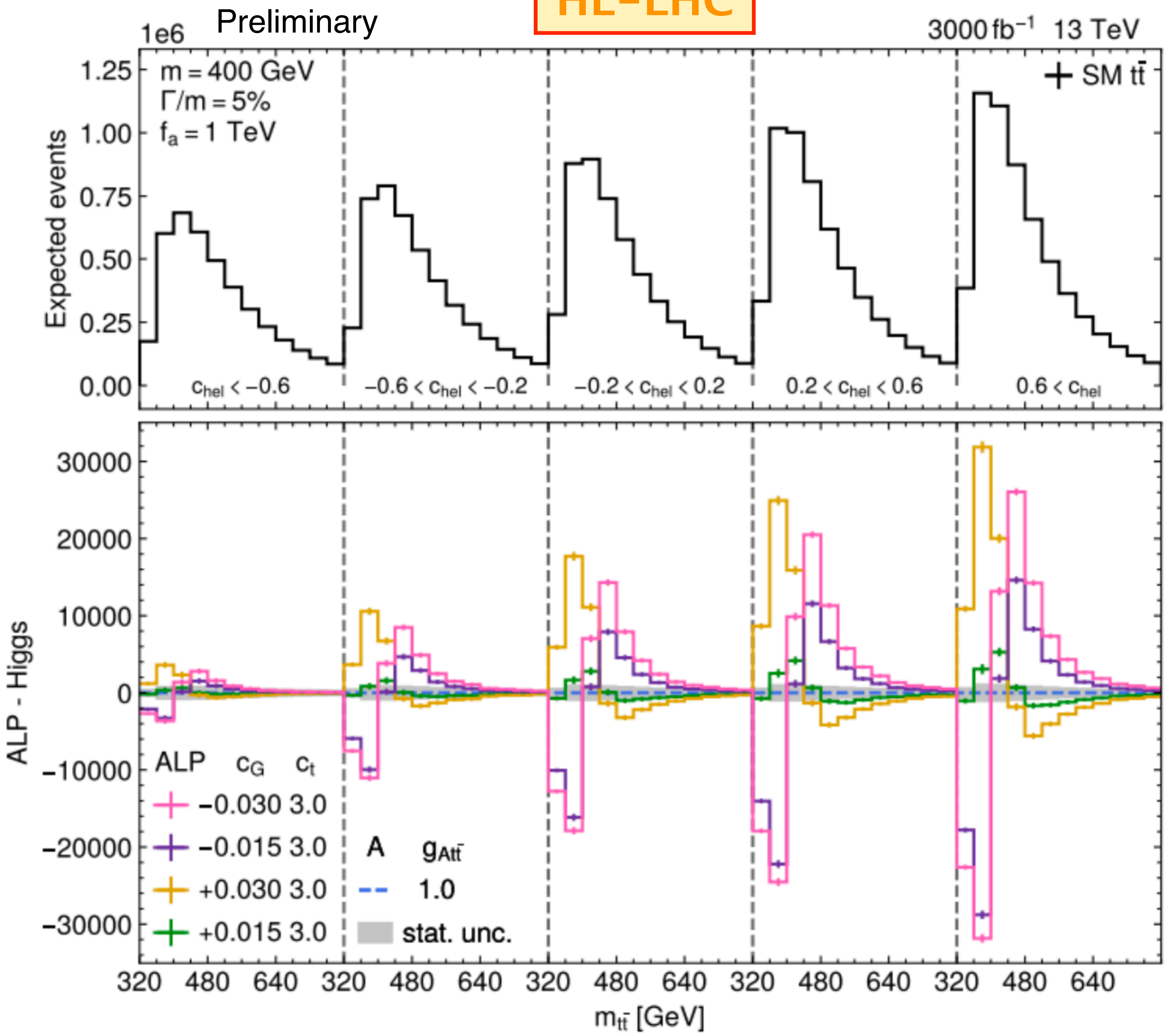


Distinguishing ALPs from pseudoscalar Higgs

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!

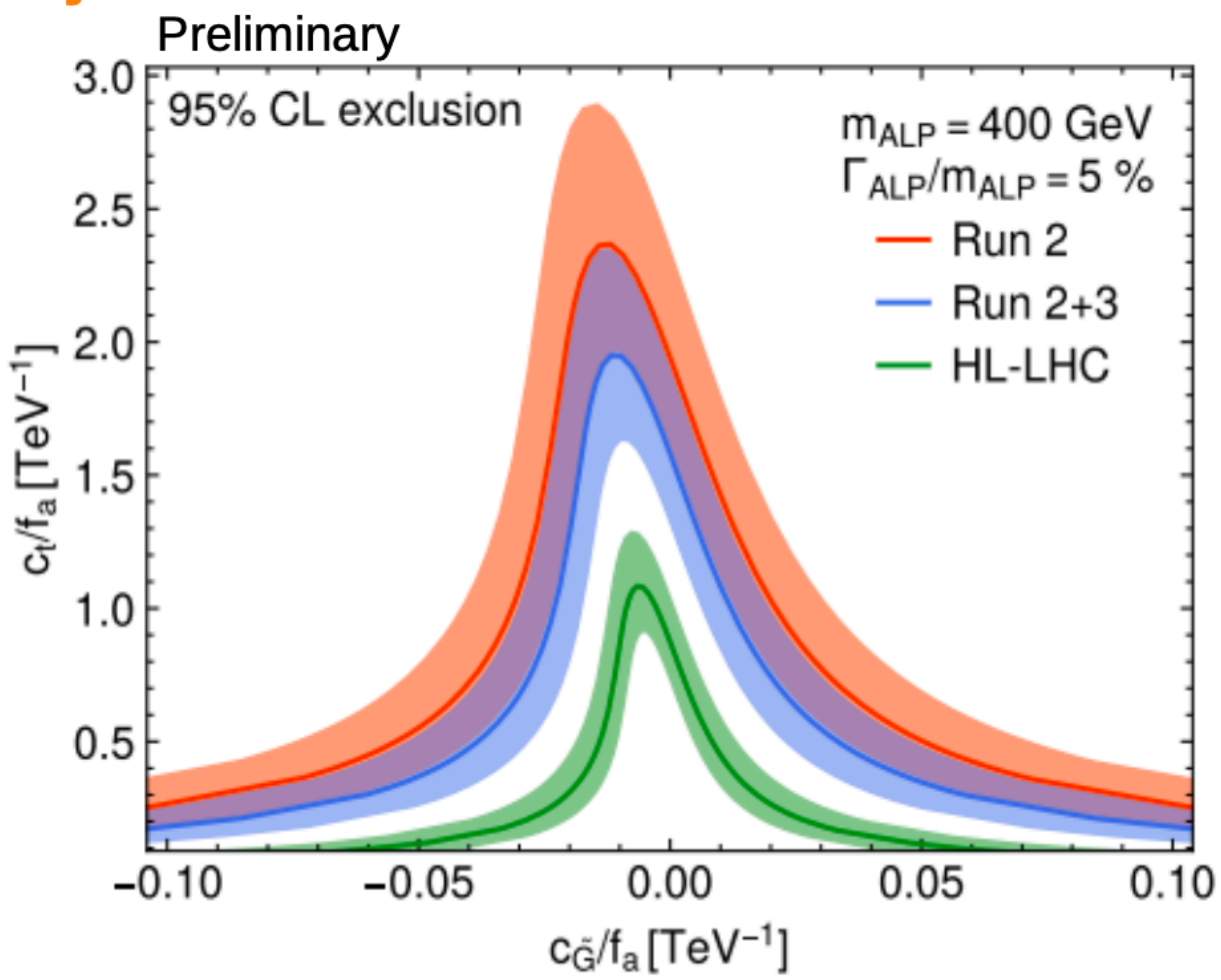
HL-LHC

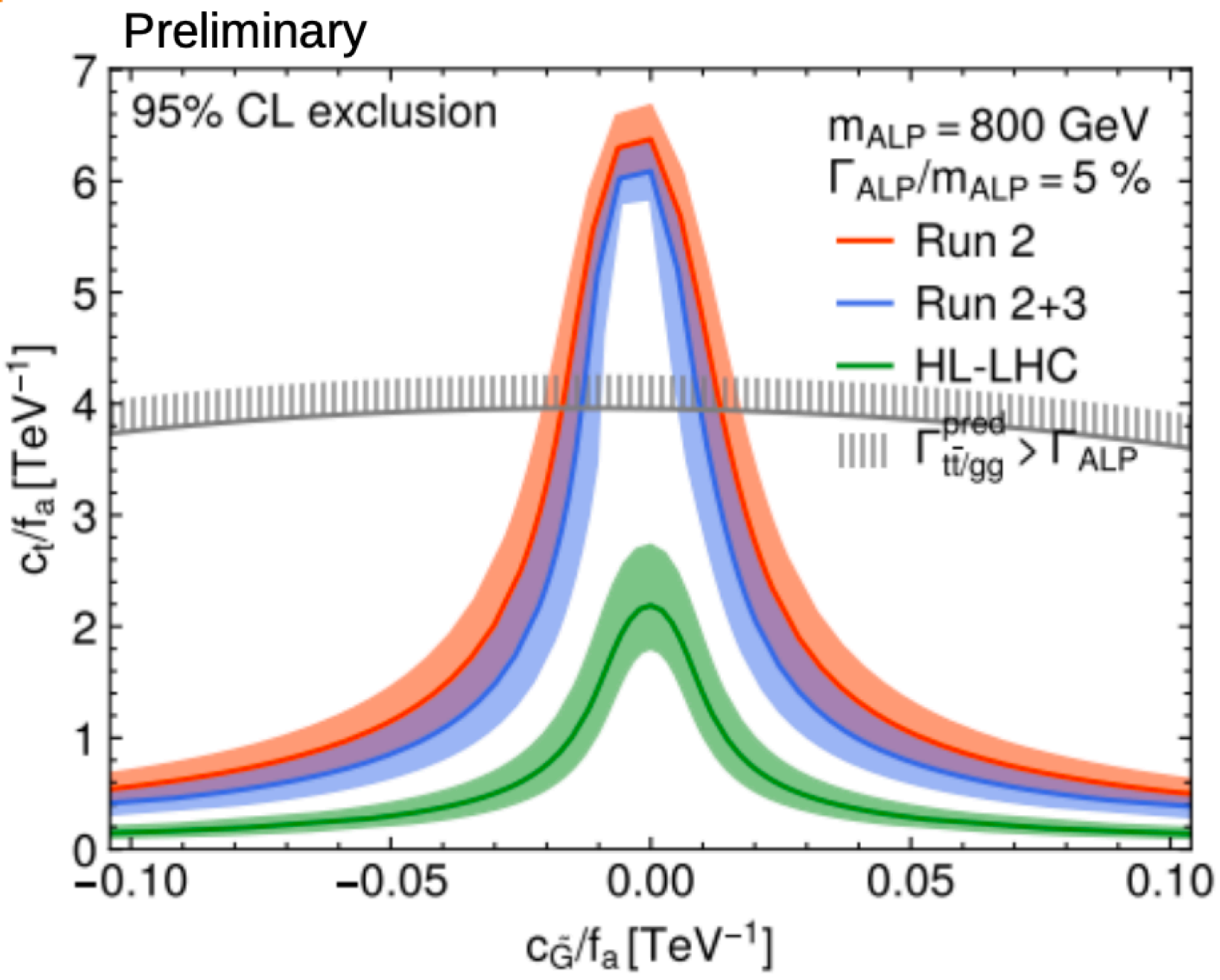


Expected constraints on ALPs couplings

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

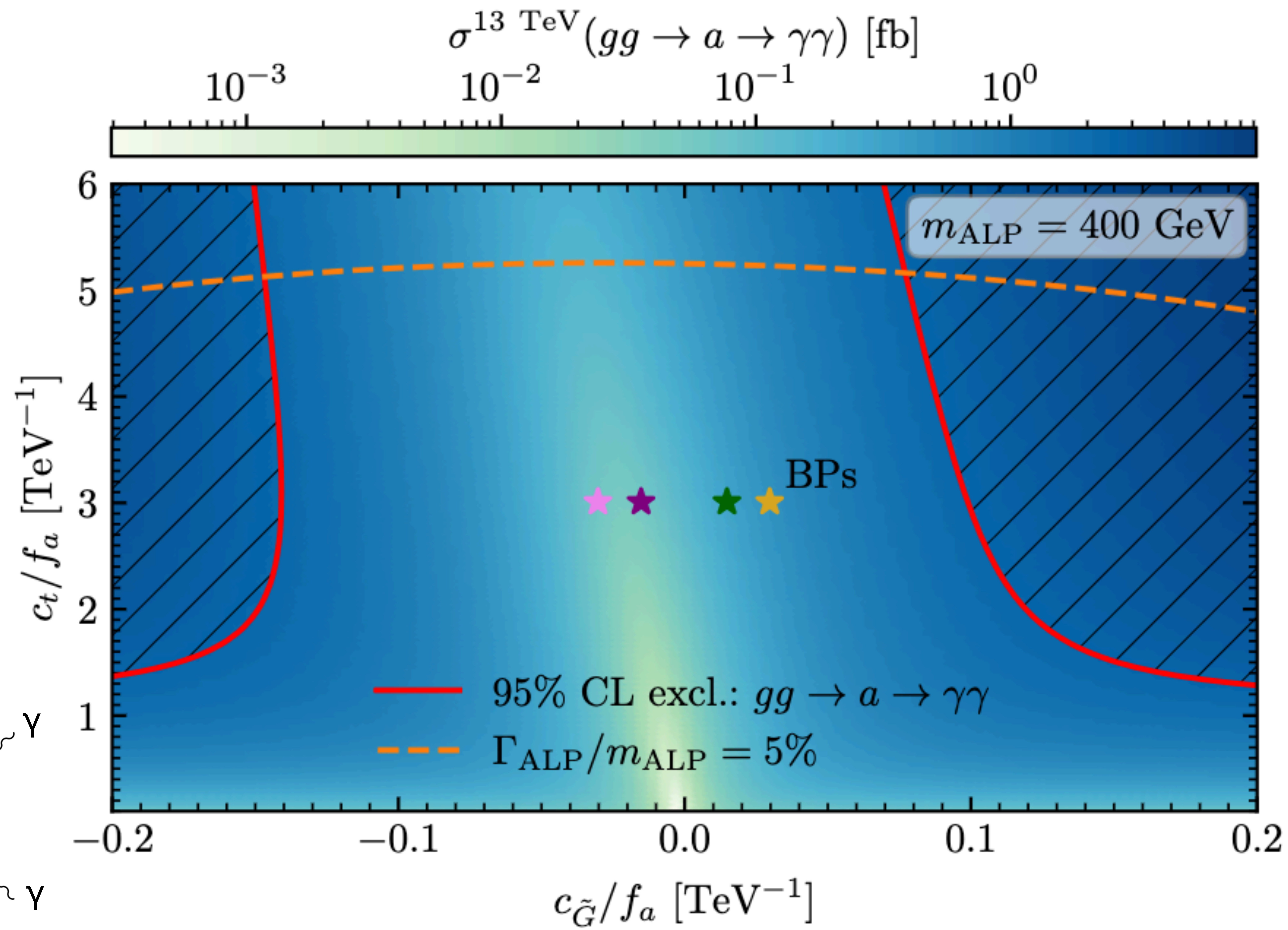
➔ Projected limits for ALPs in the c_t - c_G plane!

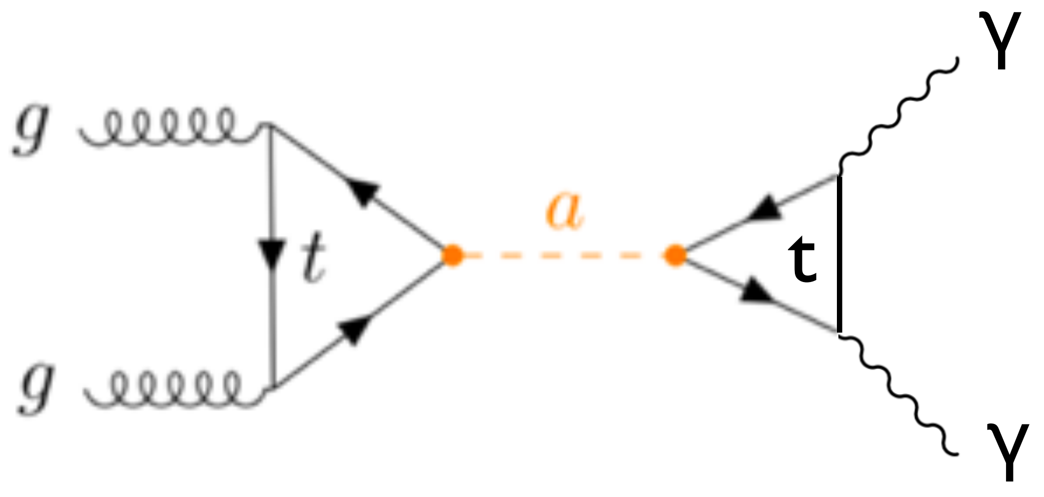




Comparison to other LHC constraints

ATLAS searches for narrow resonances decaying into photon pairs





benchmark points (BPs):

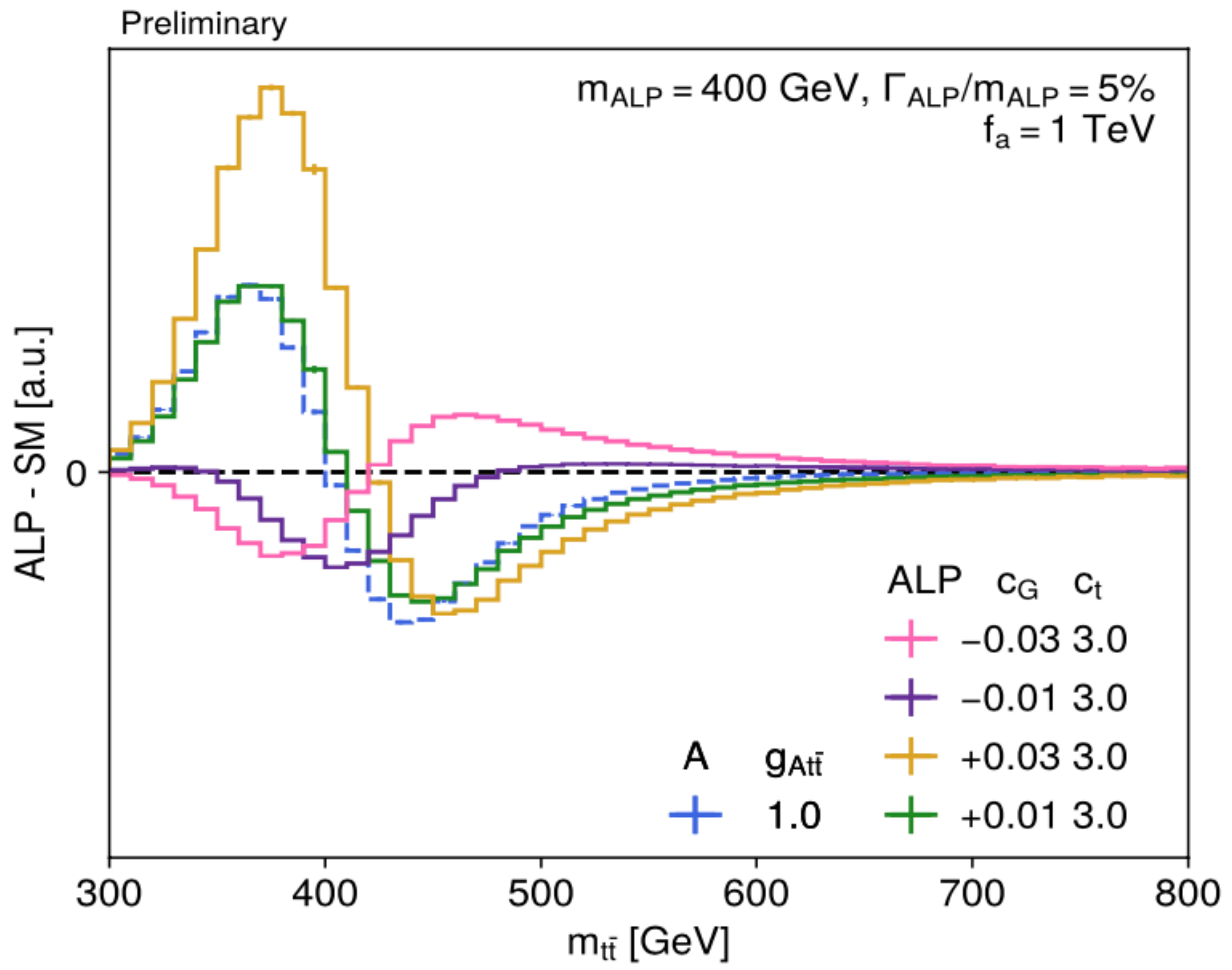
ALP	c_G	c_t
+ (pink)	−0.03	3.0
+ (purple)	−0.01	3.0
+ (gold)	+0.03	3.0
+ (green)	+0.01	3.0

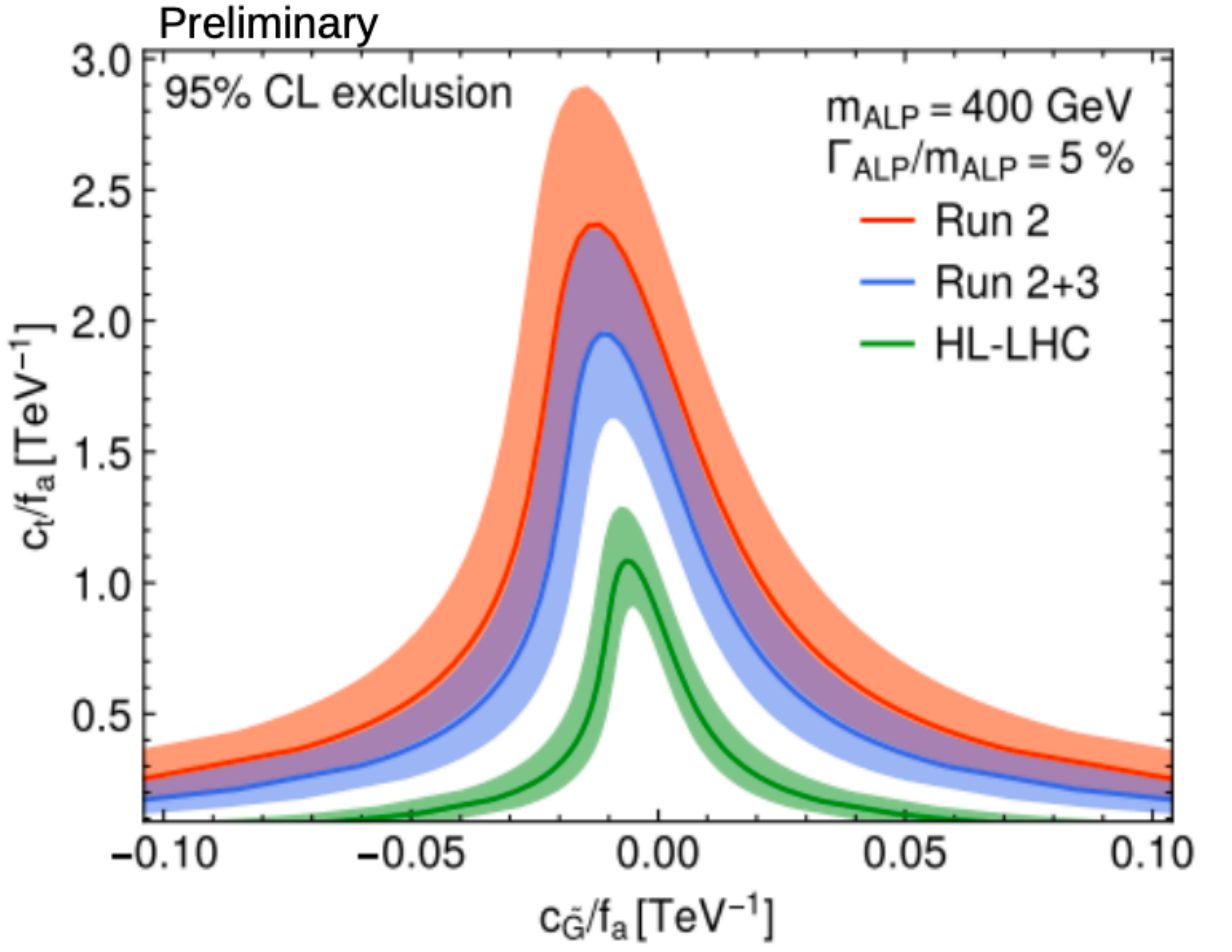
Summary

Heavy axions might be able to solve strong CP problem and could be Dark Matter particles/mediators

- Heavy ALPs can be searched for in $t\bar{t}$ final states at the LHC
- Compared ALPs to an additional pseudoscalar Higgs boson (e.g. 2HDM):
  - 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!

→ Expected constraints on ALPs couplings and compared to other photon constraints

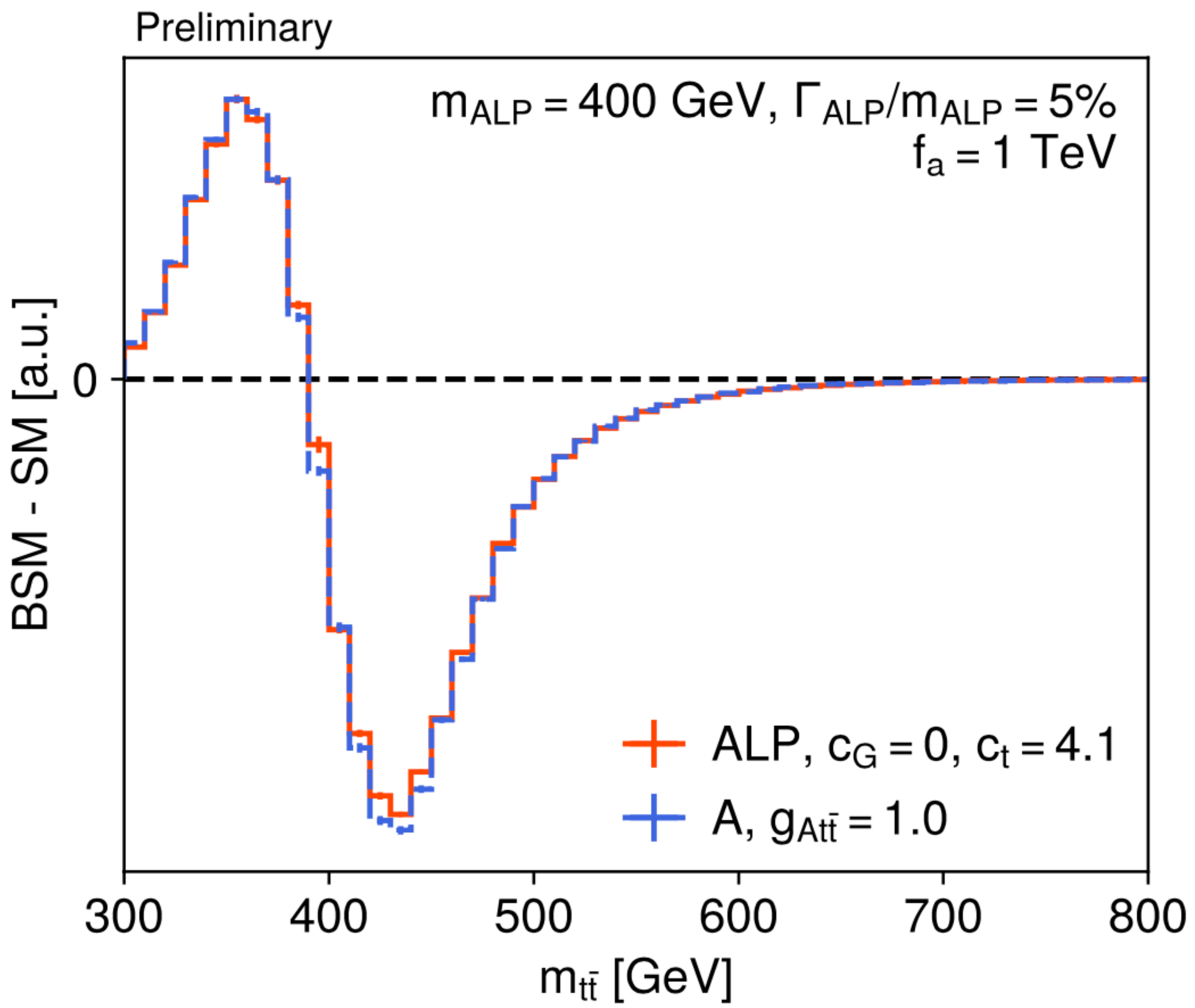




Backup

Technical Details

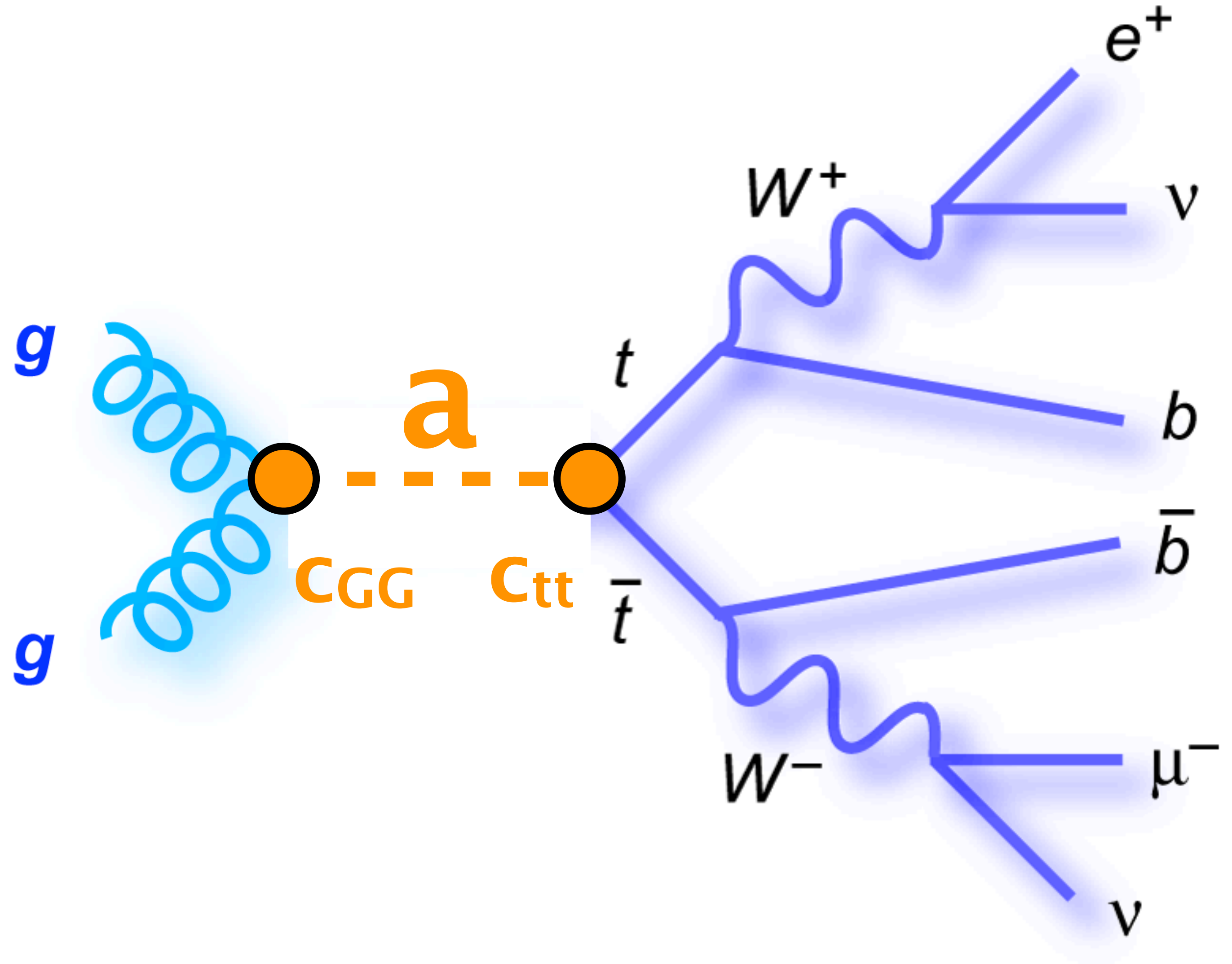
- Generator: MadGraph 5 at LO, showered with Pythia 8
- Resonance and interference terms generated seperately
- Reconstruct top quarks at truth level
- Apply Gaussian smearing ($\sigma = 7.5\%$) to model detector response in an experiment

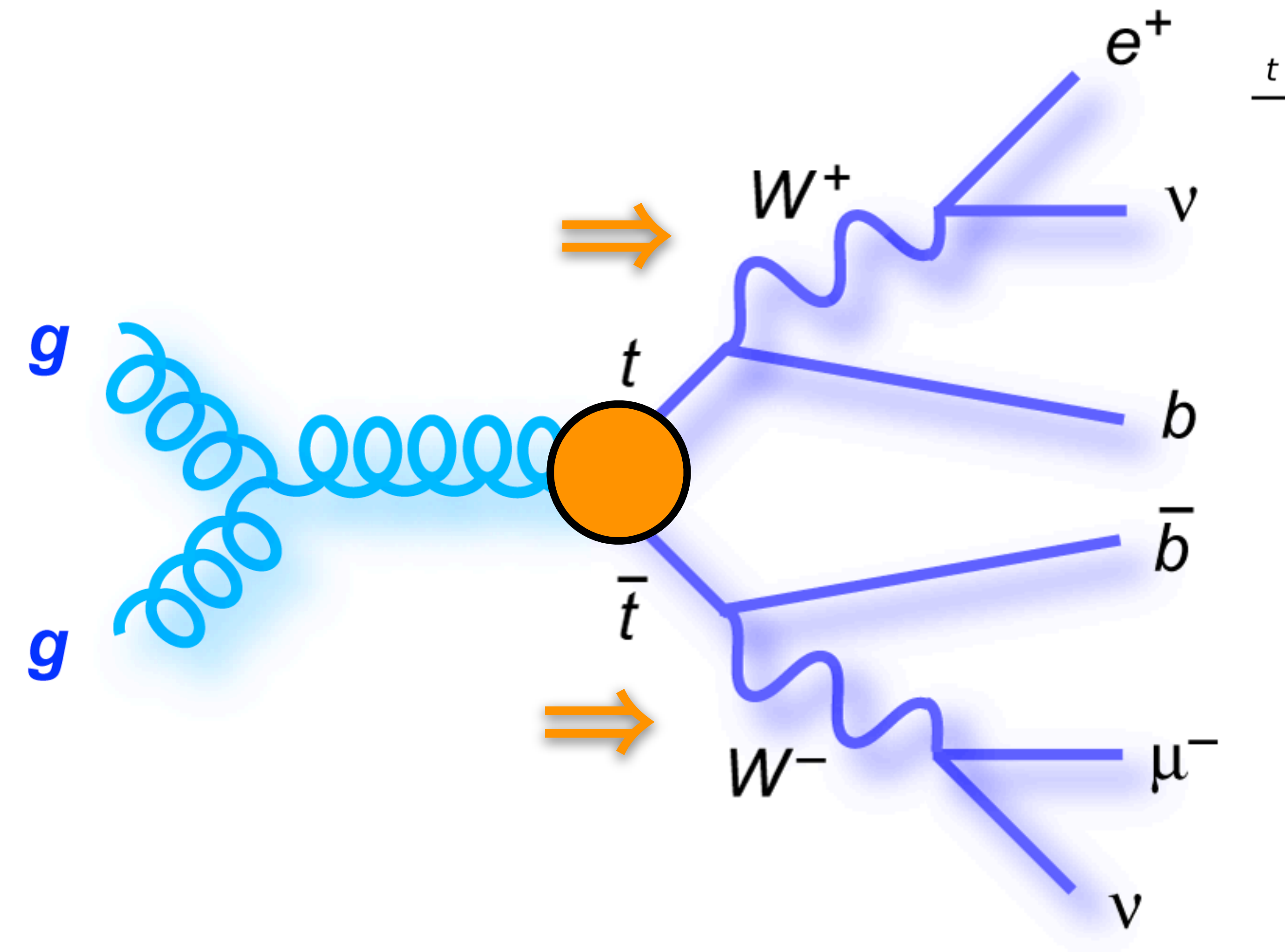


Considered systematic uncertainties

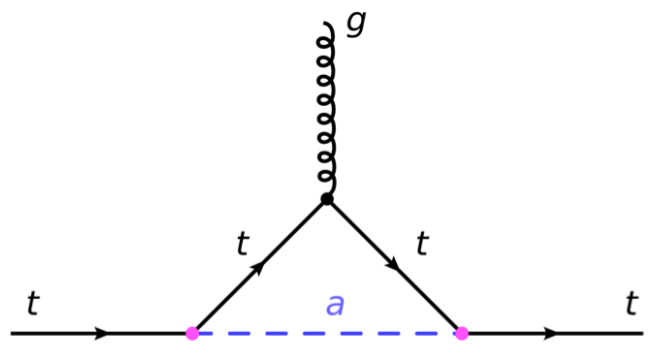
- Systematics are implemented as nuisance parameters with shape effects in the likelihood fit
- Uncertainties on both signal and SM $t\bar{t}$ background:
  - Renormalization and factorization scales: varied by 0.5 / 2.0 independently
  - PDF: 100 replicas for the NNPDF 3.1 set
- Uncertainties on the 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)

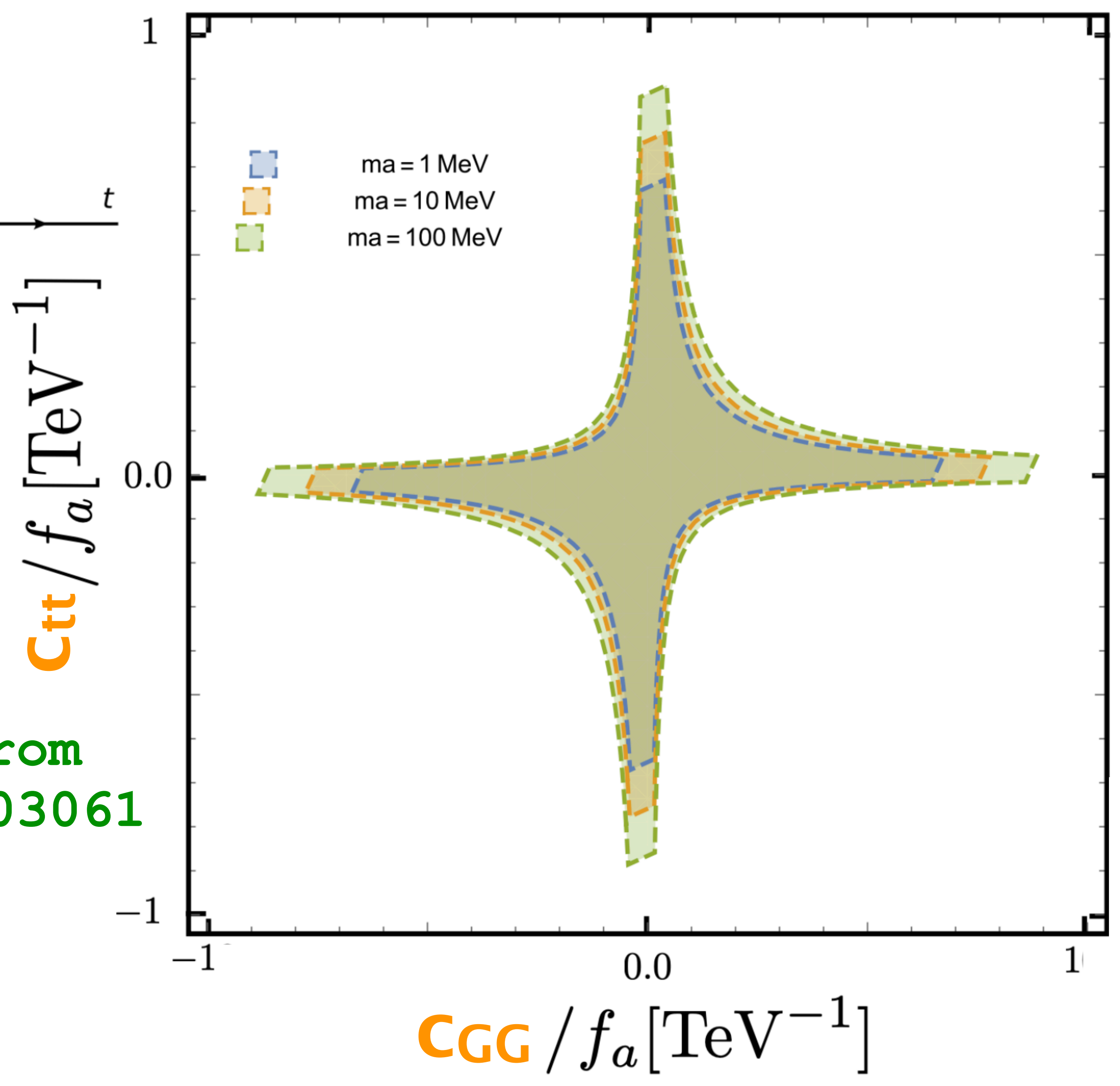
Search for ALPs with effective couplings





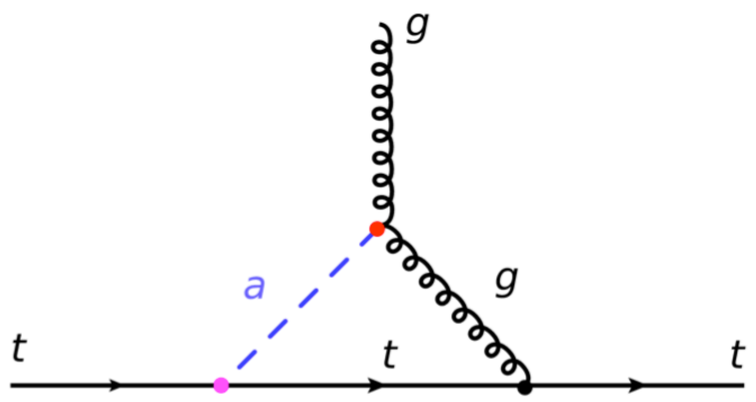
chromomagnetic dipole moment



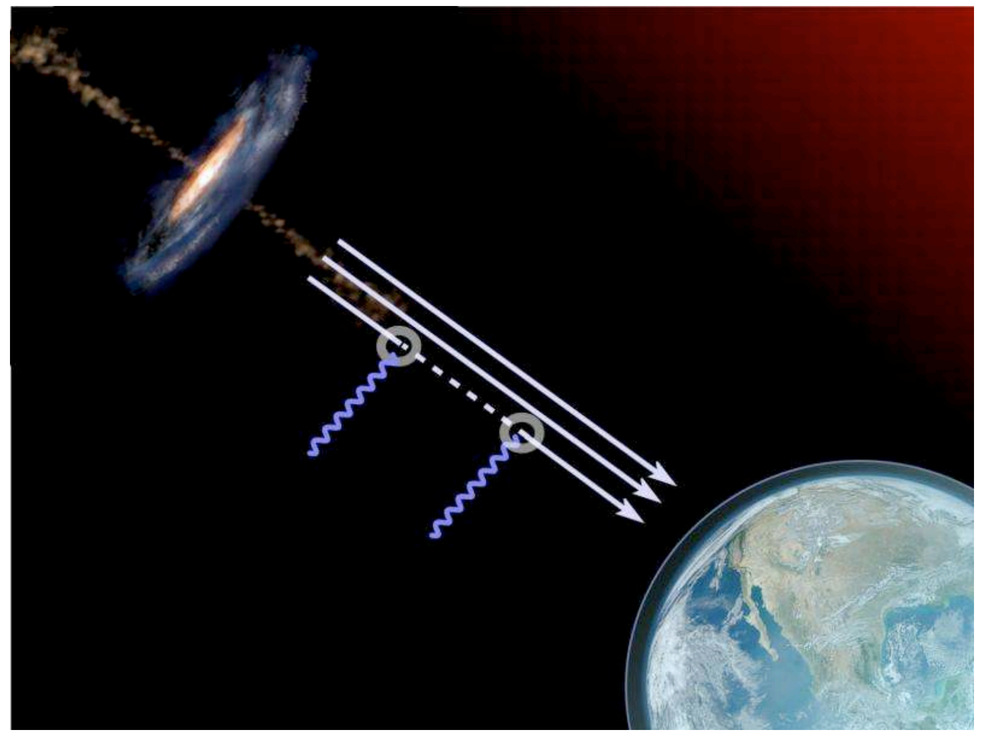


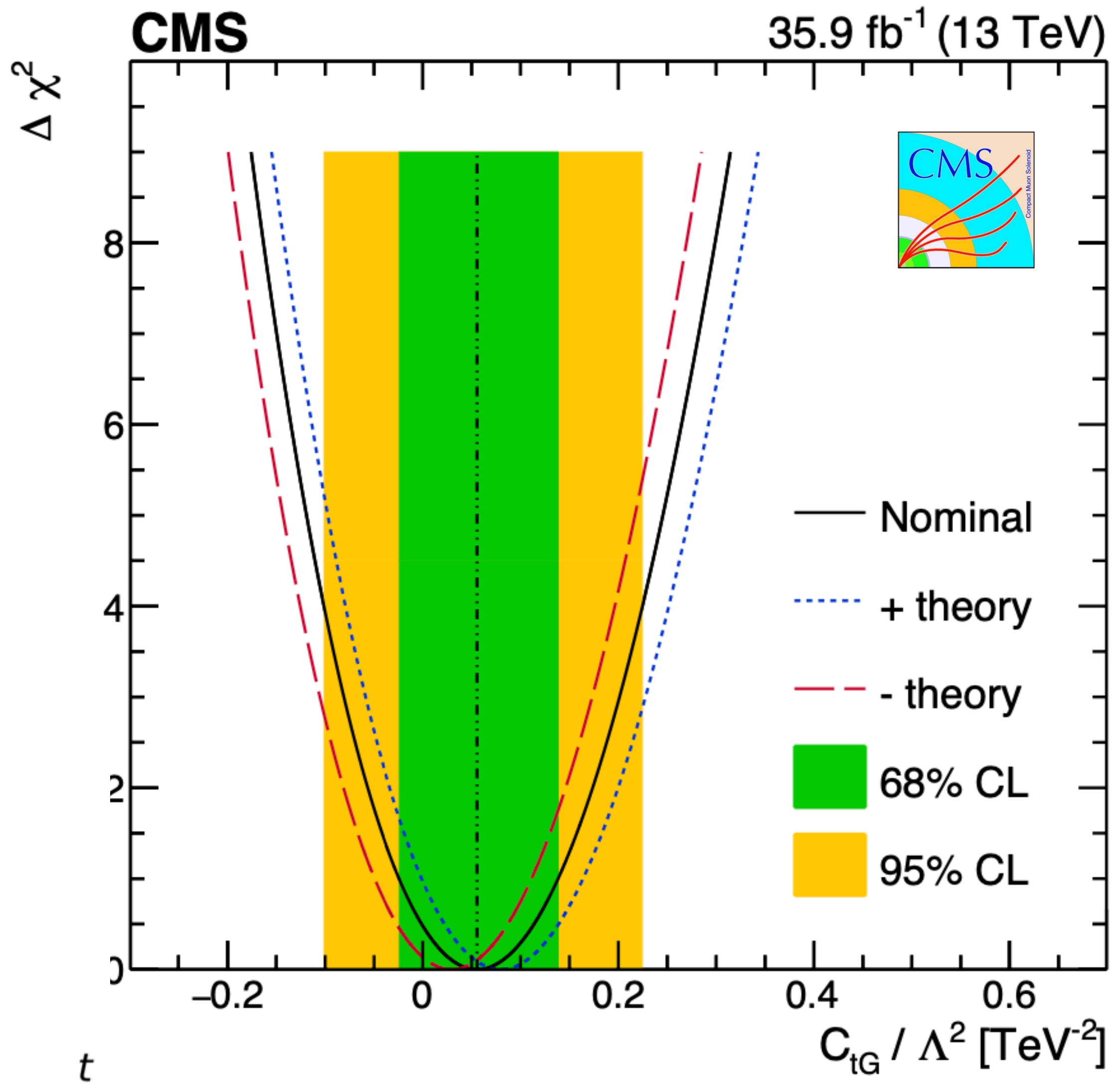
derived from arXiv:1901.03061

measure spin density matrix

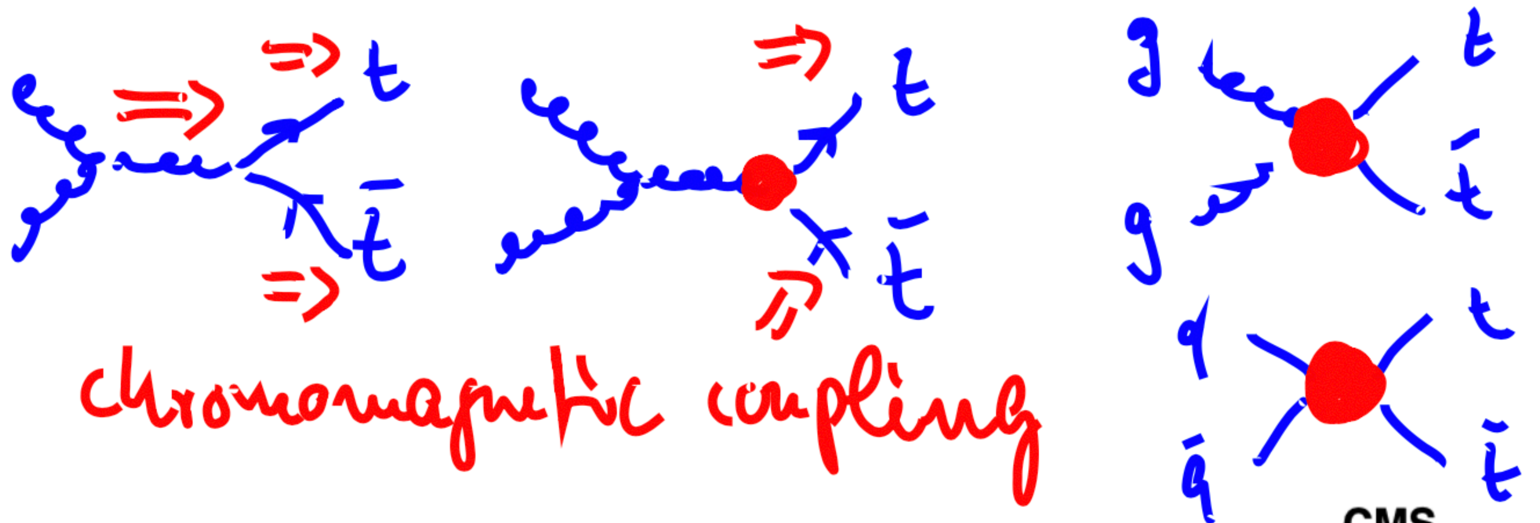


DARK MATTER

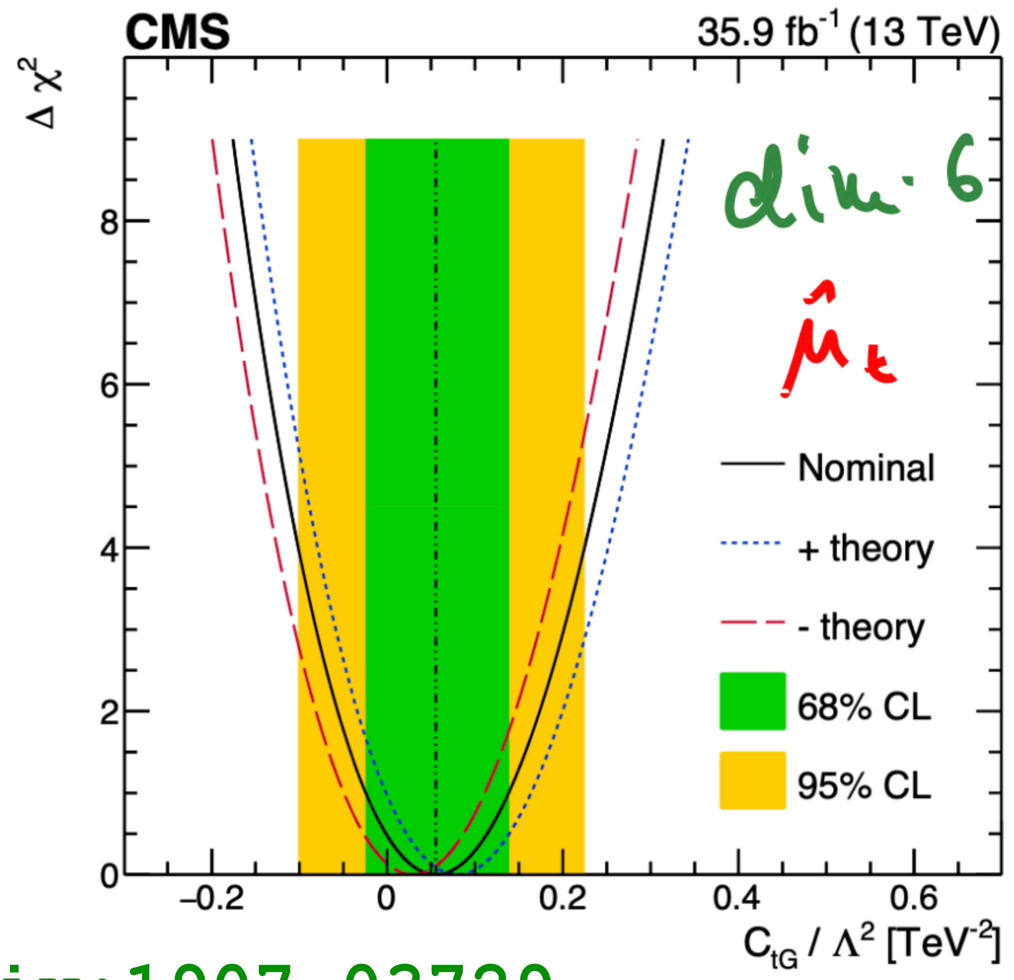


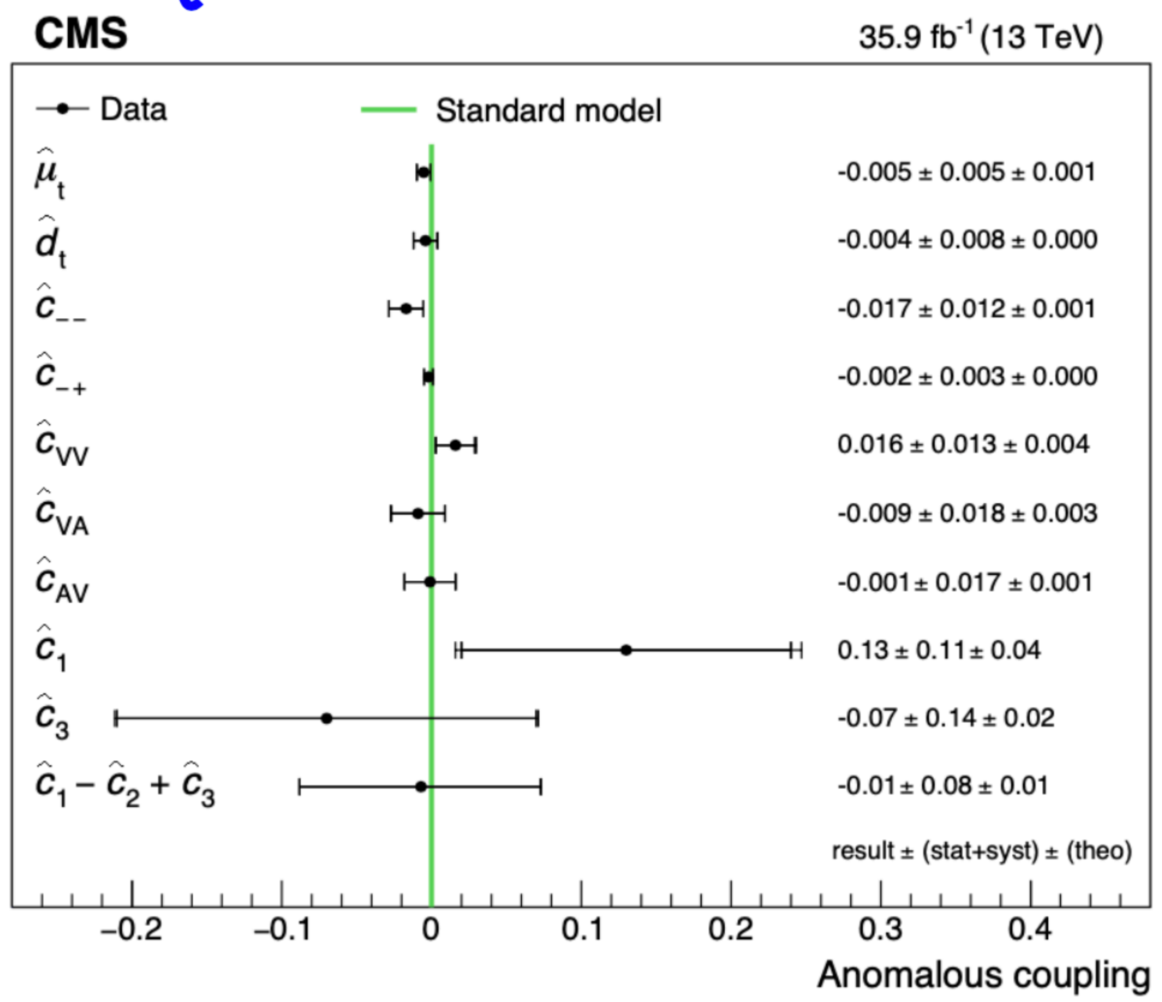


Anomalous couplings from Spin Correlations



Coupling	Operator type	Symmetry properties
$\hat{\mu}_t$	2 quarks plus gluon(s)	P-even, CP-even
$\hat{d}_t$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{--}$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{-+}$	2 quarks plus gluon(s)	P-even, CP-odd
$\hat{c}_{VV}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_{VA}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AV}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AA}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_1$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_2$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_3$	4 quarks (weak isospin 1)	CP-even





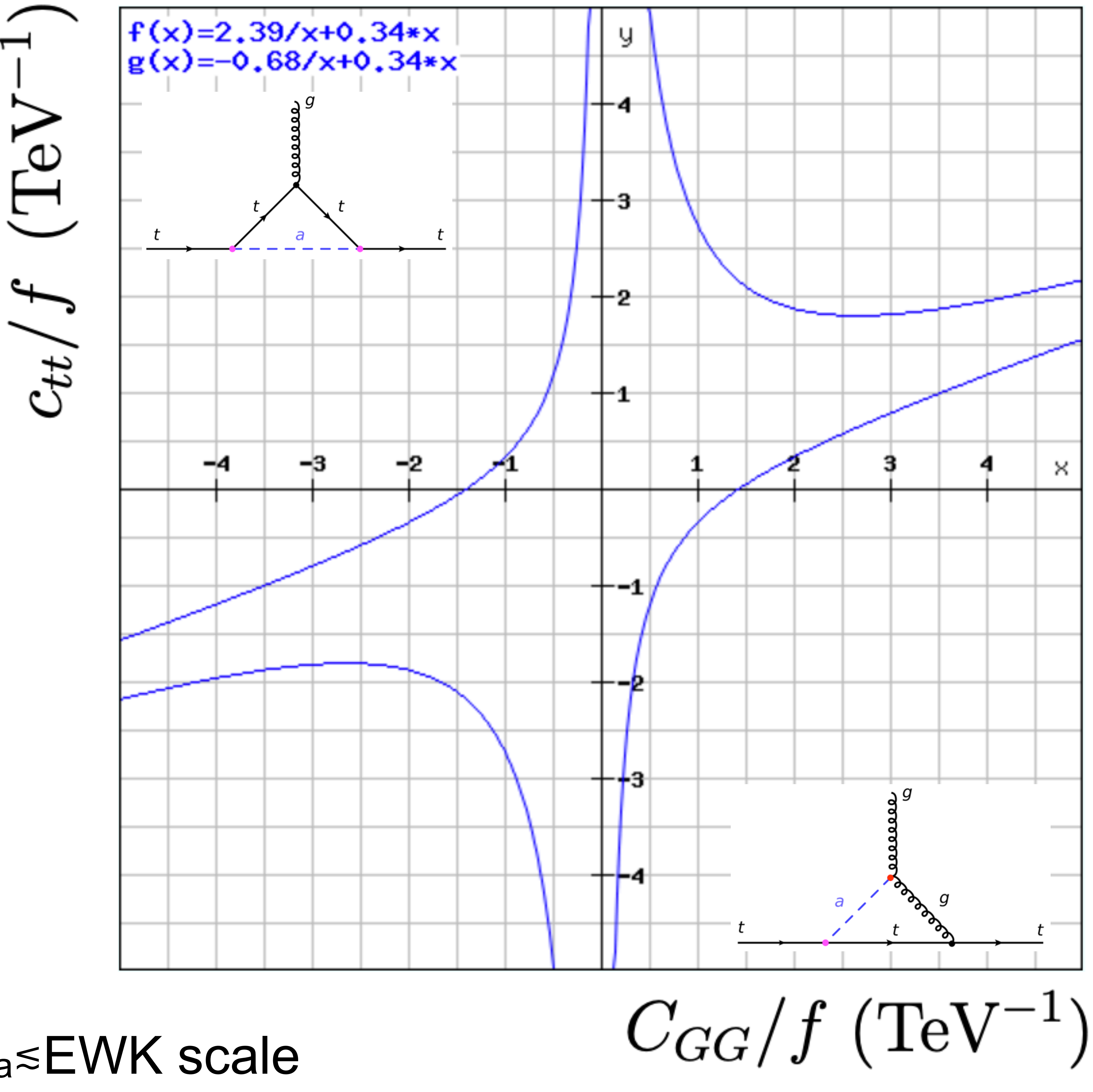
arXiv:1907.03729

Coupling	95% CL	Theoretical unc.
$\hat{\mu}_t$	$-0.014 < \hat{\mu}_t < 0.004$	± 0.001

arXiv:2105.01078

$$-0.68 < \left(c_{tt}\, C_{GG} - 0.34\, C_{GG}^2\right) \times \left[\frac{1\,\text{TeV}}{f}\right]^2 < 2.38 \qquad (95\%\ \text{CL}). \qquad (53)$$

The ALP couplings c_{tt} and C_{GG} are defined at the scale $\mu = m_t$. With the current sensitivity, the measurements of the top-quark chromo-magnetic moment probe the ALP couplings c_{tt}/f and C_{GG}/f at the level of roughly $\mathcal{O}(\text{TeV}^{-1})$.



→ are such constraints interesting?

$m_a \lesssim$ EWK scale

Lagrangians in ALPs searches

arXiv:1901.03061

$$\mathcal{L}_{eff}^{D\leq 5} = \mathcal{L}_{SM} + \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + c_{a\Phi}\frac{\partial^\mu a}{f_a}(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi) + \frac{\partial^\mu a}{f_a}\sum_F \bar{\Psi}_F \mathbf{C}_F \Psi_F - c_{GG}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{\mu\nu,a} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\tilde{W}^{\mu\nu,a},$$

$$\mathcal{L}_{eff}^{D\leq 5} = \mathcal{L}_{SM} + \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + - c_{GG}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} - c_{WW}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{a\Phi}\mathbf{O}^\psi_{a\Phi},$$

$$\mathbf{O}^\psi_{a\Phi} \equiv i\left(\bar{Q}_L \mathbf{Y}_U \tilde{\Phi} u_R - \bar{Q}_L \mathbf{Y}_D \Phi d_R - \bar{L}_L \mathbf{Y}_E \Phi e_R\right)\frac{a}{f_a} + \text{h.c.}$$

arXiv:2105.01078

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \mathcal{L}_{\text{SM+ALP}} + \mathcal{L}_{\text{SMEFT}},$$

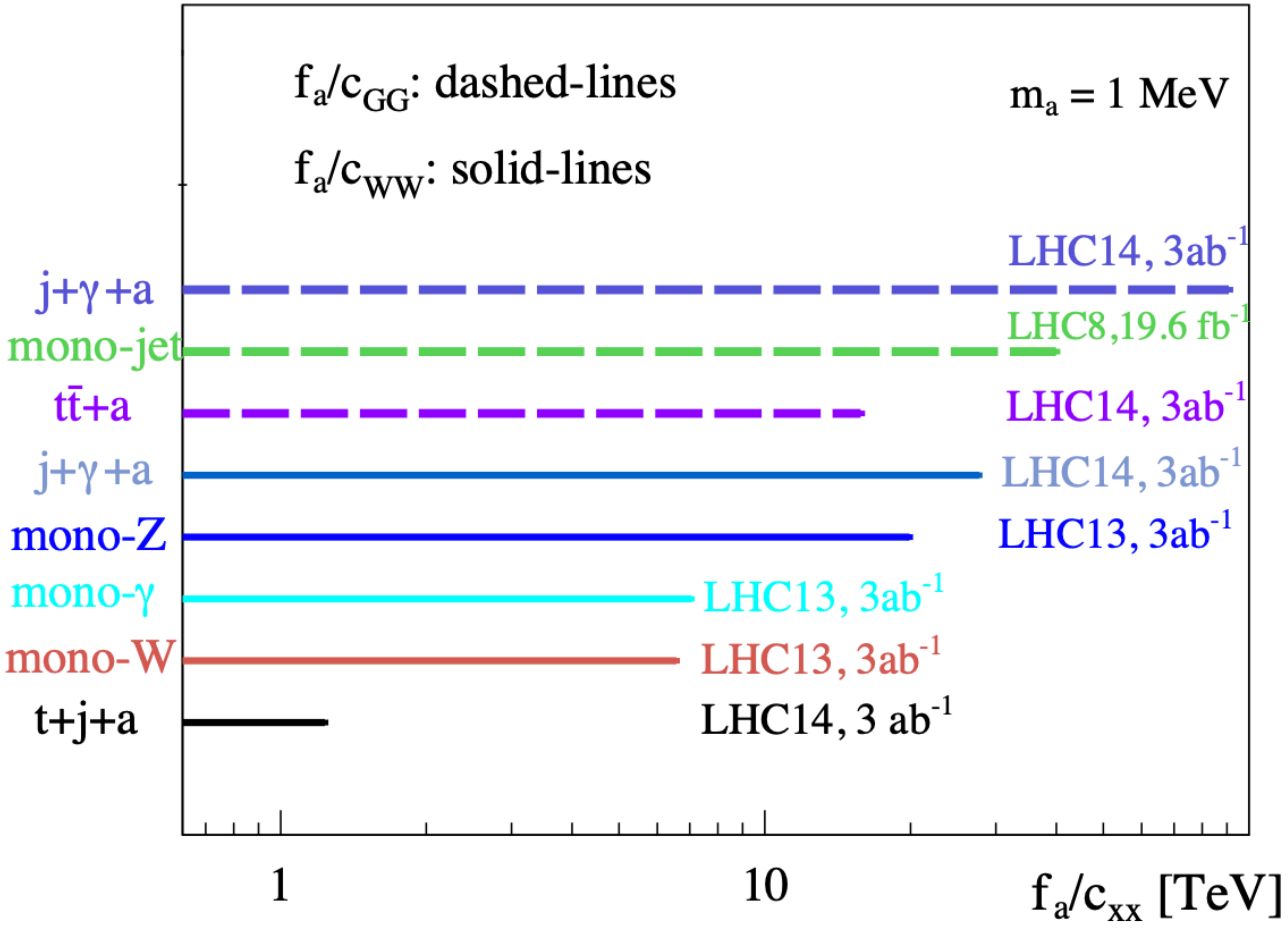
$$\mathcal{L}^{D=5}_{\text{SM+ALP}} = c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^I_{\mu\nu}\tilde{W}^{\mu\nu,I} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F \boldsymbol{c}_F \gamma_\mu \psi_F.$$

$$\mathcal{L}^{D=5\,\prime}_{\text{SM+ALP}} = C_{GG}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + C_{WW}\frac{a}{f}W^I_{\mu\nu}\tilde{W}^{\mu\nu,I} + C_{BB}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\tilde{H}\tilde{\mathbf{Y}}_u u_R + \bar{Q}H\tilde{\mathbf{Y}}_d d_R + \bar{L}H\tilde{\mathbf{Y}}_e e_R + \text{h.c.}\right),$$

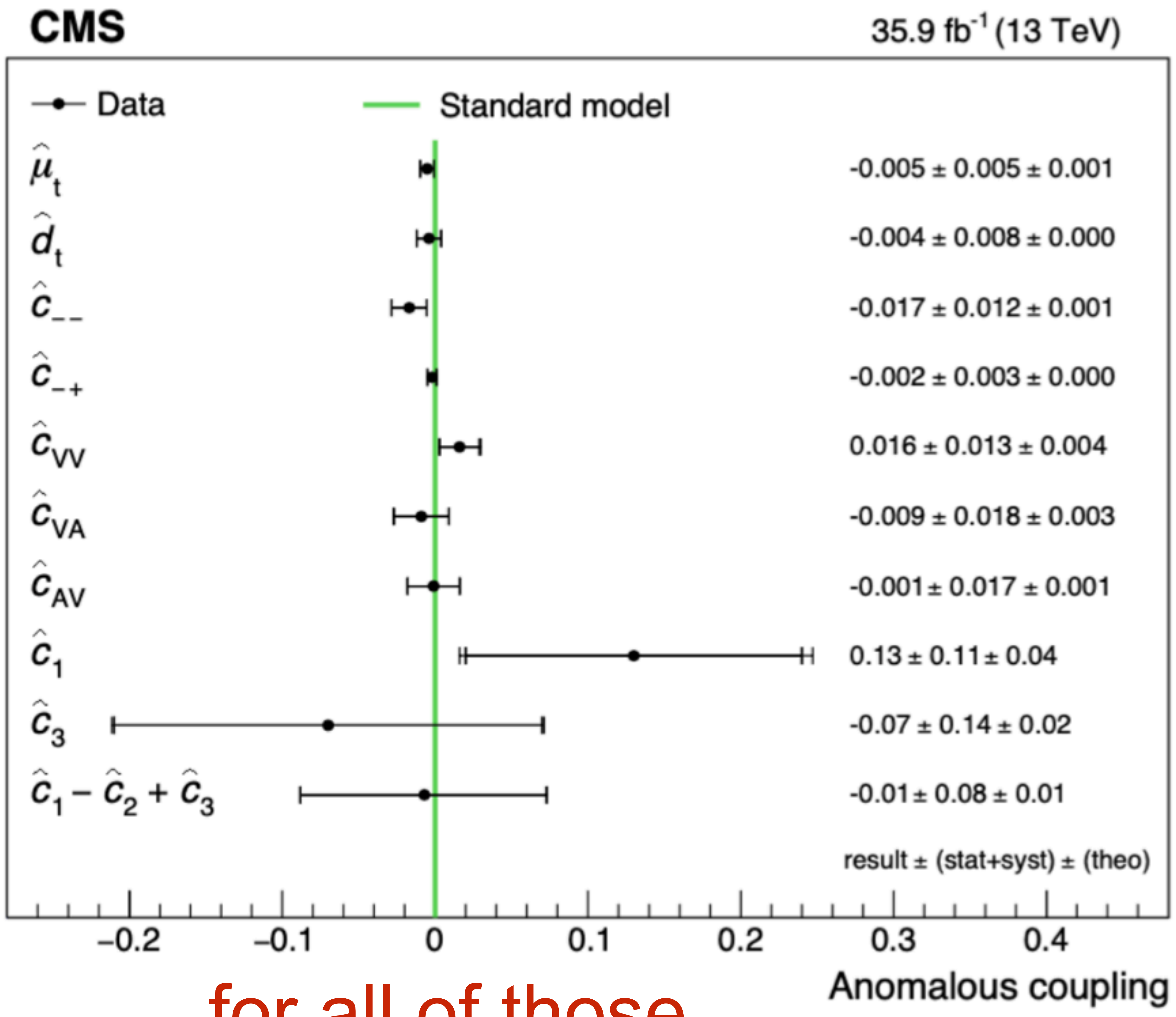
$$\tilde{\mathbf{Y}}_u = i(\mathbf{Y}_u \boldsymbol{c}_u - \boldsymbol{c}_Q \mathbf{Y}_u), \qquad \tilde{\mathbf{Y}}_d = i(\mathbf{Y}_d \boldsymbol{c}_d - \boldsymbol{c}_Q \mathbf{Y}_d), \qquad \tilde{\mathbf{Y}}_e = i(\mathbf{Y}_e \boldsymbol{c}_e - \boldsymbol{c}_L \mathbf{Y}_e)$$

Prospects in ALPs searches

arXiv:1901.03061



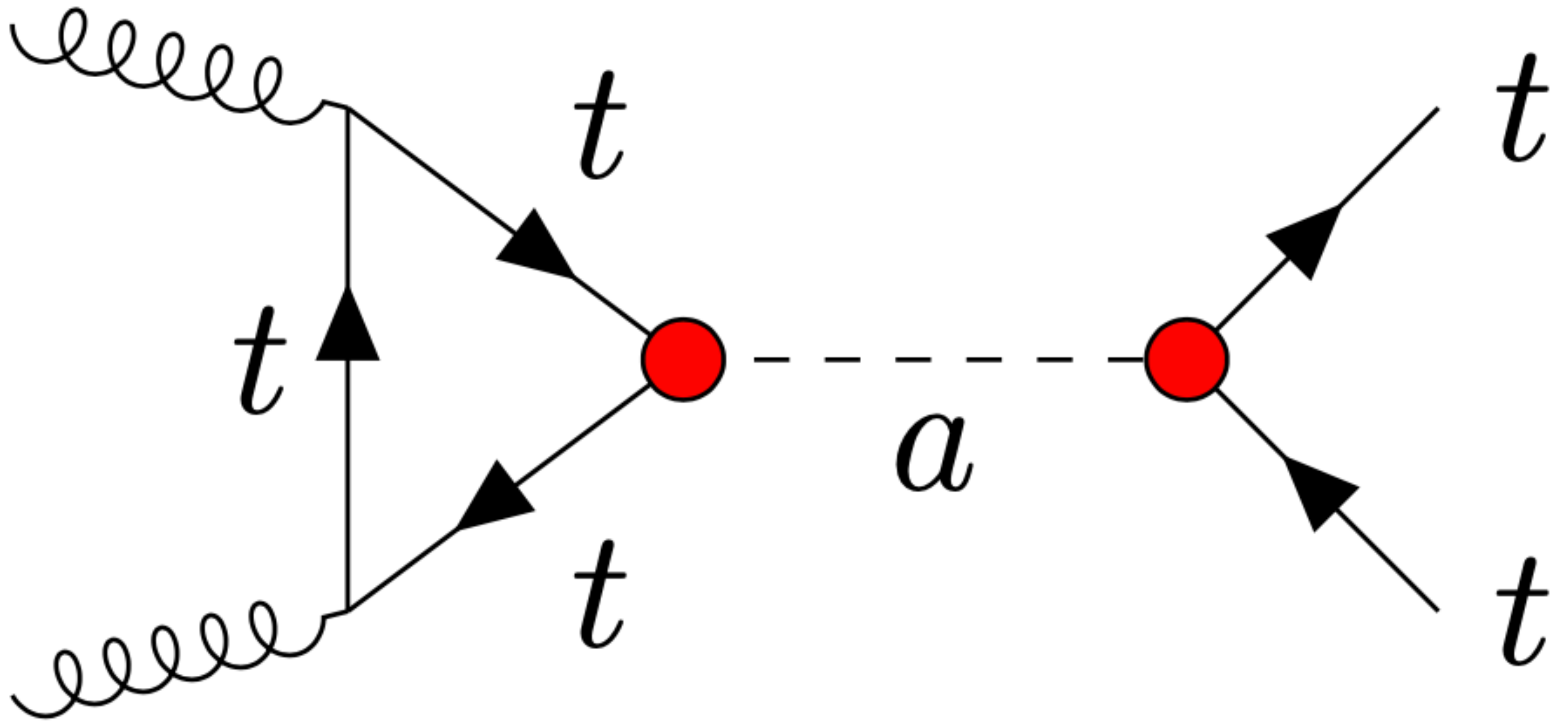
arXiv:2105.01078



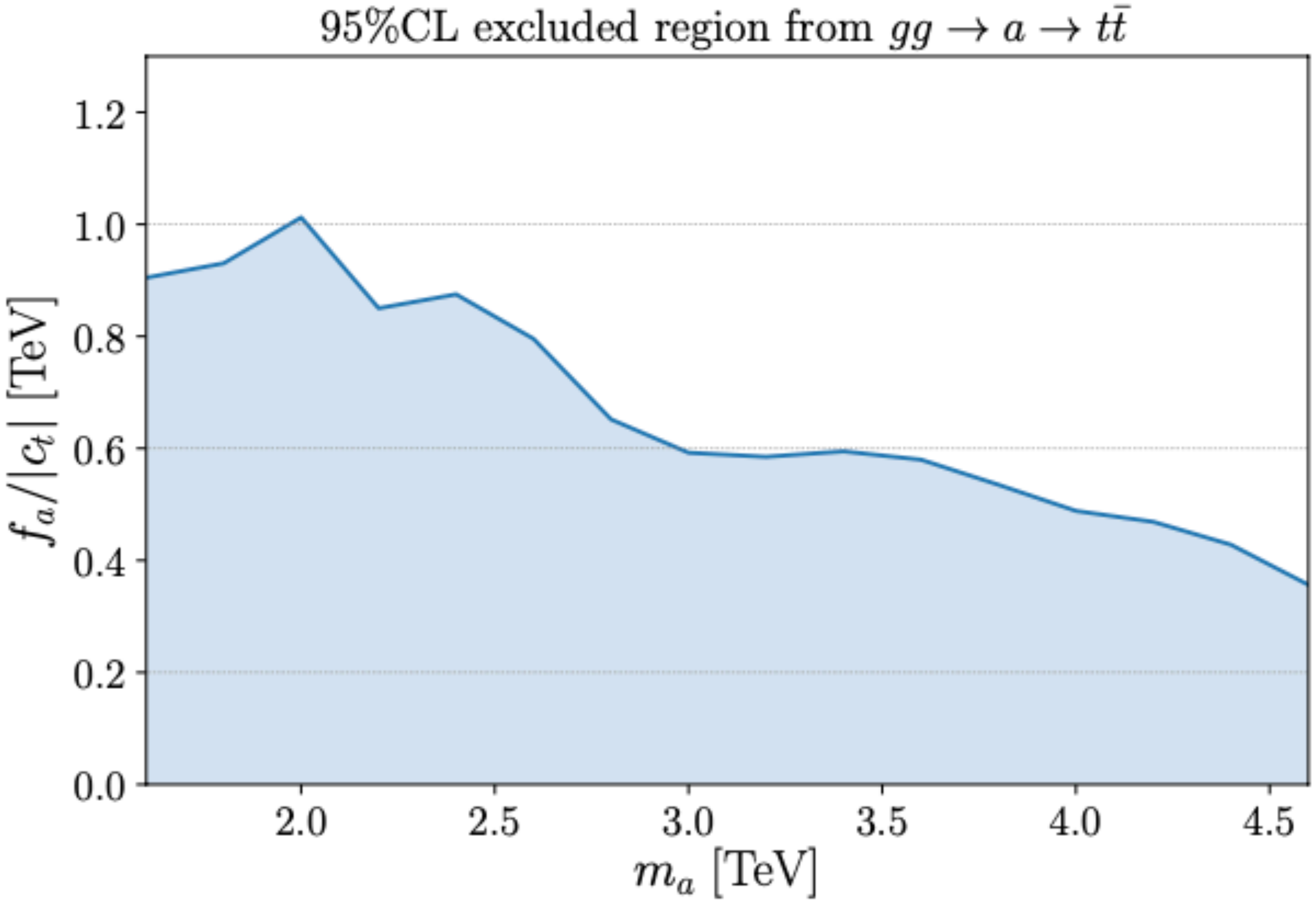
for all of those…

ALPs resonances

arXiv:2107.11392



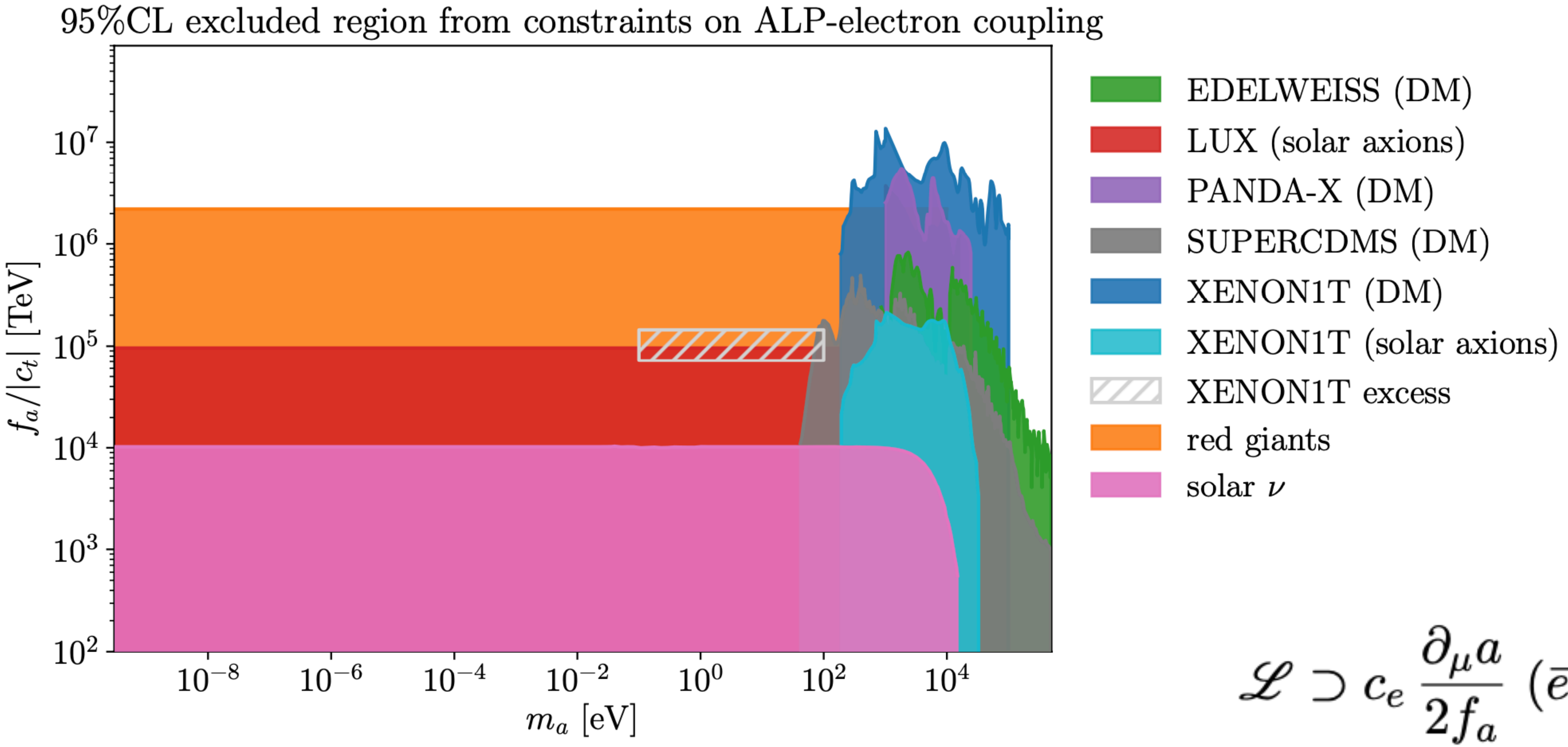
$$\mathscr{L} \supset c_t \frac{\partial_\mu a}{2 f_a} (\bar{t}\gamma^\mu \gamma_5 t)$$



extracted from the all-hadronic tt resonance search by ATLAS

Limits on top couplings for light ALPs

arXiv:2107.11392



$$\mathscr{L} \supset c_e \frac{\partial_\mu a}{2 f_a} \left(\bar{e}\gamma^\mu \gamma_5 e\right)$$