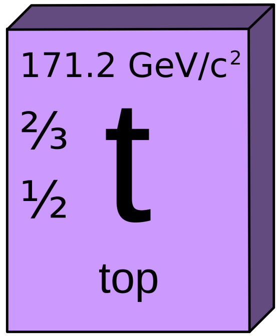
Fabian Esser
IFIC, Universidad de Valencia
LCHP 2024
Northwestern University Boston

BSM from the top

05.06.2024

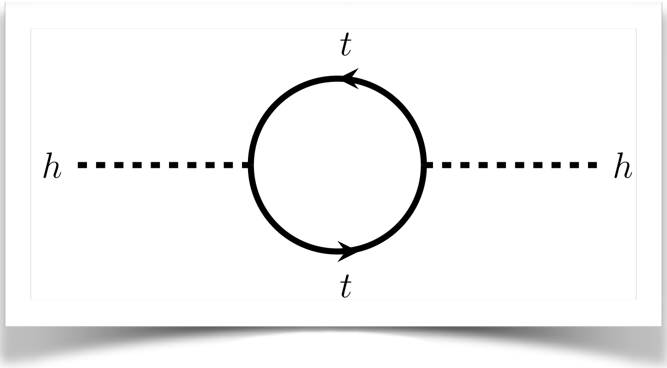
The Top quark



- The heaviest quark $m_t = \frac{v y_t}{\sqrt{2}}$ = 171 GeV, Yukawa coupling of order unity
- Due to its large mass it is strongly connected to the EW sector, affects the stability of the EW vacuum
- top-quark sector especially suitable for precision EW tests
- If there is any BSM correction to the EW sector we should see the deviation in top physics
- Unique phenomenology: dominant decays into b + W, decays before it hadronises, key to new physics searches

Higgs hierarchy problem

- Why is the Higgs mass so fine-tuned?
  $M_{Pl} = 10^{19}$ GeV but $m_h = 125$ GeV



- biggest radiative effect from the top-quark

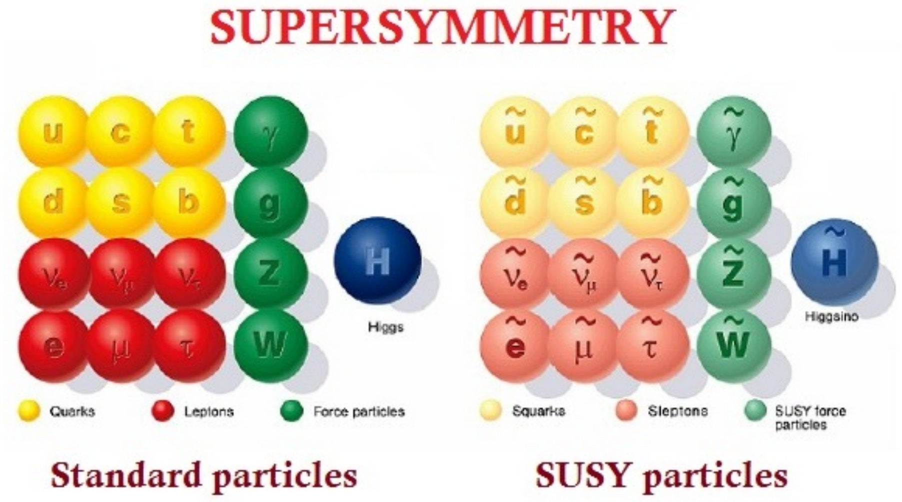
$$\Pi_{hh}(0) = -2y_t^2 \int \frac{d^4k}{(2\pi)^2} \left[\frac{1}{k^2 - m_t^2} + \frac{2m_t^2}{(k^2 - m_t^2)^2} \right]$$

  The first term is quadratically divergent $\delta m_h^2 \propto -\left(\frac{m_t}{v^2}\right)^2 \Lambda^2$

- At $\Lambda = M_{Pl}$, the correction is over 30 order of magnitudes larger than the physical SM Higgs mass

  → search for a top partner to cancel the radiative effects (SUSY, Composite-Higgs, …)

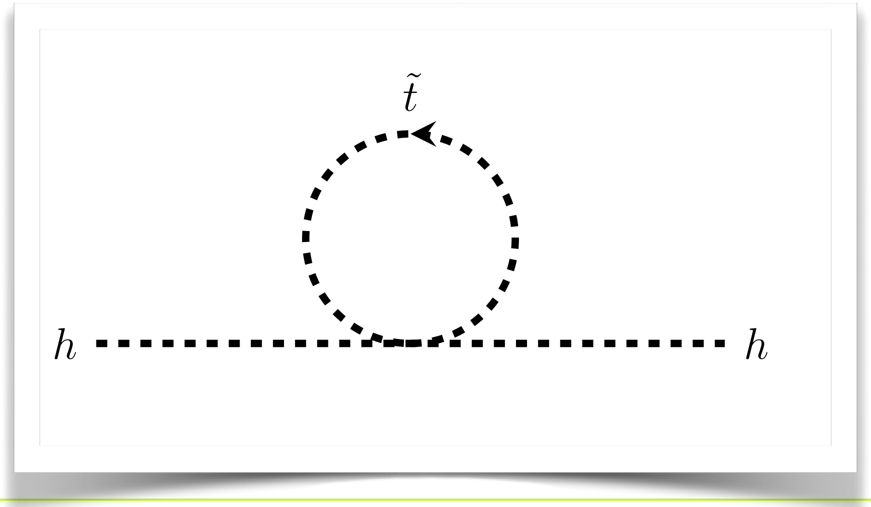
Supersymmetry



- introduce a (spontaneously broken) symmetry between fermions and bosons
- bosons and fermions have the same quantum numbers and a priori the same mass
- super-partner to the top: *stop* $\tilde{t}$
- contributes to the Higgs mass with same Λ^2 divergence but opposite sign

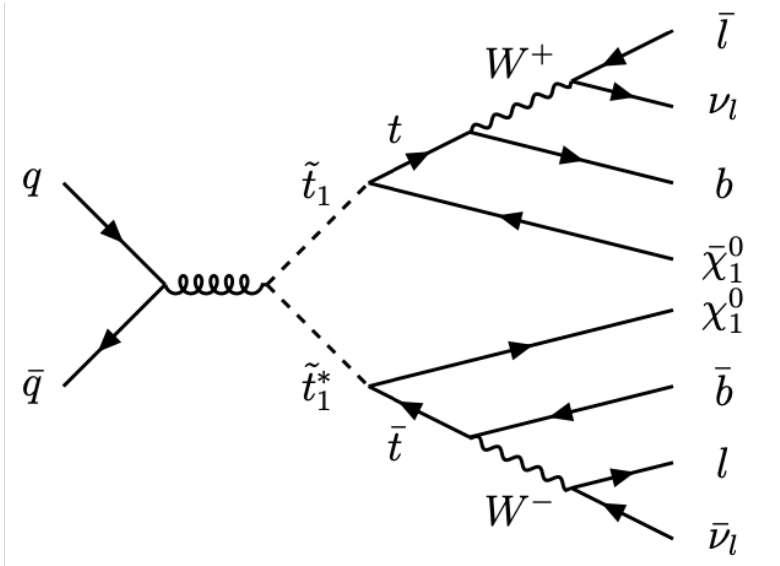
$$\Pi_{hh}(0)^{(\tilde{t})} = -2y_{\tilde{t}} \int \frac{d^4k}{(2\pi)^2} \frac{1}{k^2 - m_{\tilde{t}}^2}$$

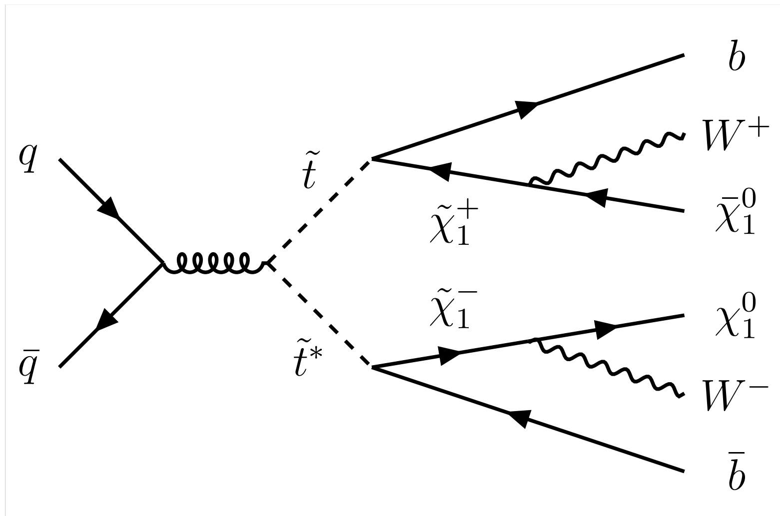
- for $y_{\tilde{t}} = -y_t^2$ and $m_{\tilde{t}} = m_t$ the contributions to m_h^2 from tops and stops cancel identically!
- for $m_{\tilde{t}} \neq m_t$ the divergence is proportional to Δm



Stop searches

- Stops decay into tops and neutralinos or bottoms and charginos
- dedicated searches for SUSY particles at the LHC
- e.g. via leptonic top decays: final state with $2b + 2l + MET$
- top quark plays an important role in many stop searches, dominant decay channel
- long standing and refined searches in multiple channels at ATLAS and CMS





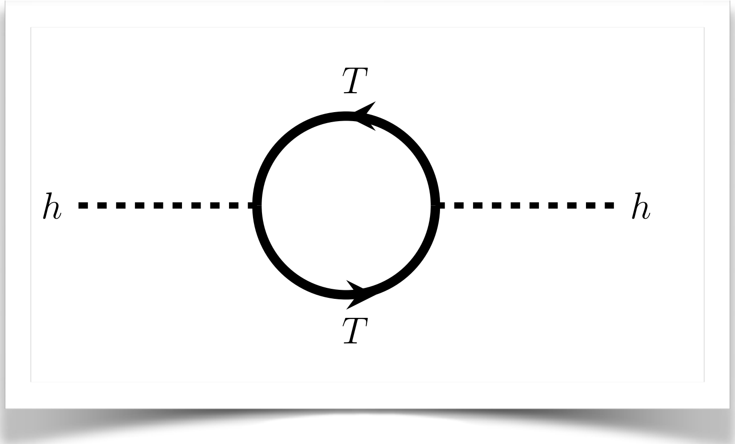
Composite Higgs Models (CHM)

- In Composite Higgs Models, the Higgs boson is not a fundamental particle
- appears as a composite bound state of heavy fermions $(F\bar{F})$ that does not exist at high energies
  $\rightarrow$ no hierarchy problem
- independently of the exact realisation, CHMs always need a top partner T with a mass close to the top quark to ensure the correct form of the Higgs potential and right mechanism for EWSB

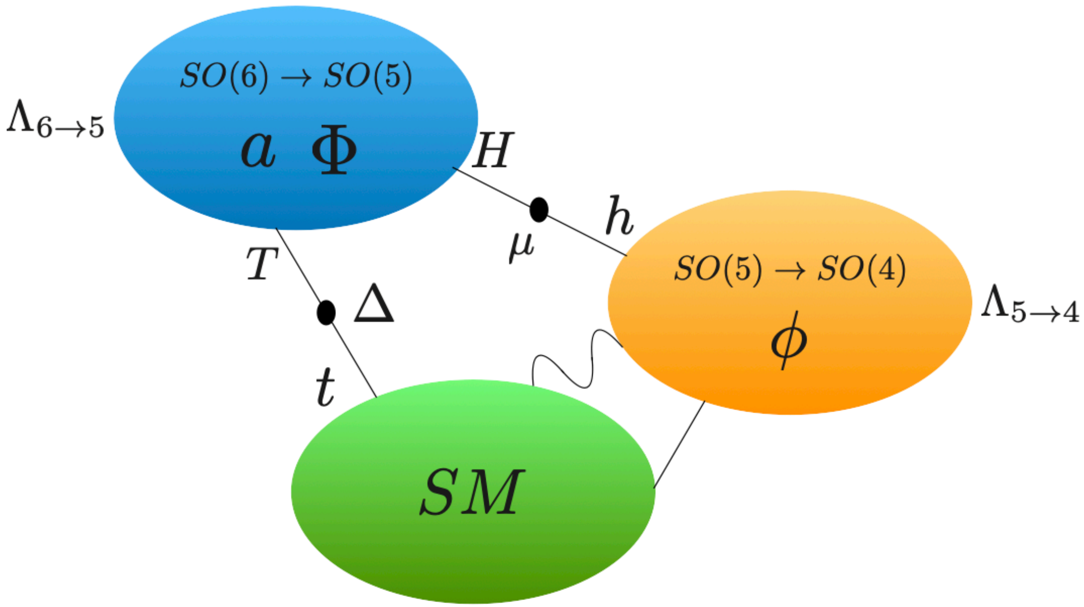
- $T = (T_L, T_R)$ mixes with top quarks through mass mixing

$$\mathscr{L} \supset \left(\bar{t}_L, \bar{T}_L\right) \begin{pmatrix} \frac{y_t v}{\sqrt{2}} & \Delta \\ 0 & M \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix},$$

  modifies couplings to the Higgs boson
- diagonalisation gives masses m_t and M_T and mixing angle θ



See-saw Composite Higgs



[Sanz, Setford '15]

[No, Sanz, Setford '16]

- 2 successive symmetry breakings
- Higgs doublets mix pGB from both symmetry breakings
- scalar pGB a associated with heavy scale $f_a \sim \Lambda_{6\to5}$ (could be an axion)
- 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-T mixing introduces top-ALP coupling

$$c_t \propto c_T \frac{\Delta^2}{m_T^2}$$

Axion Like Particles (ALPs)

- ALPs appear as (pseudo) Goldstone bosons in many SM extensions with a spontaneous breaking of a global symmetry
- pseudo-scalars with shift symmetry $a \to a + c$

  → restricts ALP couplings to SM particles

  → couplings momentum dependent

  ⇒ energy scaling for processes involving ALPs differs from background processes

- traditional searches focus on light ALPs and couplings to bosons
- searches in a larger mass range and with ALP-fermion couplings

  → top quark!

ALP-top coupling

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

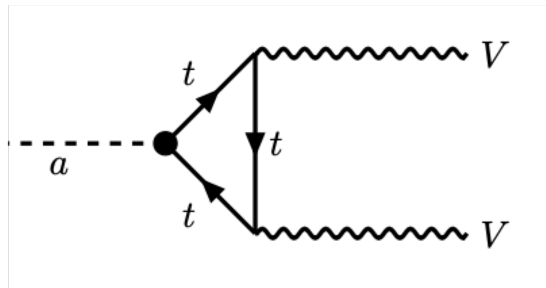
  $\Rightarrow$ EFT approach $\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_a$

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

- couplings to fermions are proportional to the fermion masses
  $\rightarrow$ special role for the top quark

$$\mathscr{L} \supset -ic_t \frac{m_t a}{2f_a} \left(\bar{t}\gamma^5 t\right)$$

- switching on only c_t , the couplings to vector bosons are generated at 1-loop level



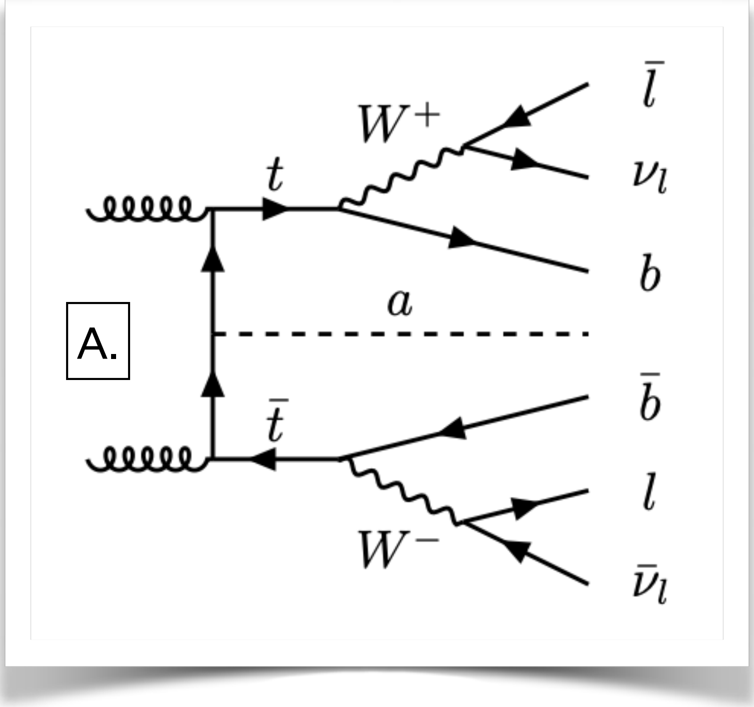
Direct ALP searches via top quarks

ALP searches at the LHC via top quarks use high-energy LHC probes in a large mass range:

A. direct limits on c_t from associated production of the ALP with top quarks

→ assume the ALP collider stable, escapes the detector as MET
→ reinterpret a Run II ATLAS SUSY search in $2l + 2b + MET$ final state
→ use ALP EFT UFO file and MG5 to generate events

[FE, Madigan, Sanz, Ubiali '23]



ATLAS top squark search: [2102.134929]

Indirect ALP searches via top quarks

B. ALP mediated non-resonant top-quark pair production

CMS: [2108.02803], ATLAS: [2202.12134]

C. reinterpret ALP mediated searches with two on-shell gauge boson final states

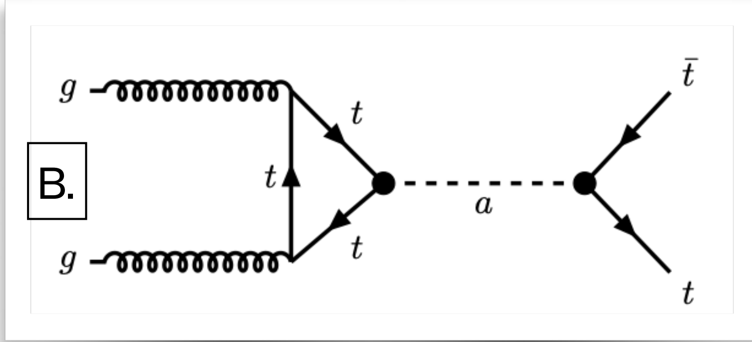
[Gavela, No, Sanz, Trocóniz, 2019], [Carra et al., 2021]

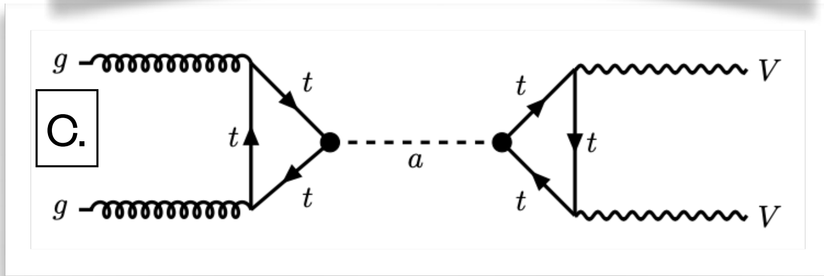
D. reinterpret ALP mediated Di-Higgs production with an associated Z boson

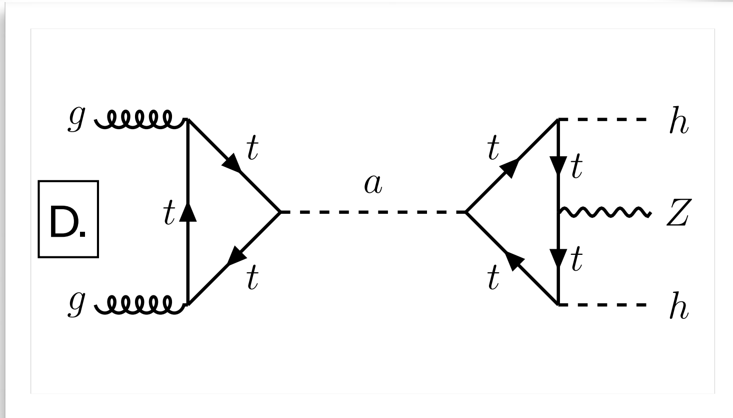
→ We interpret an ATLAS search for a Di-Higgs final state with an undetected Z ($Z \to \nu\nu$)

→ motivates a dedicated search for Di-Higgs +Z final states

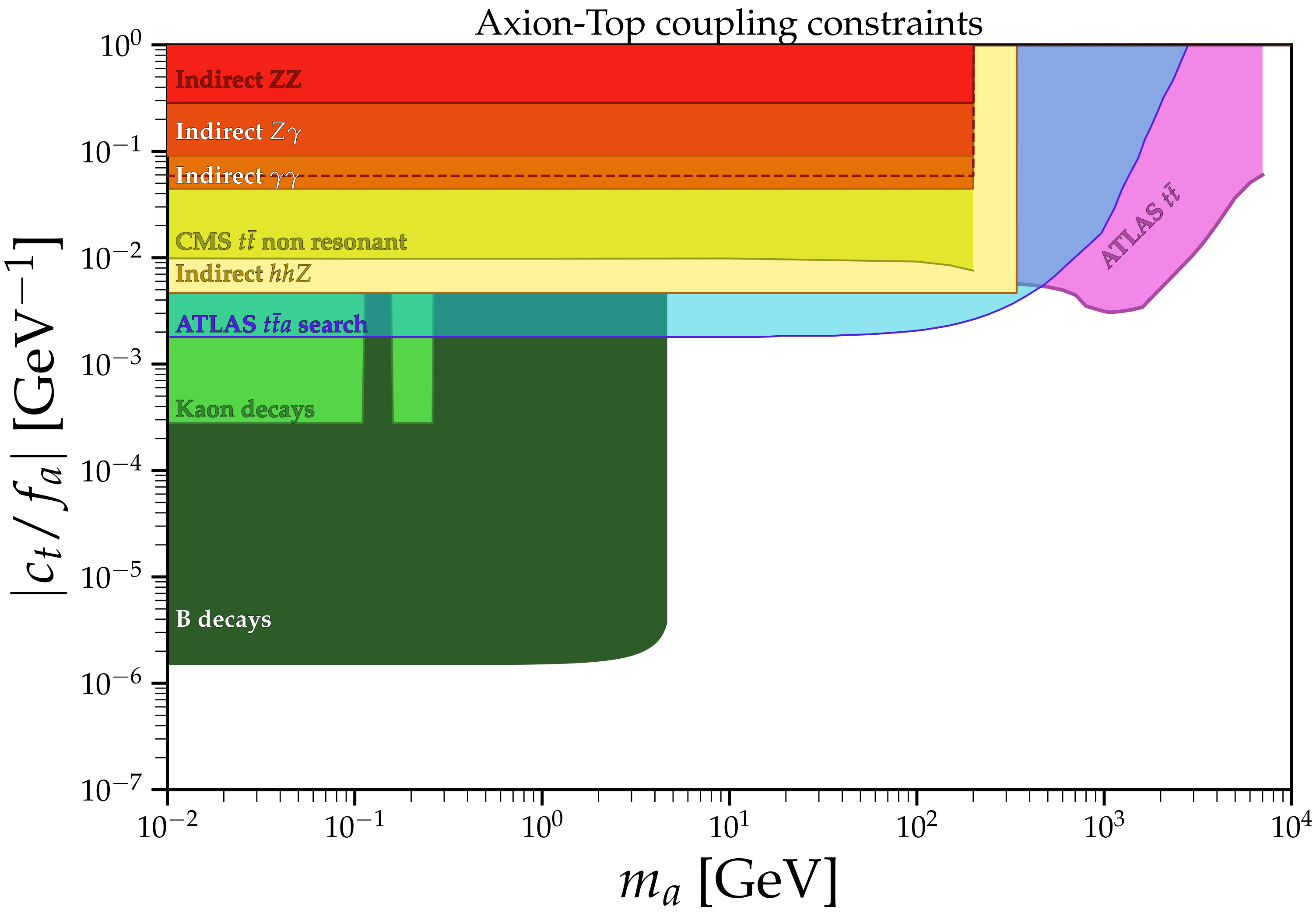
[FE, Madigan, Salas-Bernardez, Sanz, Ubiali '24]







Constraints on the ALP-Top coupling



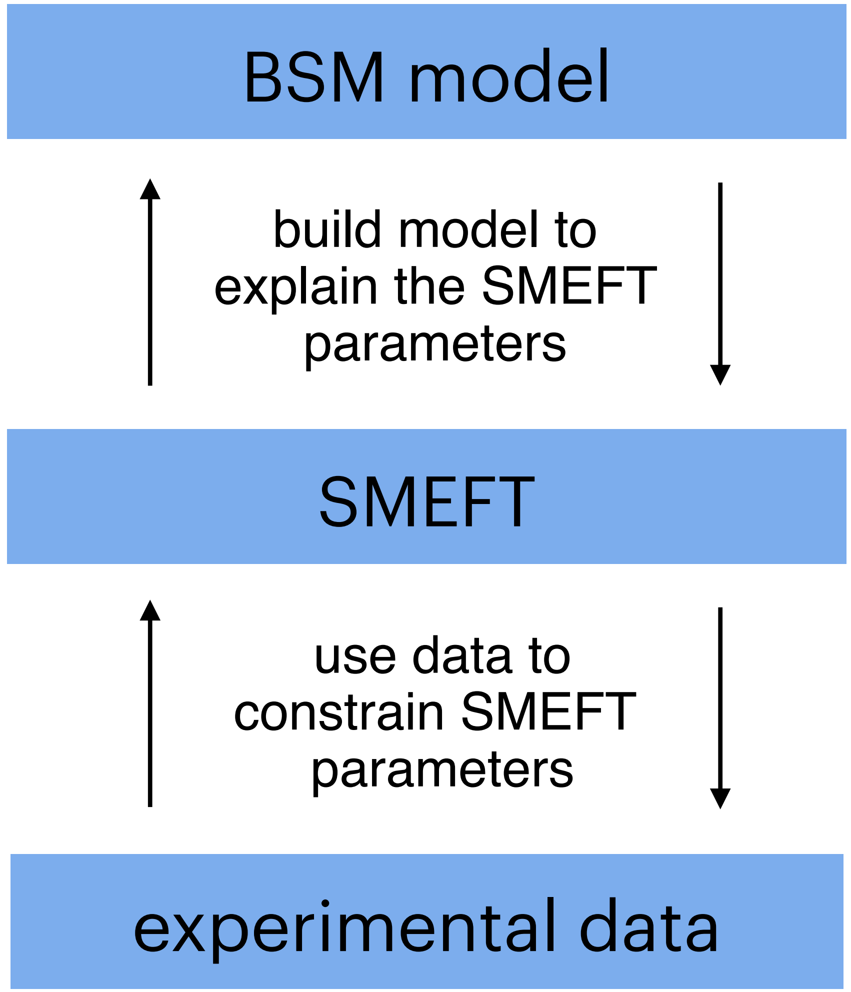
[FE, Madigan, Salas-Bernardez, Sanz, Ubiali '24]

SMEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \delta\mathscr{L}^{d\leq 4} + c_5\mathcal{O}_5 + \sum_i c_{6i}\mathcal{O}_{6i} + \sum_i c_{8i}\mathcal{O}_{8i} + \ldots$$

- describe low-energy dynamics independently of the details at high energies
  → series of higher dimensional operators
- split model-to-data analysis in 2 steps:

1. constrain Wilson coefficients from precise low-energy measurements (e.g. global SMEFT fit)
   → model independent!
2. motivate and constrain new models to explain the Wilson coefficients



UV benchmark models for 4F operators

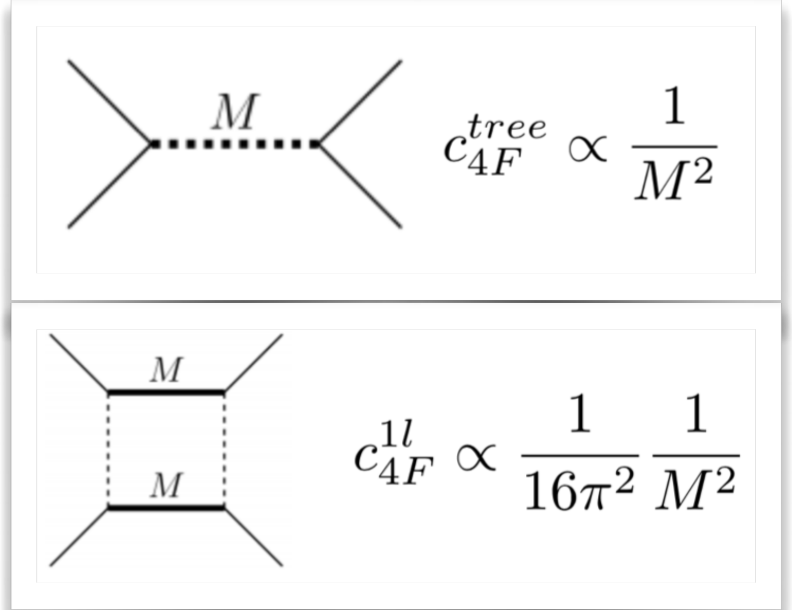
- strong SMEFT bounds come from 4F operators
- 4-top operators at dim-6:

$$\mathscr{L}_{4t} = \frac{c_{qq}^{(1)}}{\Lambda^2}(\bar{q}_3\gamma^\mu q_3)(\bar{q}_3\gamma_\mu q_3) + \frac{c_{qq}^{(3)}}{\Lambda^2}(\bar{q}_3\gamma^\mu\tau^I q_3)(\bar{q}_3\gamma_\mu\tau^I q_3) + \frac{c_{qu}^{(1)}}{\Lambda^2}(\bar{q}_3\gamma^\mu\tau^I q_3)(\bar{u}_R\gamma_\mu\tau^I u_R)$$
$$+\frac{c_{qu}^{(8)}}{\Lambda^2}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{u}_R\gamma_\mu T^A u_R) + \frac{c_{uu}}{\Lambda^2}(\bar{u}_R\gamma^\mu\tau^I u_R)(\bar{u}_R\gamma_\mu\tau^I u_R)$$

- 4F operators at 1-loop via box diagrams could contain lighter resonances than at tree-level

  → Interesting interplay between constraints from low-energy precision measurements and direct collider searches

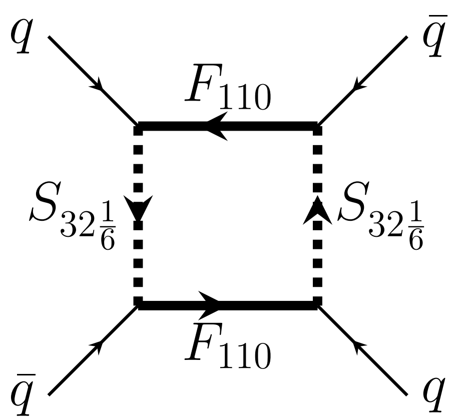
  → automatically guaranteed for DM candidates with Z_2 symmetry



SMEFT benchmark models for first generation

Models with DM candidates (e.g. F_{110}) are 2-particle extensions, constrained by

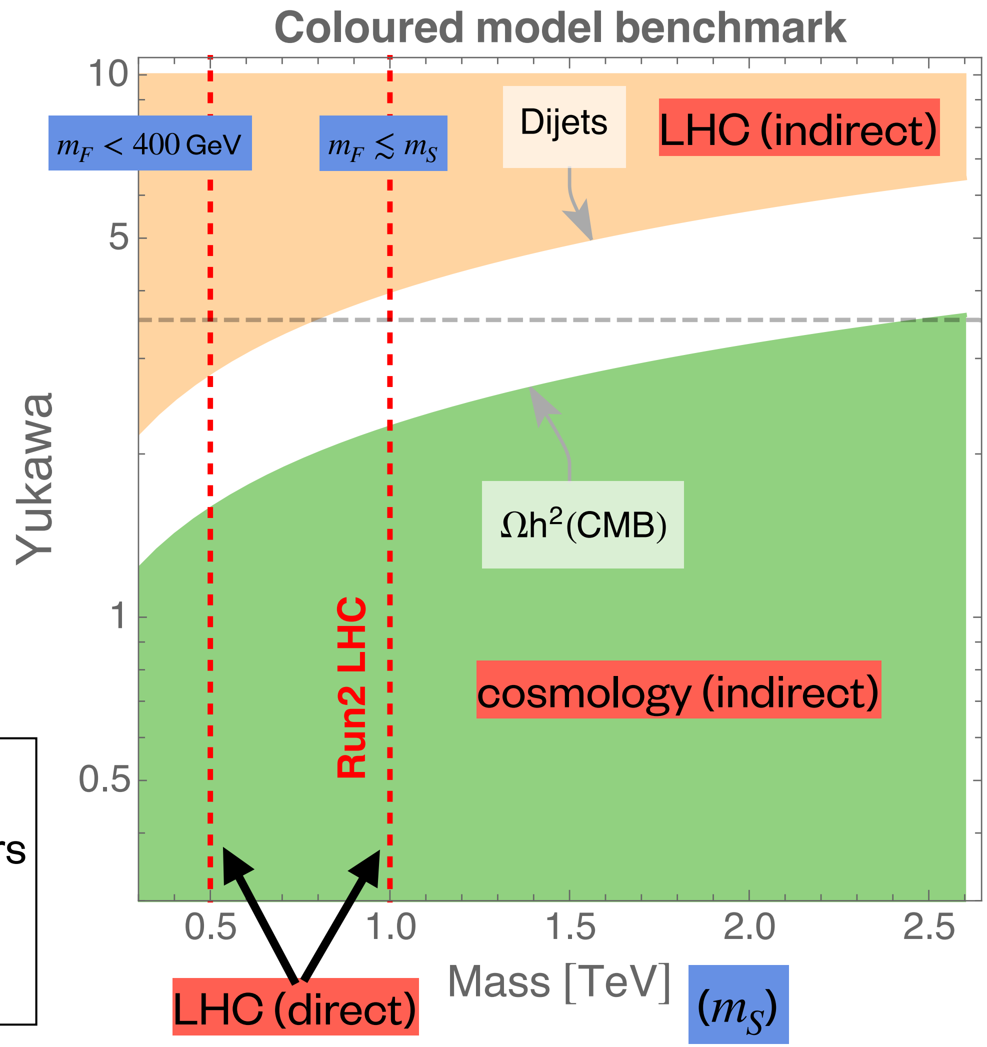
- the DM relic abundance
- indirect LHC searches
- direct LHC searches



- 1st and 2nd generation: strong constraints from low-energy measurements, need heavy partners
- 3rd generation: top partners need to be light!

  ⇒ Completely different pheno!

[Cepedello, FE, Hirsch, Sanz '23]



SMEFT benchmarks for third generation

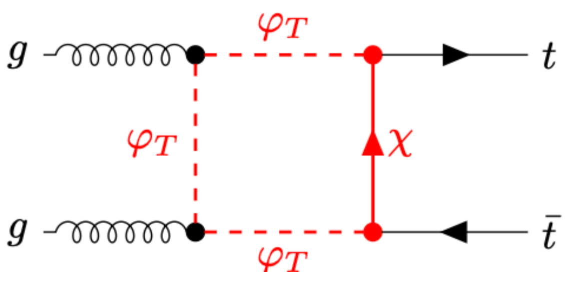
Scalar top partner φ_T and fermionic DM candidate χ

$$\mathcal{L}_{BSM} = \bar{\chi}\left(i\partial\!\!\!/ - \frac{1}{2}m_\chi\right)\chi + |D_\mu \varphi_T|^2 - m_T^2|\varphi_T|^2 - \left(y_{\text{DM}}\varphi_T^\dagger \bar{\chi} t_R + h.c.\right)$$

1.) Indirect searches in $pp \to t\bar{t}$:

For $\sqrt{s} \sim \sqrt{5}m_T$ the validity of the EFT is not guaranteed

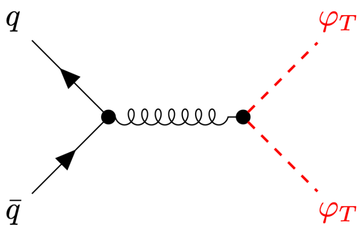
→ 1-loop calculation in the full UV theory



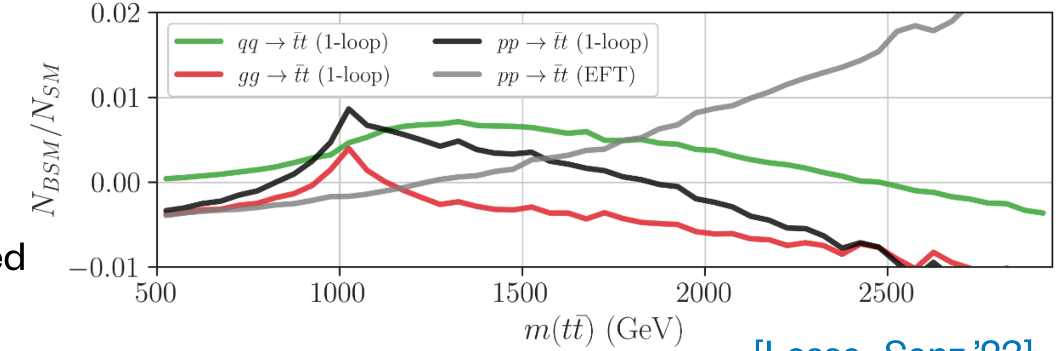
Visible effects in $m_{t\bar{t}}$ and p_T distribution

2.) Direct searches: on-shell φ_T production

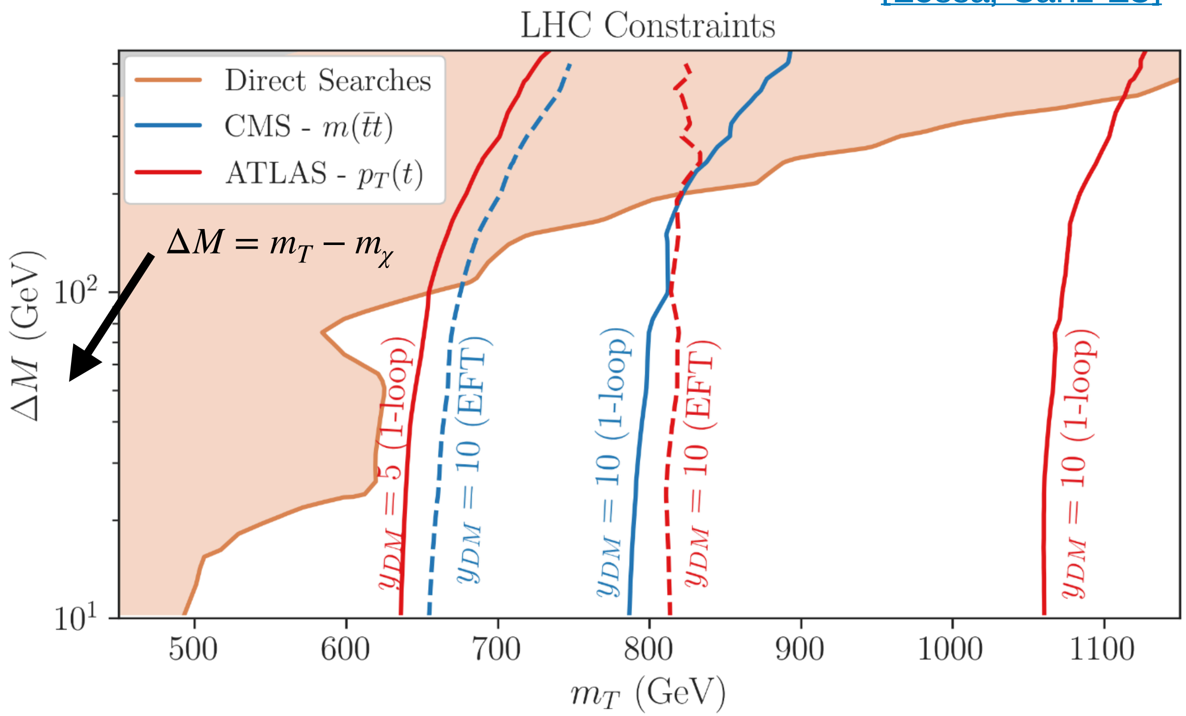
with $t + \chi$ decay, $t\bar{t}$ + MET final state



Distributions for $t\bar{t}$ invariant mass for $m_T = 500$ GeV, $m_\chi = 400$ GeV, $y_{DM} = 5$



[Lessa, Sanz '23]



Summary

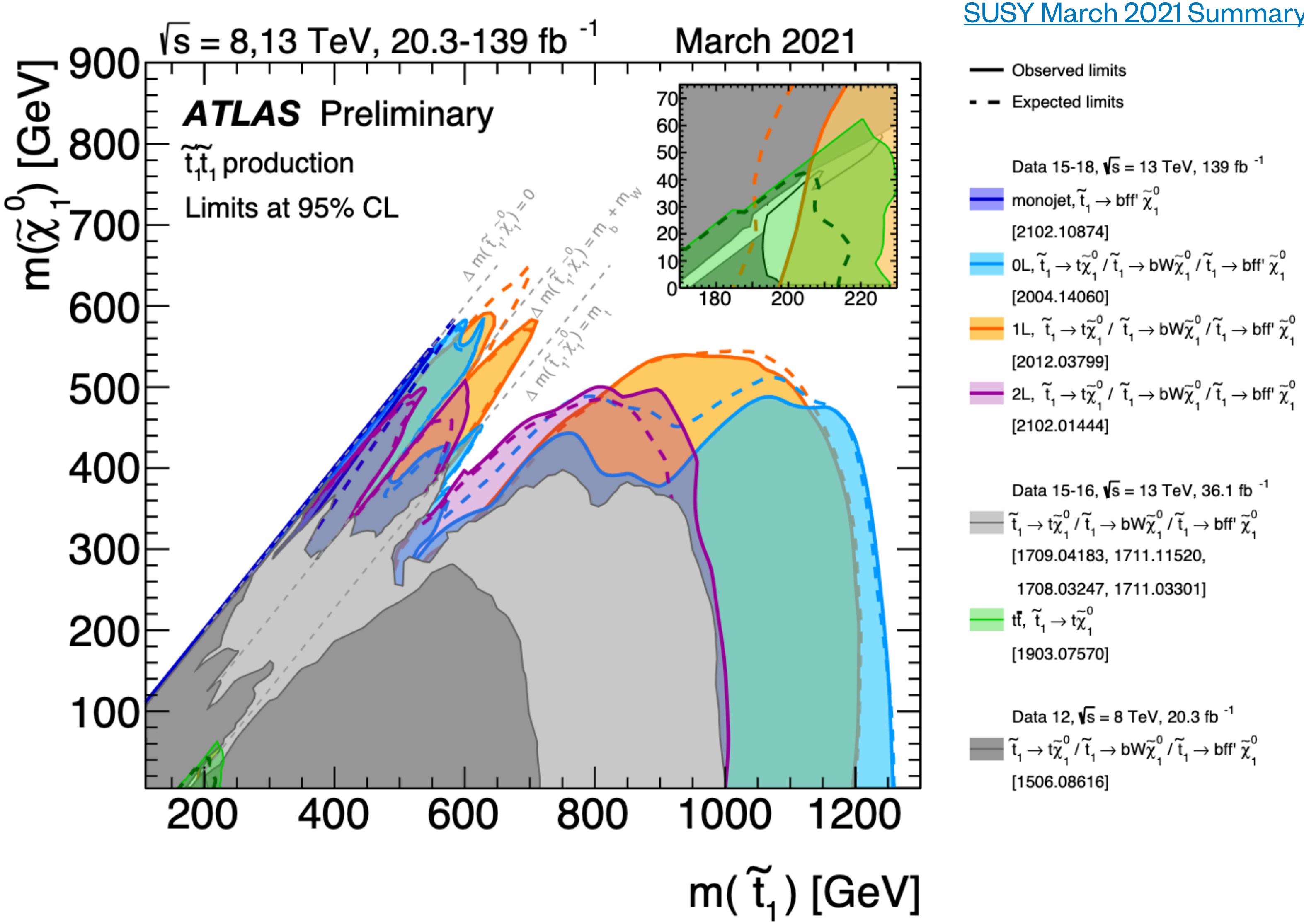
- Top quarks are strongly connected to the EW sector due to their heavy mass
- Top quarks are well-suited for EW precision physics
- Existence of a light scalar (Higgs) motivates searches for (light) top-partners (e.g. Supersymmetry, Composite Higgs models)
- Additionally, top quarks couple strongly to ALPs and play a key role in the search for ALPs
- Furthermore, operators involving top-quarks can be used in the SMEFT framework to classify and constrain new BSM models including DM


Thank you!

Back-up slides

Third generation SUSY searches

[SUSY March 2021 Summary Plot Update]



Reinterpreting a SUSY top-squark search

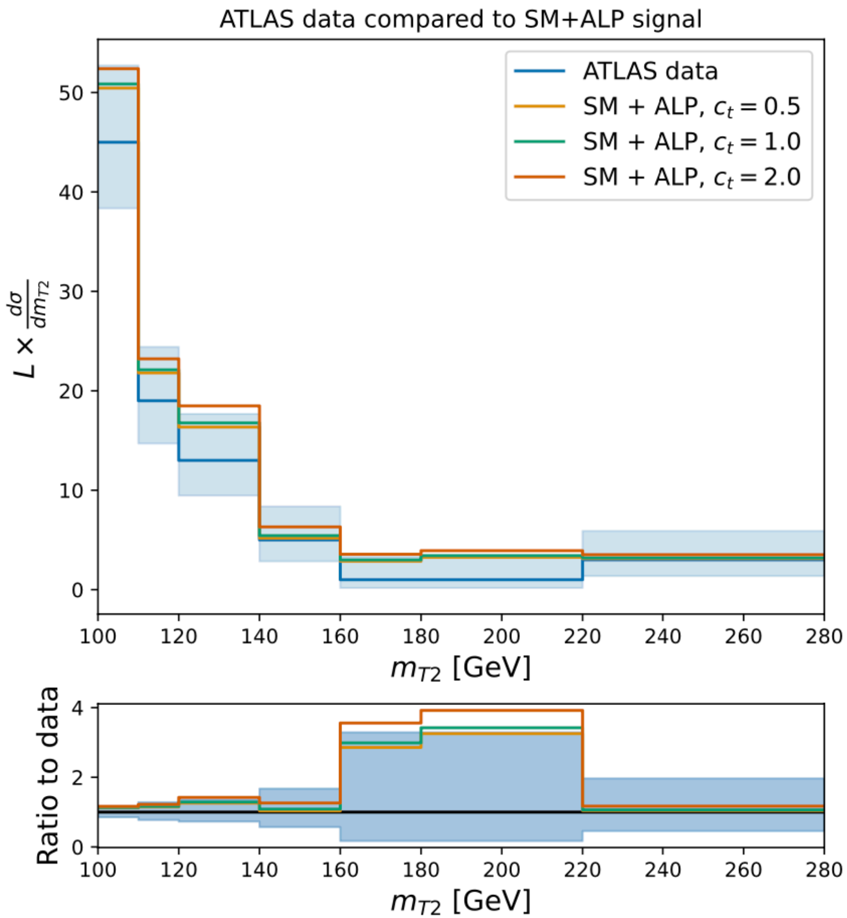
- SM background, ALP signal and SUSY benchmarks all lead to the **same final state topology** of

$$2l + 2j + MET$$

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

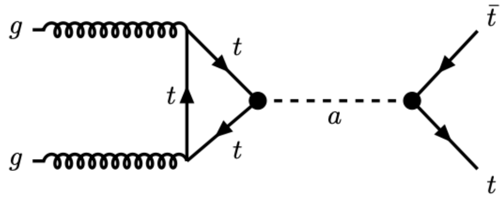
- compare ALP signal + SM background for different c_t to data
- assume a Poison likelihood and use a profiled likelihood ratio to derive limits on c_t/f_a

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



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

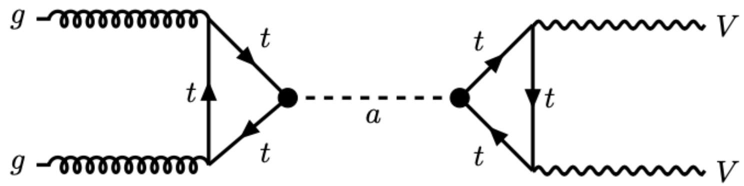
1. **CMS**: $m_{t\bar{t}}$ **distribution** in the lepton + jets channel, Run-II data [2108.02803], lower bins and ALP-SM interference dominate:

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

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

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

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]

Summary of constraints from Run-II data