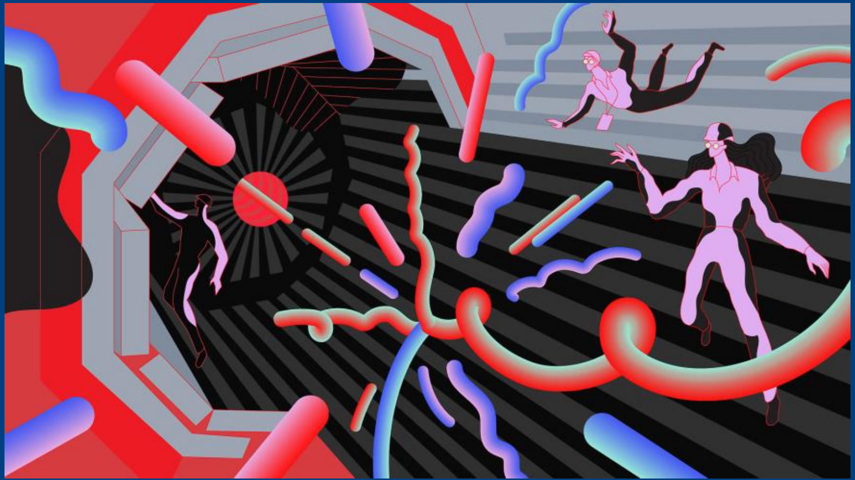
Inauguration workshop RTG 2994, Würzburg, 17-18 March, 2025



Credit: Illustration by Sandbox Studio, Chicago with Ana Kova

The Top Quark: Unlocking New Physics Beyond the Standard Model

Aurelio Juste (ICREA/IFAE)

ICREA

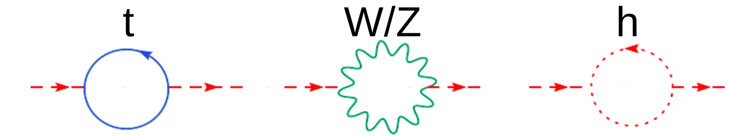
IFAE Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

Top as a window to New Physics

- The top quark dramatically affects the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale Λ:

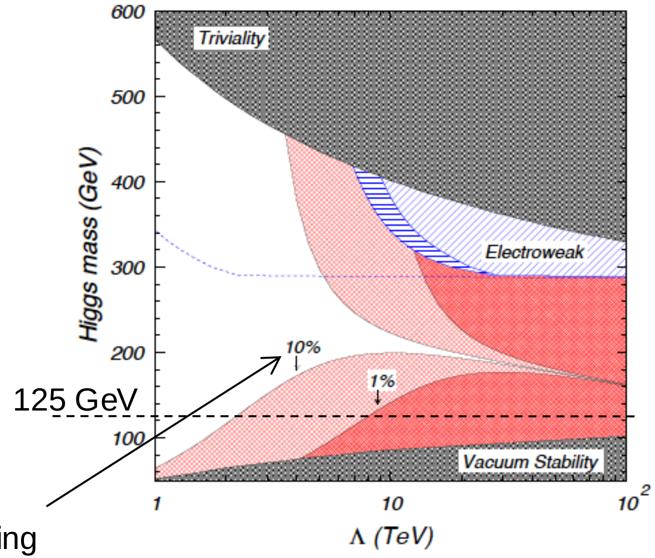


$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Bare mass

Quantum corrections

Λ= New physics cutoff



Amount of fine tuning

Either New Physics appears at a scale Λ or there has to be a very delicate cancellation

If cut-off is at $\Lambda = M_{Pl} = 10^{19}$ GeV, need: $(125\ \mathrm{GeV})^2 \approx (10^{19}\ \mathrm{GeV})^2 - (10^{19}\ \mathrm{GeV})^2$

listening to your favorite radio needs the tuned frequency to match that of the radio channel:

```
radio freq. = 59.05871852091501091981287962349857612 kHz
tuned freq. = 59.05871852091501091981287962349857987 kHz
```

Top as a window to New Physics

- Some proposed solutions to the Hierarchy problem:

  1. **Denial**:
     There is no problem. Naturalness is our problem, not Nature's.
  2. **Weakly-coupled model at the TeV scale:**
     Introduce new particles to cancel SM "divergences".
  3. **Strongly-coupled model at the TeV scale:**
     New strong dynamics enters at ~1 TeV.
  4. **New space-time structure:**
     Introduce extra space dimensions to lower the Planck scale cutoff to ~1 TeV.

Top is the only natural quark

New scalar/vectors possibly strongly coupled with top, exotic top decays,..

tt resonances, BSM 4-top production,…

- More generally, in many BSM models that attempt to address shortcomings of the SM, 3rd-generation fermions, and in particular the top quark, play a key role.

Top as a window to New Physics

- Some proposed solutions to the Hierarchy problem:

  1. Denial:
  There is no problem. Naturalness is our problem, not Nature's.

  2. Weakly-coupled model at the TeV scale:
  Introduce new particles to cancel SM "divergences".

  3. Strongly-coupled model at the TeV scale:
  New strong dynamics enters at ~1 TeV.

  4. New space-time structure:
  Introduce extra space dimensions to lower the Planck scale cutoff to ~1 TeV.

Top is the only natural quark

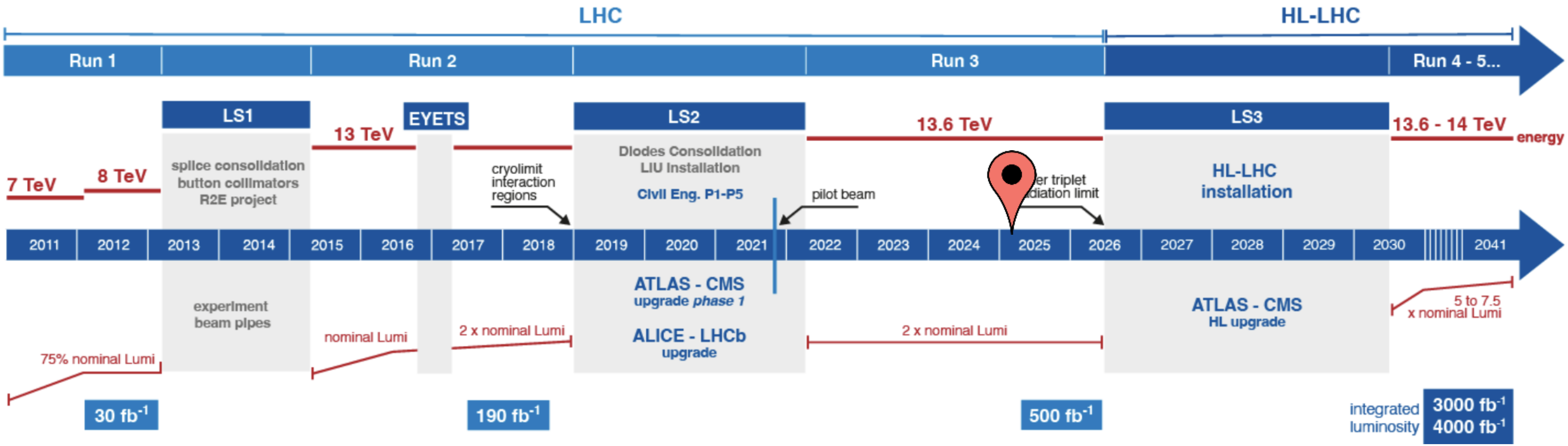
New scalar/vectors possibly strongly coupled with top, exotic top decays,..

tt resonances, BSM 4-top production,…

- More generally, in many BSM models that attempt to address shortcomings of the SM, 3rd-generation fermions, and in particular the top quark, play a key role.

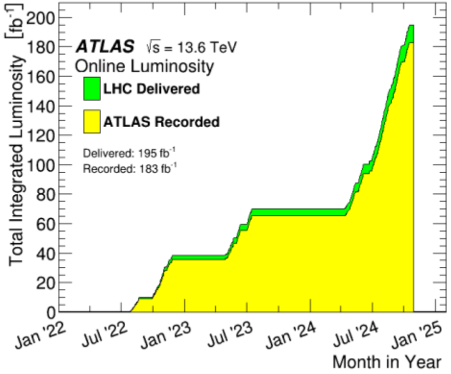
Searches for anomalous top-quark production/decay → New Physics ← Precision measurements of top-quark properties

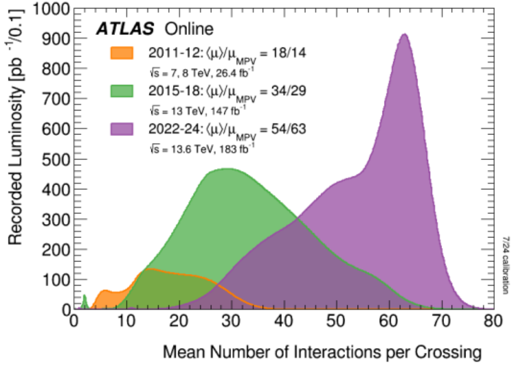
The LHC and the Energy Frontier



- Extremely successful Run 2: 140 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV (good for physics)➔ today's results.
- Run 3 ($\sqrt{s}$=13.6 TeV) underway, till June 2026.

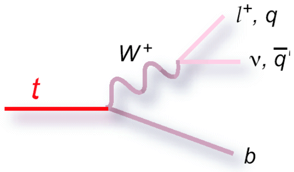
  Expect ~380 fb^{-1} delivered.
- The huge samples of top-quark events collected allow an unprecedented scrutiny of the top-quark sector!



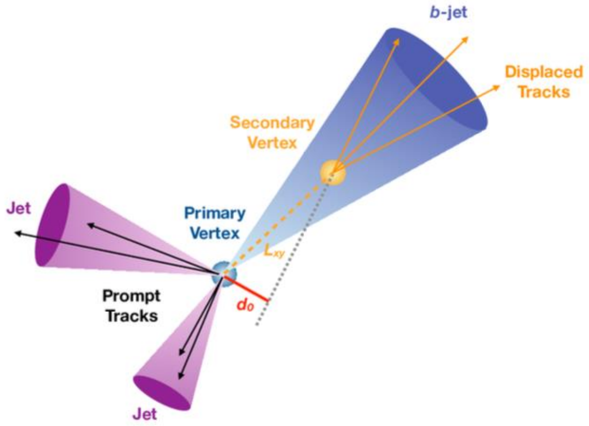


Tools of the trade: b-tagging

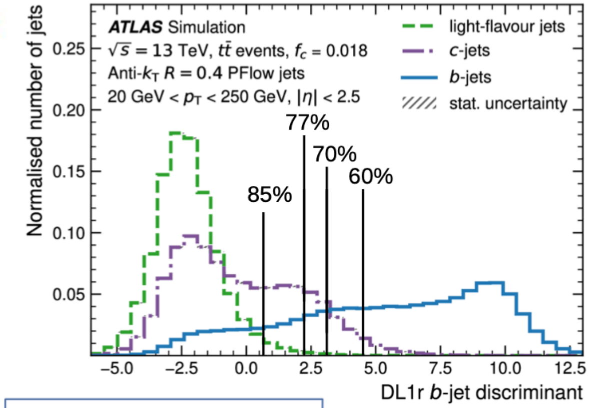
- Top-quark decays within the SM involve a variety of different objects: leptons, E_T^{miss}, jets, b-jets.



- Identification of b-jets is crucial. E.g. in ATLAS:
  - High-level DL1r algorithm based on graph Neural Network operating on outputs from layer of intermediate algorithms (exploiting secondary vertex or impact parameter information).
  - Multi-class output: probabilities for jet being of type b, c or light.
  - Discriminant for b-jets calculated from output probabilities.

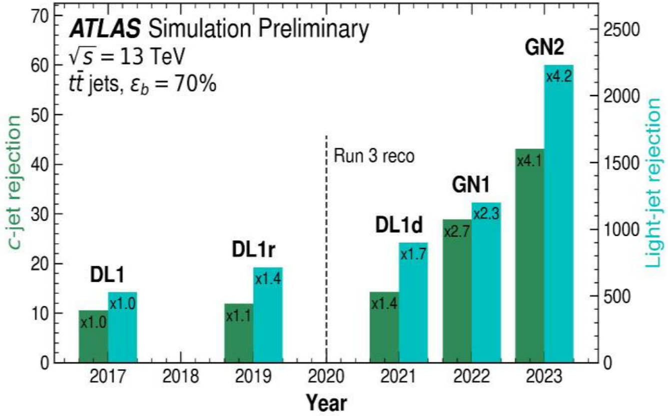


arXiv:2211.16345



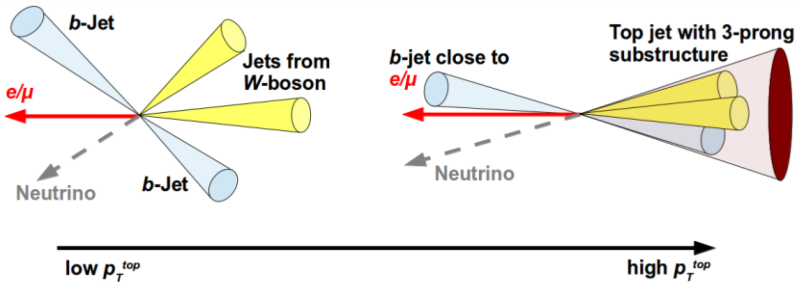
$$D_{\mathrm{DL1r}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\mathrm{light}}}\right)$$

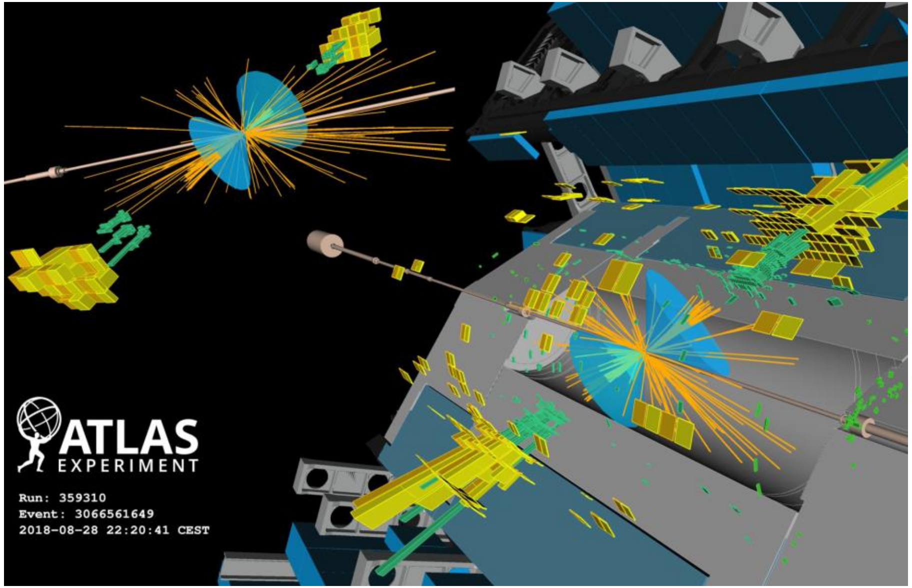
f_c = parameter for tuning charm- and light- jet rejection



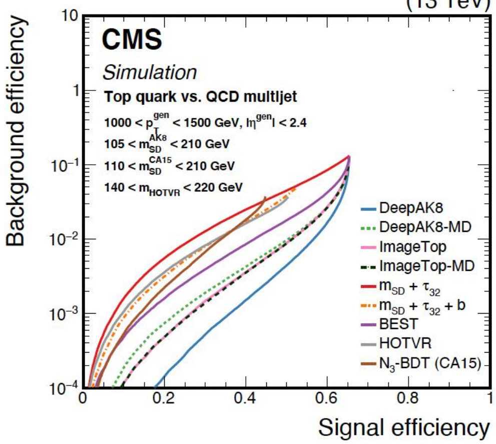
Tools of the trade: top tagging

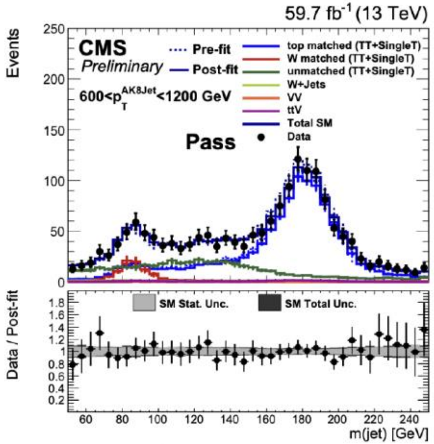
- Decay topology highly dependent on top-quark boost.
- A wide range of top-tagging techniques have been deployed.





[arXiv:2004.08262](https://arxiv.org/abs/2004.08262)

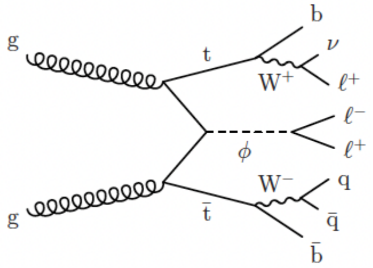




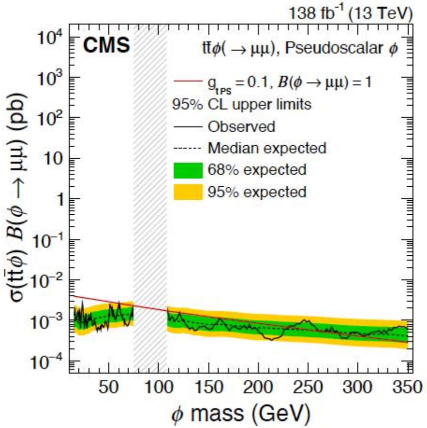
Top and light New Physics

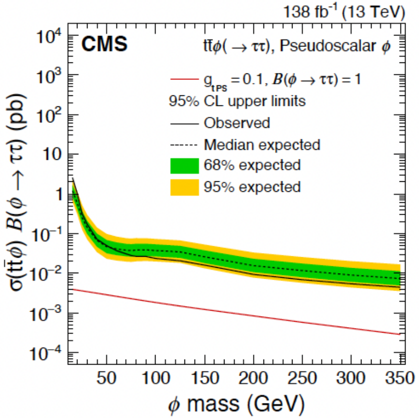
Light neutral scalars

- Naturally light (pseudo-)scalars could be present in the spectrum. Many BSM examples: ALPs, portal dark matter models, Composite Higgs, etc.
- Consider a top-philic ALP: $\mathcal{L}^{(5)}_{top} = c_t \frac{\partial^\mu a}{f_a} \bar{t}_R \gamma_\mu t_R$
- Top couplings induces light fermion couplings and effective couplings between ALP and gauge bosons.
- Particularly unconstrained is the $10<m_a<200$ GeV mass window.
    - Most promising production mode is pp→tta.
    - Main decay mode is a→bb, followed by a→cc, ττ.
    - Also expect virtual effects/off-shell contribution to affect tt differential cross-sections, 4-top production, etc.

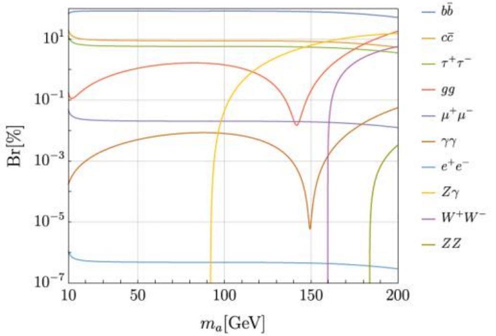


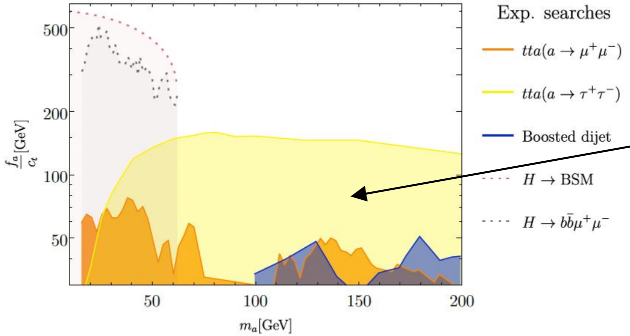
arXiv:2402.11098





arXiv:2311.16048

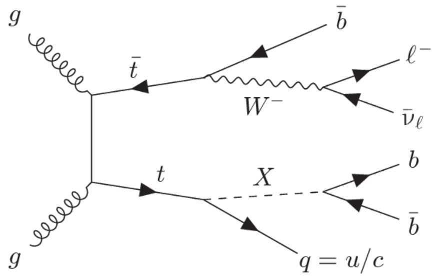


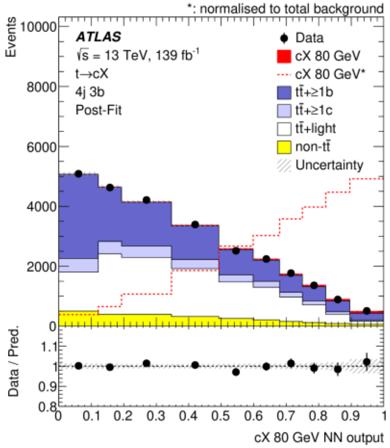


ATLAS result on tta(→bb) imminent!

Light flavour-violating neutral scalars

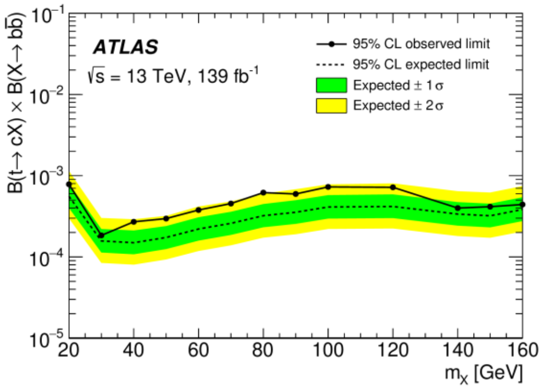
- Light flavour-violating scalars with preferential couplings to the top quark are predicted in several BSM scenarios (flavons, ALPs, etc).
- E.g. flavons appear in models that address the flavour puzzle via the Froggatt-Nielsen mechanism. The lightest flavon is a pseudoscalar with couplings to SM fermions proportional to their Yukawas.
- **Production**: in top decays, t→ac (for $m_a<m_t$)
  gg/bb→a and gc→ta
- **Decay:** bb, followed by cc/ττ (for $m_a<m_t$)
  tc (for $m_a>m_t$)





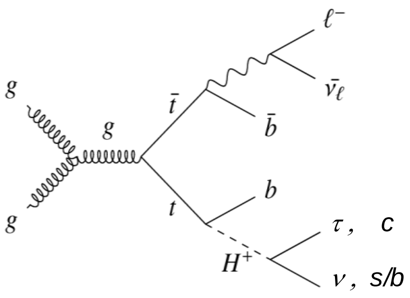
arXiv:2301.03902

- Search focused on a light flavor-violating scalar produced in top-quark decays and decaying into bb.
- Analysis targets lepton+jets channel with ≥3b (60% WP).
- Sophisticated MVAs used to discriminate signal from background.
- Complementary to searches for a→tq and qq→tt (SS tops), which target heavier flavons.



Comparable limits for t→uX

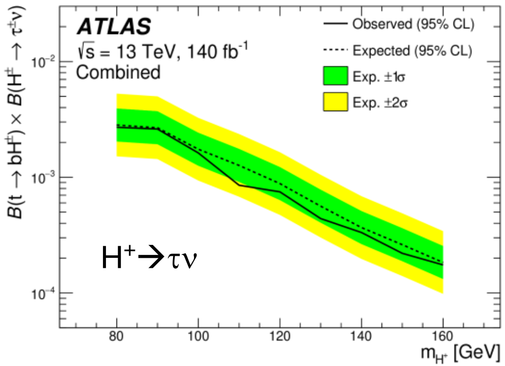
Light charged scalars



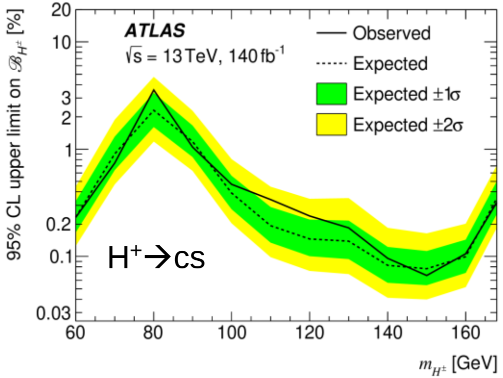
- In 2HDMs, the top quark can decay into a light charged Higgs boson (or be produced in association with it, for heavier m_{H+}).
- Typical decay modes $H^+ \to \tau\nu$, cs being probed down to BRs at the per-mille level.

- In 3HDMs (and other models) the charged Higgs boson can dominantly decay into cb.
- First ATLAS search targeting this signal.
- 3.0σ local (2.5σ global) excess at 130 GeV. Consistent with mass resolution.
- Being followed up in Run 3!

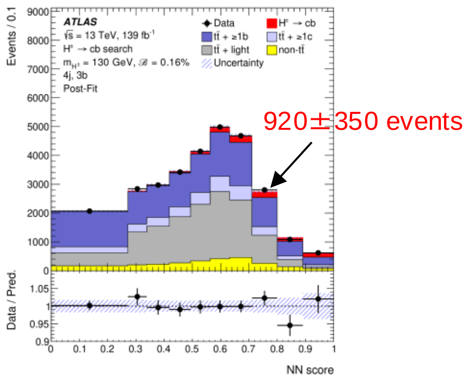
arXiv:2412.17584

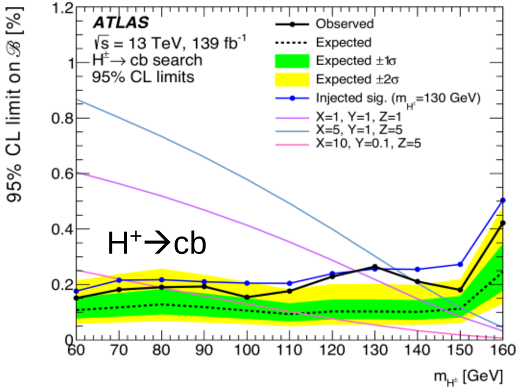


arXiv:2407.10096



arXiv:2302.11739

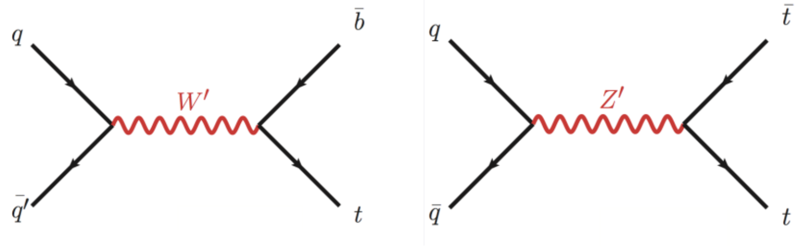




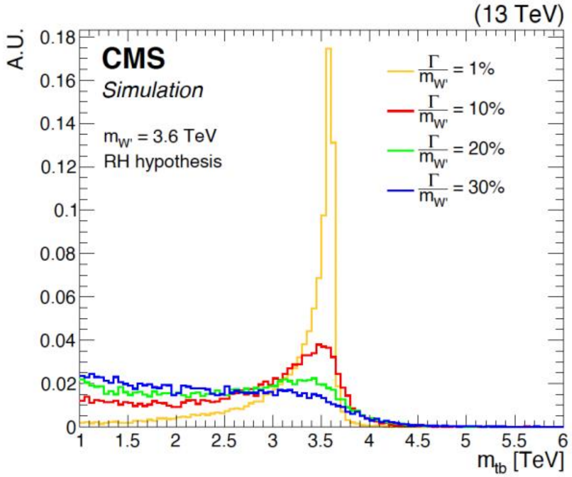
Top and heavy New Physics

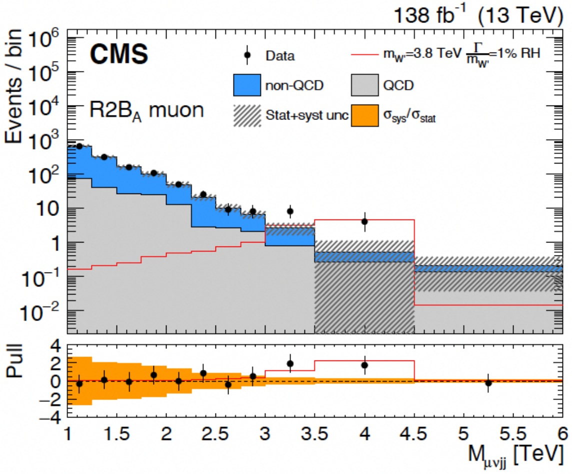
Top-philic heavy resonances: W', Z'

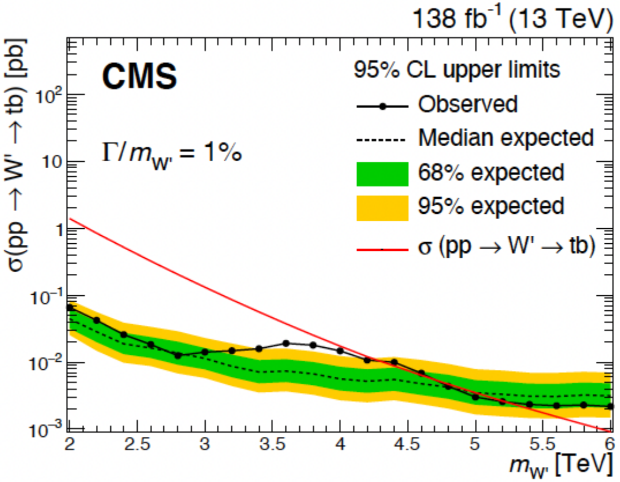
- Many BSM scenarios include heavy W' and Z' preferentially coupled to 3rd generation fermions.
- The signal can be searched for as a peak in the invariant mass distribution (small Γ/M) or a tail enhancement (large Γ/M).
- At high mass boosted hadronic top/W decay products merge into a large-R jet. Need dedicated boosted-object tagging!
- In the case of leptonic W decays, need optimized lepton isolation to handle the overlap of the lepton with the b-jet from the top decay.



arXiv:2310.19893

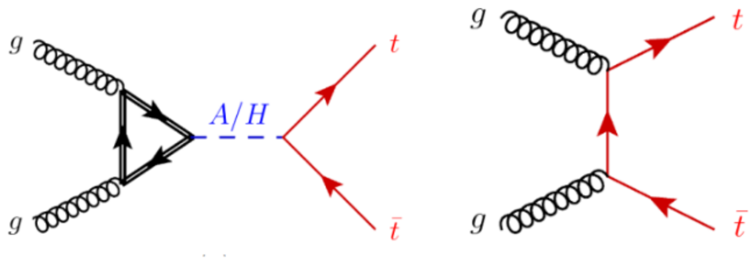






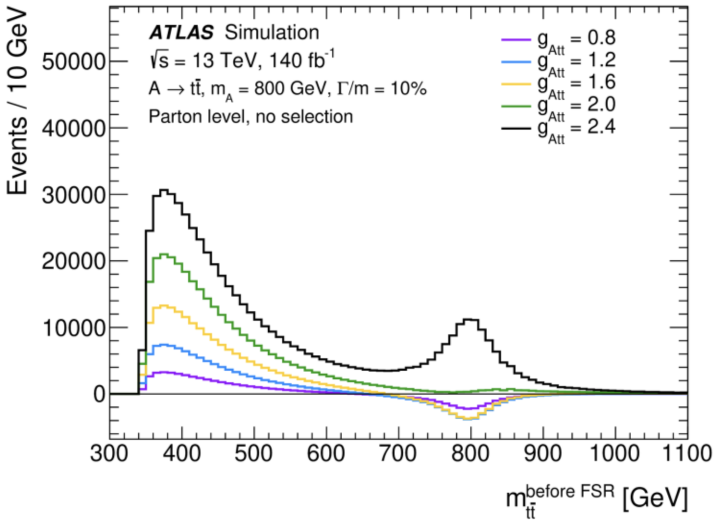
Top-philic heavy resonances: H/A

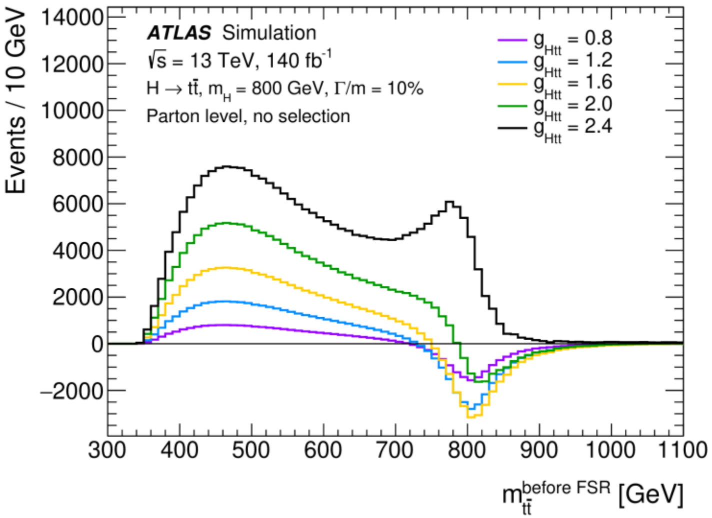
- A search for a H/A→tt is quite different from a search for Z'→tt:
  - Typically target lower masses ($m_{H/A}$<1 TeV).
  - There is strong interference between signal and SM tt production, and the interference pattern depends strongly on the model parameters.
- Requires to achieve the best possible mass resolution and exquisite control over the background shape and normalization.



arXiv:2404.18986

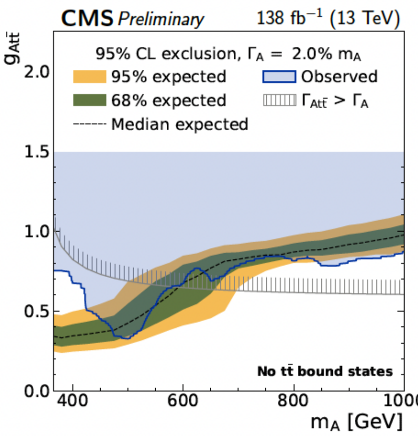
Signal-plus-interference distributions at parton level

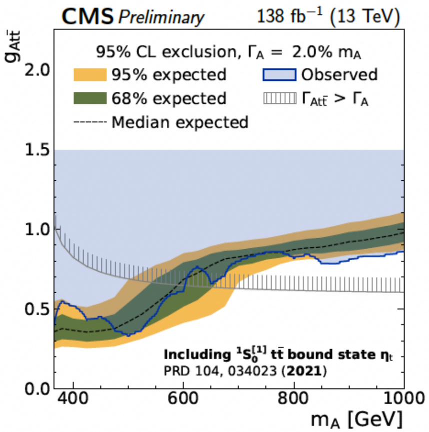


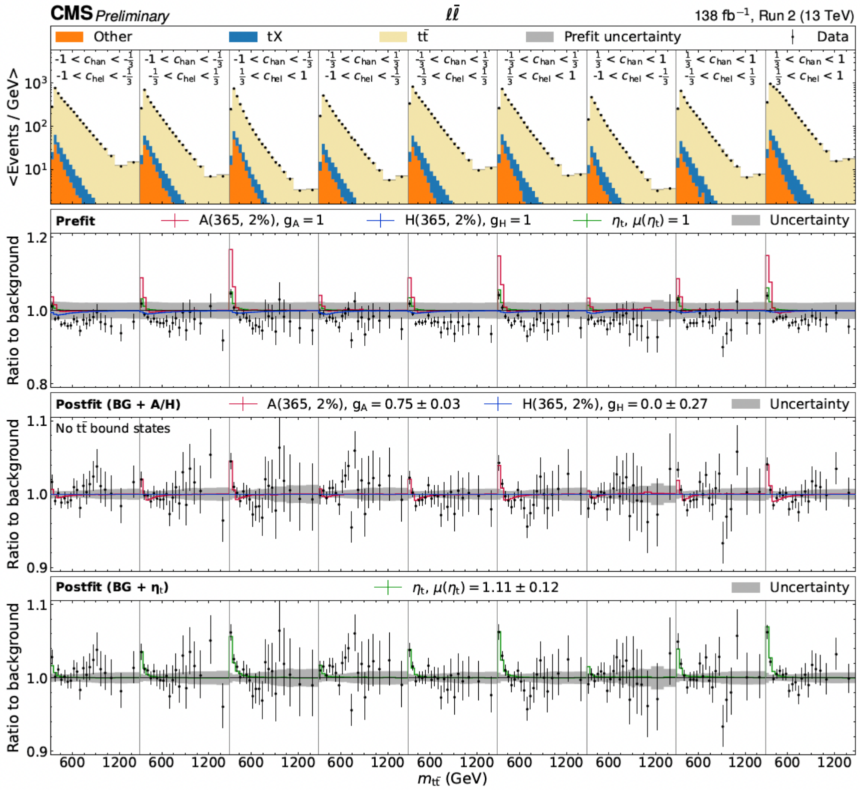


Top-philic heavy resonances: H/A

- Search targets the 1L+jets and 2LOS+jets channels.
- Kinematic reconstruction is applied to both channels.
- Events categorized using angular variables sensitive to the spin and CP state of the tt system.
- A fit is performed to the m_{tt} distributions across all event categories using a sophisticated systematic model. Still, non-trivial pulls and constraints are obtained on the nuisance parameters.
- No significant excess found when including in the fit the contribution from toponium (see Andreas's talk).





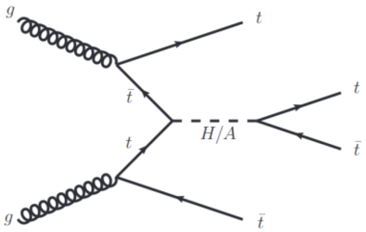


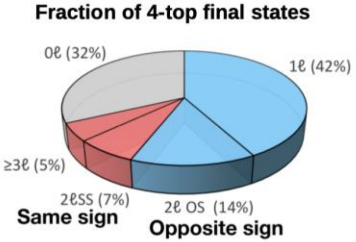
ATLAS search has similar sensitivity but no significant excess at low m_A

HIG-22-013
arXiv:2404.18986

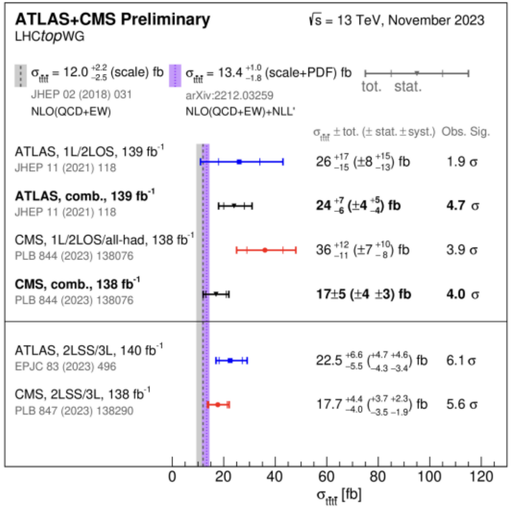
Top-philic heavy resonances: ttH/A→tttt

- Measured 4-top cross-section somewhat above the SM prediction.
- Motivates search for top-associated production of H/A decaying into tt.
- Compared to gg→H/A→tt, subdominant production mode but interference with SM background expected to be small.
- Search targets separately multilepton (2LSS/3L) and 1L/2LOS final states, with high b-jet multiplicity.
- Sophisticated Neural Networks for signal-to-background discrimination.
- All channels combined and results interpreted in Type-II 2HDM.

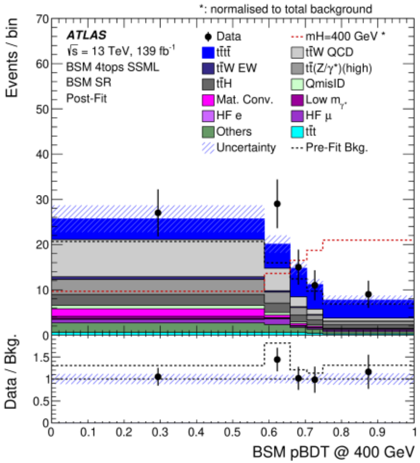


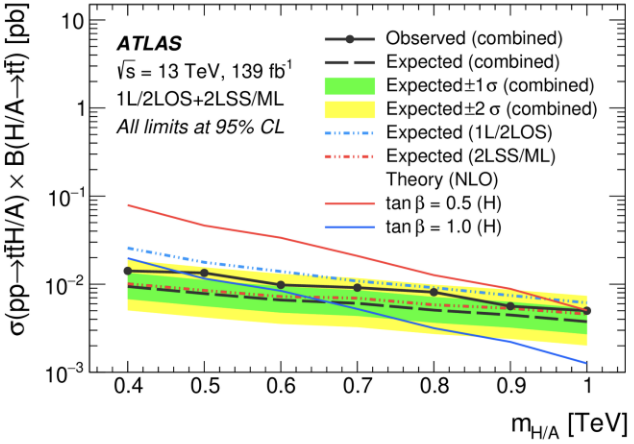


arXiv:2408.17164



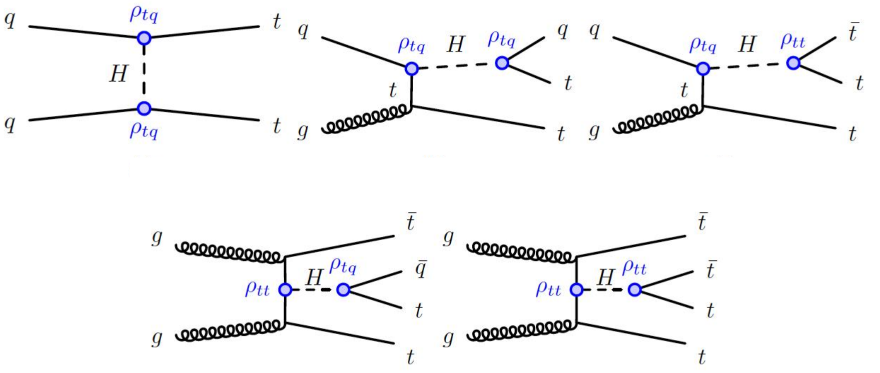
arXiv:2211.01136

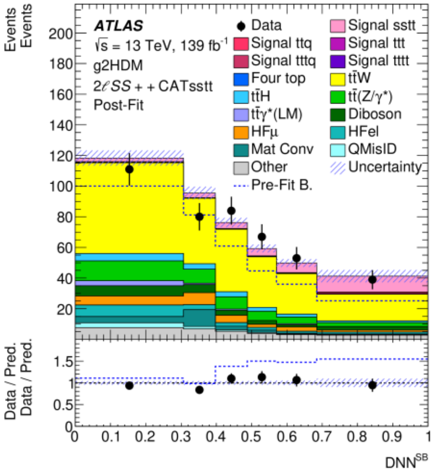


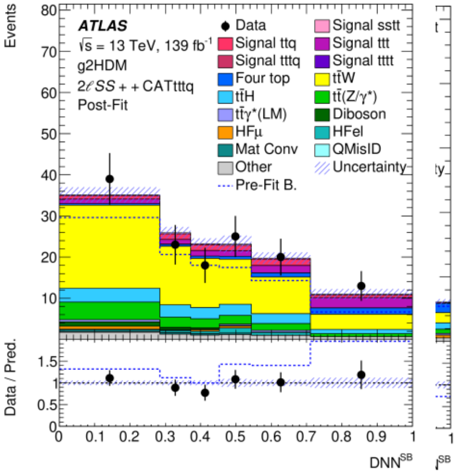


Heavy flavour-violating neutral scalars

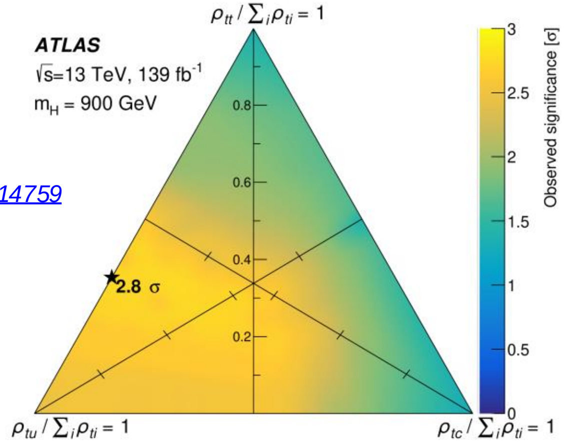
- Broad search for flavour-violating scalars in a general 2HDM.
  - Could also be interpreted in the context of flavon models.
- Target SS tops, SS tops+jet, 3-tops, 3-tops+jet and 4-top processes in multilepton final states (2lSS, 3l, 4l).
- Exploiting charge asymmetry and kinematics (via a mass-independent NN).
- Most significant local excess 2.8σ at m_H=900 GeV, ρ_{tt}=0.6, ρ_{tc}=0, ρ_{tu}=1.1, but excess broad in parameter space.
- Being followed up in Run 3!





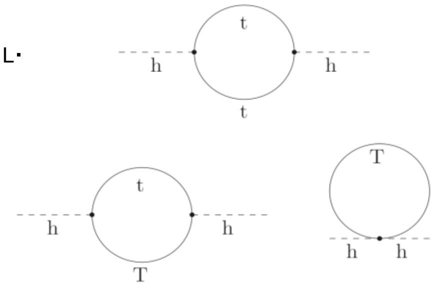


[arXiv:2307.14759](https://arxiv.org/abs/2307.14759)

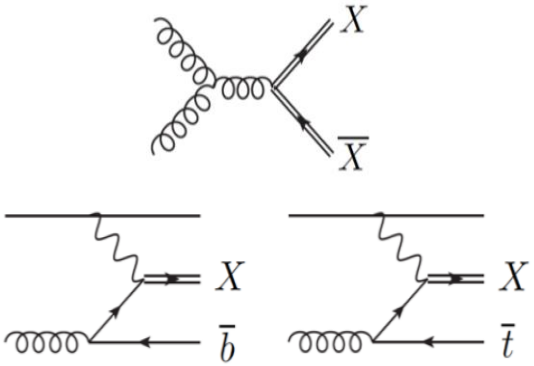


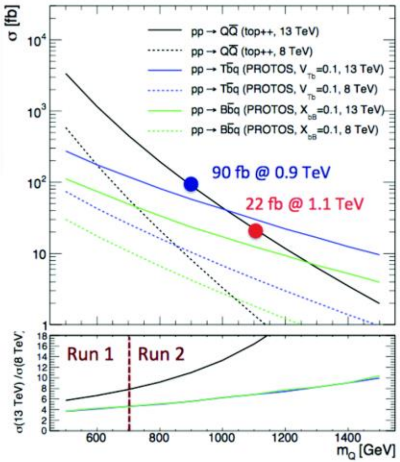
Vector-like quarks

- Colored spin-1/2 fermions whose left and right components transform the same under $SU(2)_L$.
- Present in many BSM extensions: e.g. Composite Higgs, extra dimensions.
- Can mix with their SM counterparts and regulate the Higgs mass-squared divergence
  ➔ attractive solution to the Hierarchy Problem.
- Typically assume preferred mixing with the 3rd generation ➔ vector-like top/bottom.

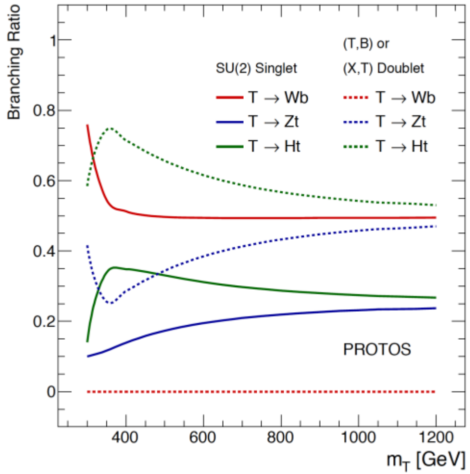


Production:
- Pair production: via QCD, "universal" production mode (just depends on m_Q).
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.





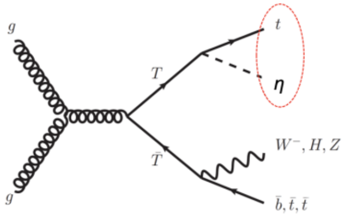
Decay:
- T➔Wb, Zt, Ht, all with sizable BR

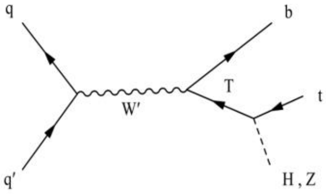


Vector-like quarks

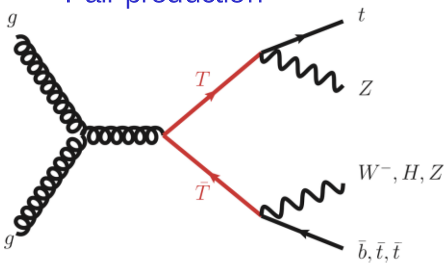
- Broad program of pair production and single production searches using full Run 2 dataset.
- Pair production reach is typically ~1.5 TeV when combining multiple searches.
- Single production searches extend reach to higher mass depending on the assumed coupling strength.

- New efforts targeting non-minimal Composite Higgs scenarios and resonant VLQ production, e.g.:
  - T→tη, η=pseudoscalar
  - Exotic VLQ production through heavy vector resonances.

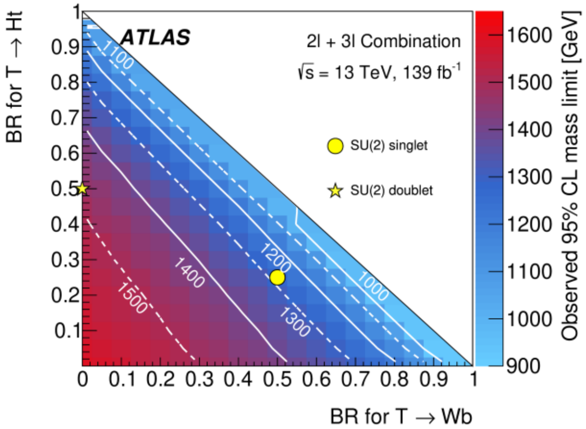




Pair production

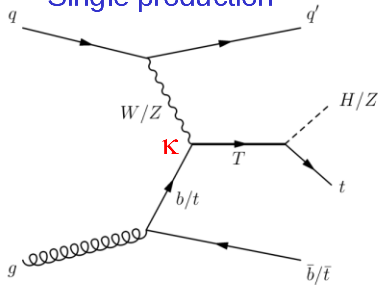


Signature: Z(→ll)+Multiple tags (t/H/V)

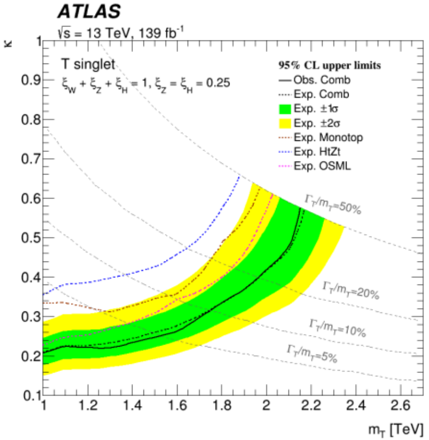


arXiv:2210.15413

Single production



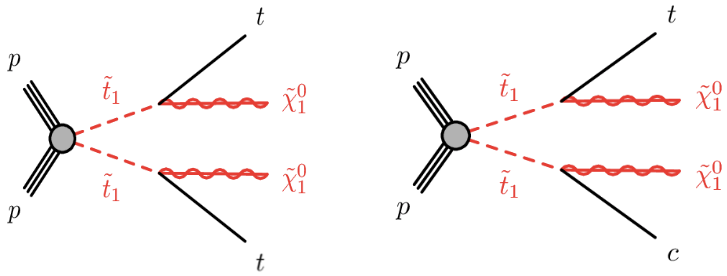
ATLAS combination of single T→tH/tZ searches

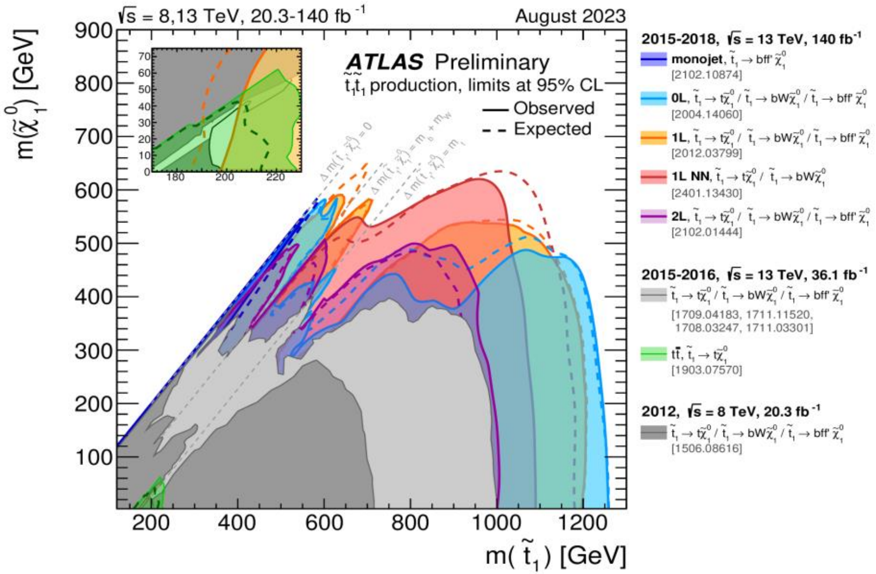


arXiv:2408.08789

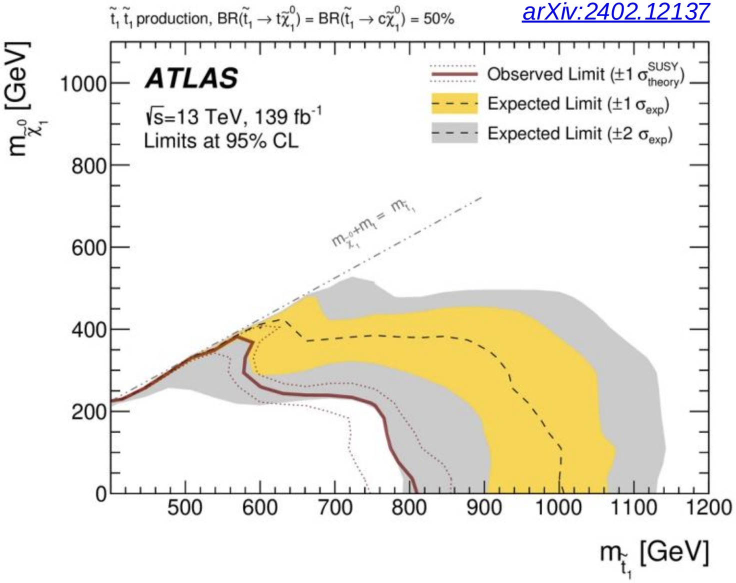
Top and Natural SUSY

- In the context of Natural SUSY, the search for light stops is one of the highest-profile topics at the LHC.
- Depending on the mass spectrum, the main decay mode of a light stop is into a top and neutralino, resulting in a tt+E_T^{miss} signature.
- In some SUSY scenarios, stops can decay into a top or a charm, giving tc+E_T^{miss}.



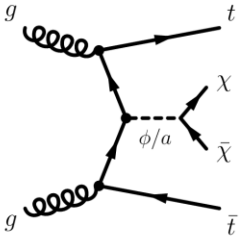


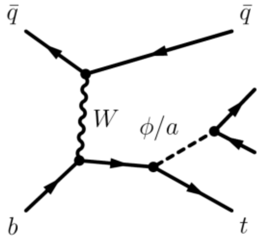
[arXiv:2402.12137](https://arxiv.org/abs/2402.12137)

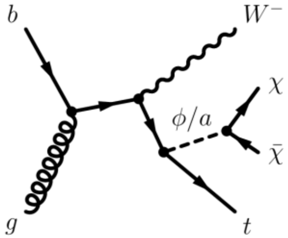


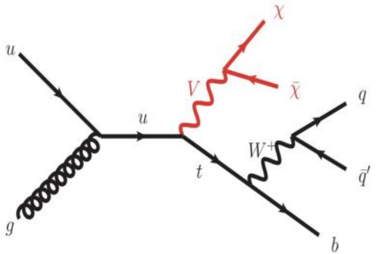
Top and dark matter

- Several DM models include spin-0 mediators or flavour-violating vector mediators preferentially coupled to top.
- This results in final states with tt+E_T^{miss}, tq+E_T^{miss}, tW+E_T^{miss} and even just t+E_T^{miss} (monotop).

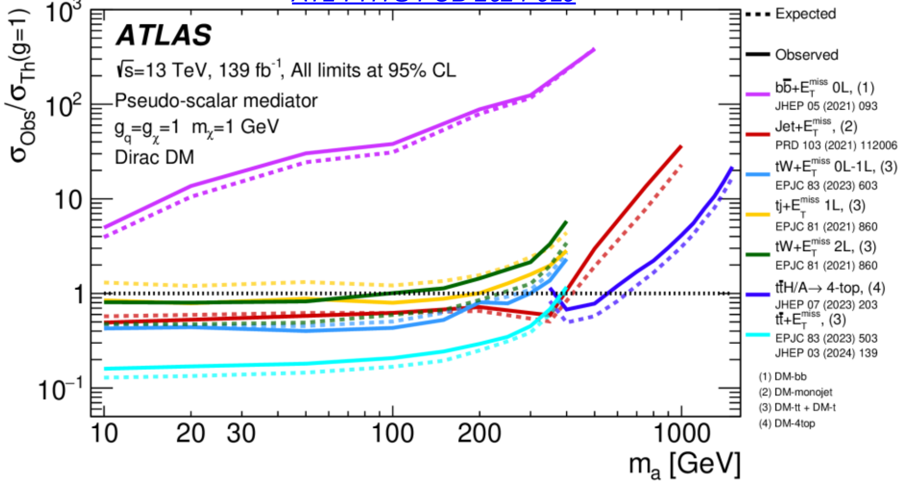




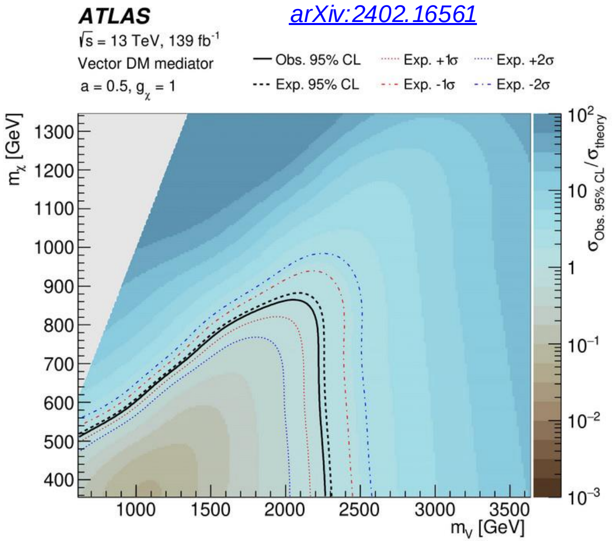




[ATL-PHYS-PUB-2024-010](https://cds.cern.ch/)

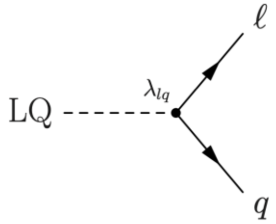


arXiv:2402.16561

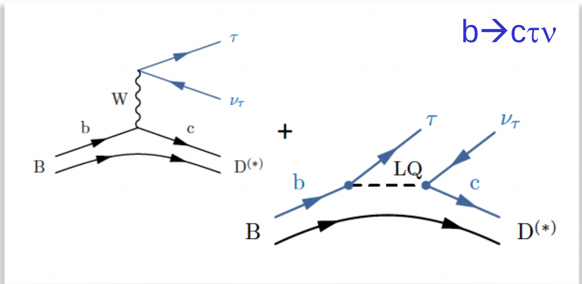


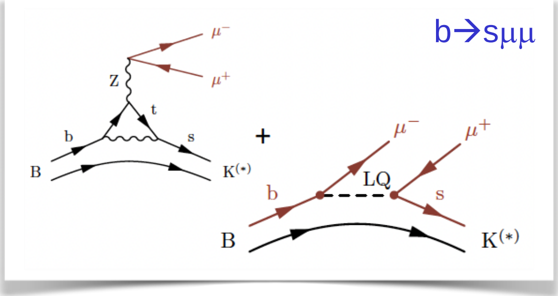
Leptoquarks

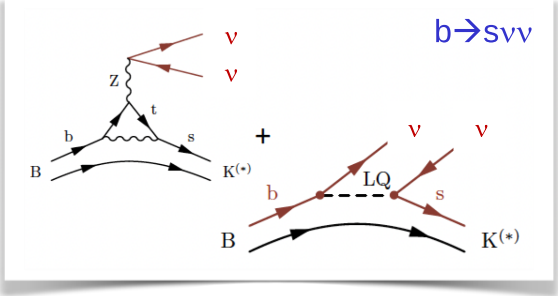
- Leptoquarks (LQ) appear in BSM extensions trying to address the SM flavour (and other) puzzles, e.g. GUT SU(5), Pati-Salam SU(4), RPV SUSY, Composite Higgs models.
  - Scalars (*S*, *R*) or vectors (*U*)
  - Have fractional charge and carry color, B and L quantum numbers
  - Mediate interactions between quarks and leptons

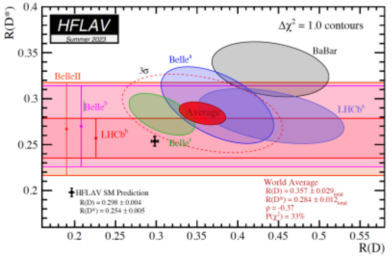


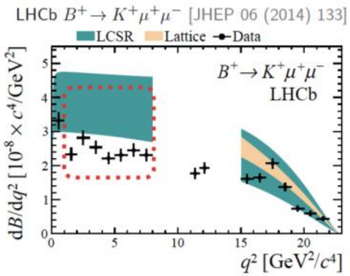
- Can provide an explanation for different flavour anomalies:

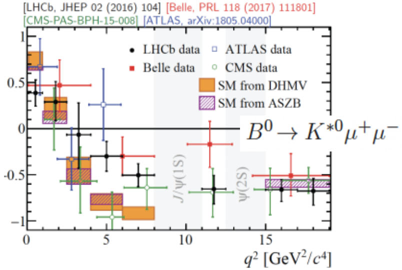


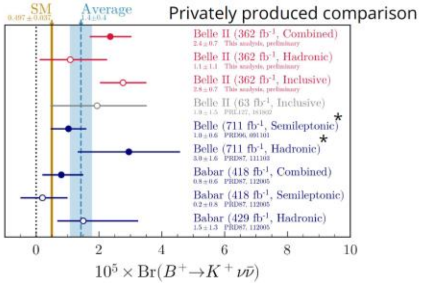






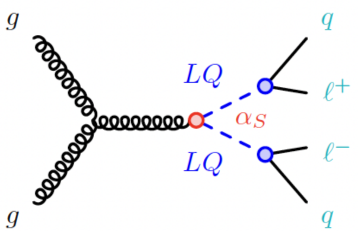






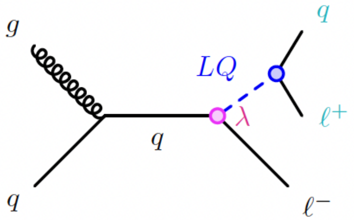
Leptoquarks

Pair production



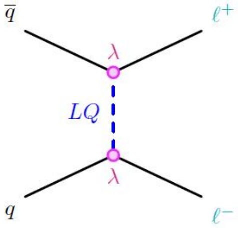
QCD production (universal mode)
σ only depends on m_{LQ}
Sensitivity to low m_{LQ}

Single production

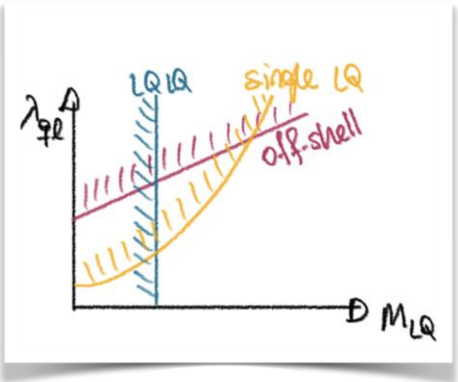


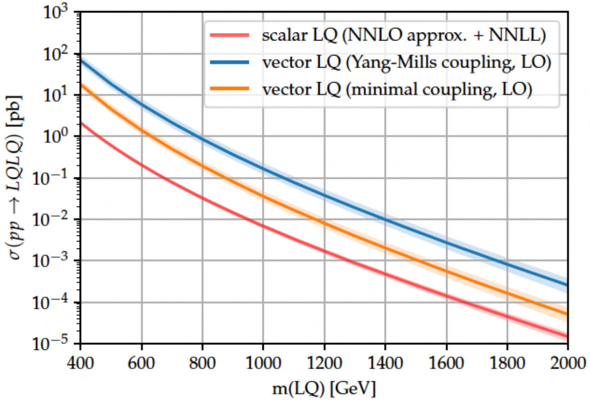
Depends on q PDF
$\sigma \sim \lambda^2$
Sensitivity to higher m_{LQ}
if λ sufficiently large

Off-shell production



(Depends on q PDF)^2
$\sigma \sim \lambda^4$
Sensitivity to very high m_{LQ}
if λ sufficiently large





- Explanations of the flavor anomalies put the focus on particular couplings:

E.g. for the U_1 LQ: $$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \approx \begin{pmatrix} 0 & 0 & +0.04 \\ 0 & +0.02 & +0.2 \\ 0 & -0.2 & 1 \end{pmatrix}$$

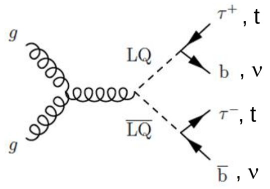
arXiv:2103.16558

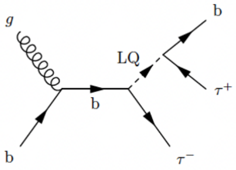
$LQ \approx LQ_3$

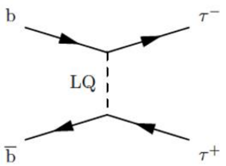
- However, other coupling textures are possible and there may be other LQs that do not affect flavor anomalies ➔ Need a broad program!

Leptoquarks

- Broad program of searches for pair-production for both scalar and vector LQs.
- Growing program of single LQ searches.
- Increasing focus on non-resonant production to reach highest masses.

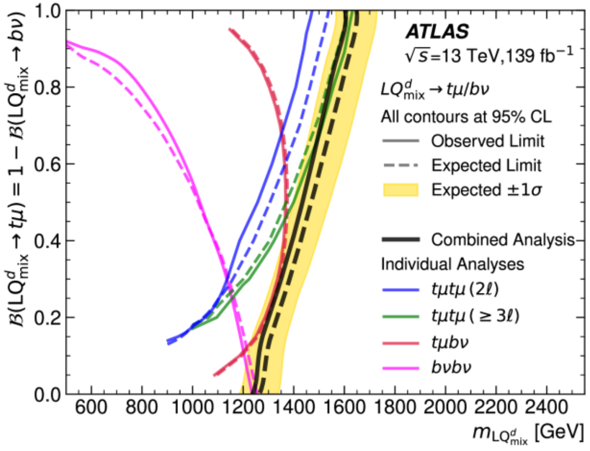


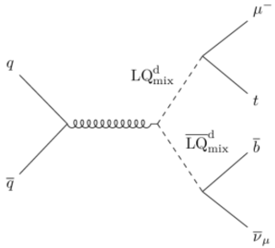




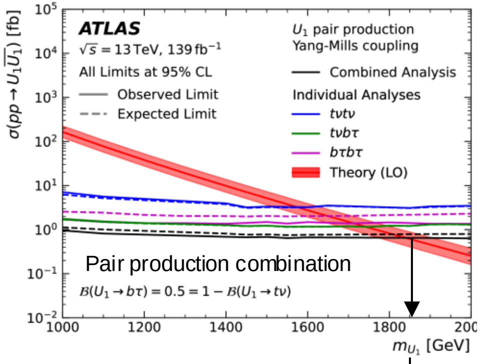
- Also consider scalar LQs with cross-generational mixing, e.g.:

arXiv:2401.11928

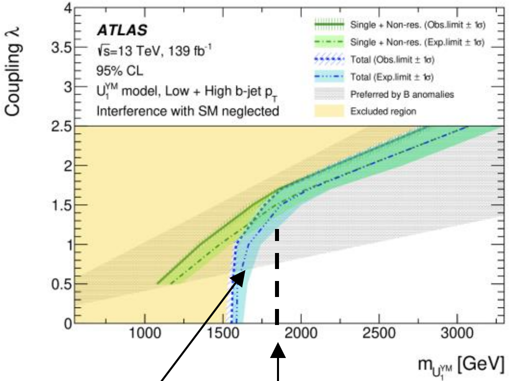




arXiv:2401.11928



arXiv:2305.15962

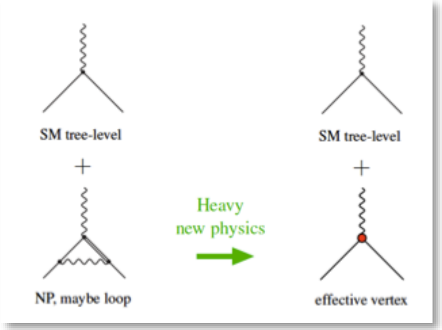


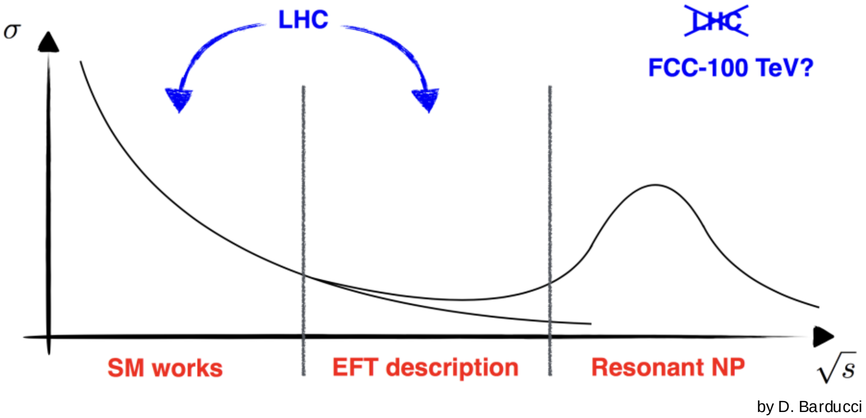
Combination of U_1 production modes

Top and ultra-heavy New Physics

Effective Field Theory

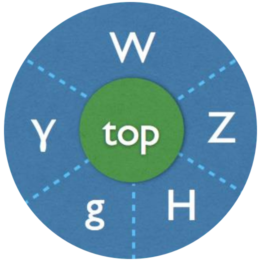
- The experimental results so far point to a situation where $M_X >> \sqrt{s}$.
  ➔ New states too heavy to be resonantly produced.
- Integrate out explicitly heavy mediator and have instead an effective interaction.





- Assume production & decay dominated by SM.
- Search for new physics indirectly through precision measurements of SM observables.

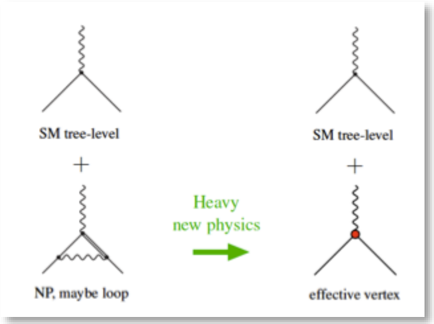
Top couplings in the SM and beyond



- The top quark couples to the other SM fields through its gauge and Yukawa interactions with well-defined Lorentz structure.

to W boson	$\frac{g_W}{\sqrt{2}} \sim 0.45$	$\frac{g_W}{\sqrt{2}} V_{tq} \bar{t}_L \gamma^\mu q_L \, W_\mu^-$
to Z boson	$g_Z = \frac{g_W}{4\cos\theta_W} \sim 0.14$	$g_Z t_L \left[(1 - \frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu\gamma_5\right] t_L \, Z_\mu$
to photon	$e_t = \frac{2}{3} e \sim 0.21$	$e_t \bar{t} \gamma^\mu t \, A_\mu$
to gluon	$g_s \sim 1.12$	$g_s \bar{t}_j \gamma^\mu \, T_{jk}^{SU(3)} t_k \, G_\mu$
to Higgs	$Y_t = \frac{g_W m_t}{\sqrt{2} M_W} \sim 1$	$\frac{Y_t}{\sqrt{2}} \bar{t} t \, H$

- New Physics contributions can lead to deviations from the SM prediction.



Effective Vf_if_j vertices, V=W, Z, γ, g:

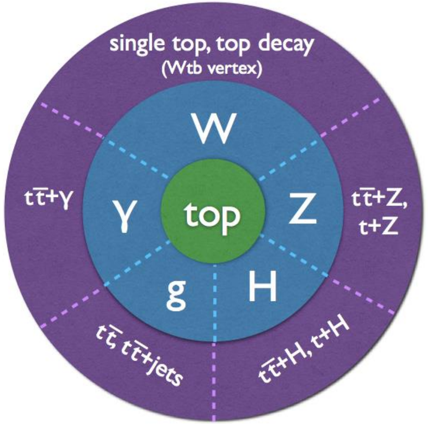
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R)\, t\, W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R)\, t\, W_\mu^- + \text{H.c.}\,.$$

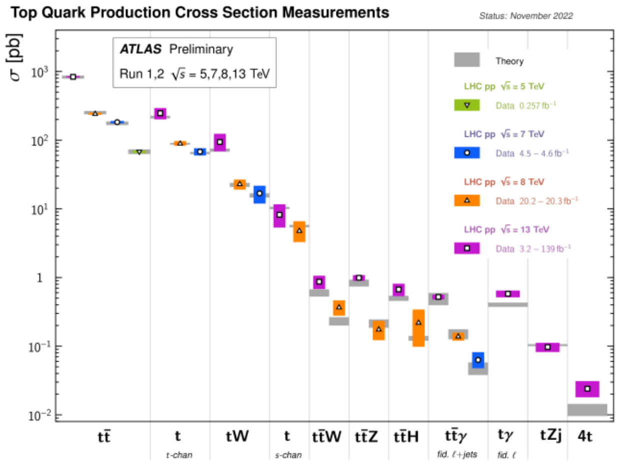
$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W} \bar{t} \gamma^\mu \left(X_{tt}^L P_L + X_{tt}^R P_R - 2s_W^2 Q_t\right) t\, Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (d_V^Z + i d_A^Z \gamma_5)\, t\, Z_\mu\,,$$

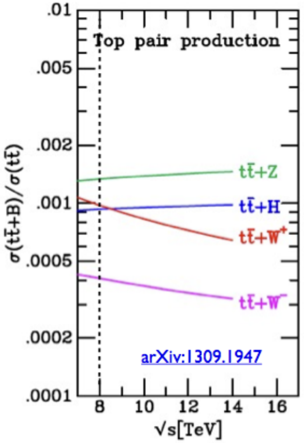
$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t} \gamma^\mu t\, A_\mu - e\bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^\gamma + i d_A^\gamma \gamma_5)\, t\, A_\mu$$

$$\mathcal{L}_{gtt} = -g_s \bar{t} \frac{\lambda^a}{2} \gamma^\mu t\, G_\mu^a - g_s \bar{t} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (d_V^g + i d_A^g \gamma_5)\, t\, G_\mu^a$$

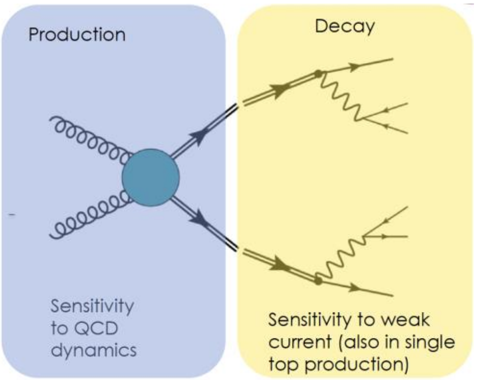
Probing top couplings at the LHC





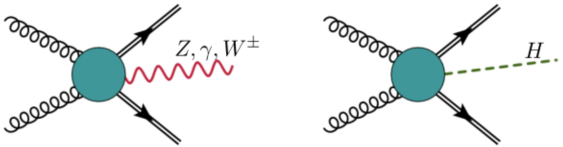


tt / single-top production & decay



The LHC is not only a top-quark factory, but it opens the door to a whole new class of processes:

tt+X production



Associated production adds sensitivity to neutral currents (Z/γ) and Yukawa interactions (Higgs)

13 TeV	Run 2 (140 fb^{-1})
tt	~120 M
tt+γ	~400k
tt+Z	~140k
tt+H	~80k

The SM Effective Field Theory (SMEFT)

- The effects of new physics at a scale Λ can be described by an effective Lagrangian.
- Consider all higher-dimensional operators that can be built from SM fields and respecting the SM symmetries:

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

O_i = dim 6 gauge invariant operators

C_i=complex constants

Operators involving the top quark

$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I$$
$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W_{\mu\nu}^I$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G_{\mu\nu}^A$$
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$
$$O_{\varphi G} = g_s^2 (\varphi^\dagger\varphi)\, G_{\mu\nu}^A G^{A\mu\nu}$$

4-fermion ops

- Complete, independent set of dim-6 operators: Warsaw basis.
- These operators can induce corrections to SM couplings.

  E.g. Effective Lagrangian for Wtb interaction:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu (V_L P_L + V_R P_R)\, t\, W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu} q_\nu}{M_W}(g_L P_L + g_R P_R)\, t\, W_\mu^- + \text{H.c.}\,.$$

$$\delta V_L = C_{\phi q}^{(3,33)*}\frac{v^2}{\Lambda^2}, \qquad \delta g_L = \sqrt{2} C_{dW}^{33*}\frac{v^2}{\Lambda^2};$$
$$\delta V_R = \frac{1}{2} C_{\phi\phi}^{33}\frac{v^2}{\Lambda^2}, \qquad \delta g_R = \sqrt{2} C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

- But many operators to consider!

The SM Effective Field Theory (SMEFT)

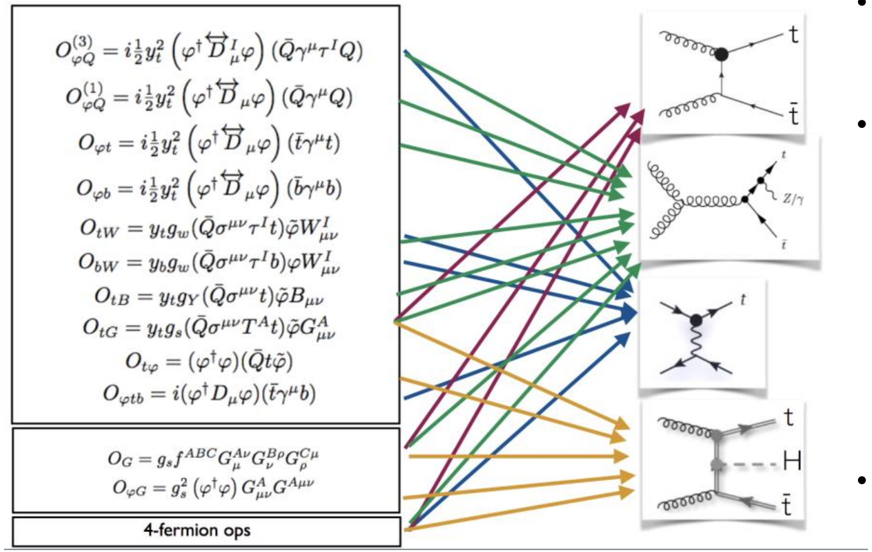
- The effects of new physics at a scale Λ can be described by an effective Lagrangian.
- Consider all higher-dimensional operators that can be built from SM fields and respecting the SM symmetries:

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

O_i = dim 6 gauge invariant operators

C_i=complex constants

Operators involving the top quark



- Multiple measurements can be sensitive to the same operator and vice-versa (e.g. ttZ cross section sensitive to the coupling to the gluon and to the Z boson).
- The ultimate goal is to find observables that are sensitive to the various possible EFT operators coefficients

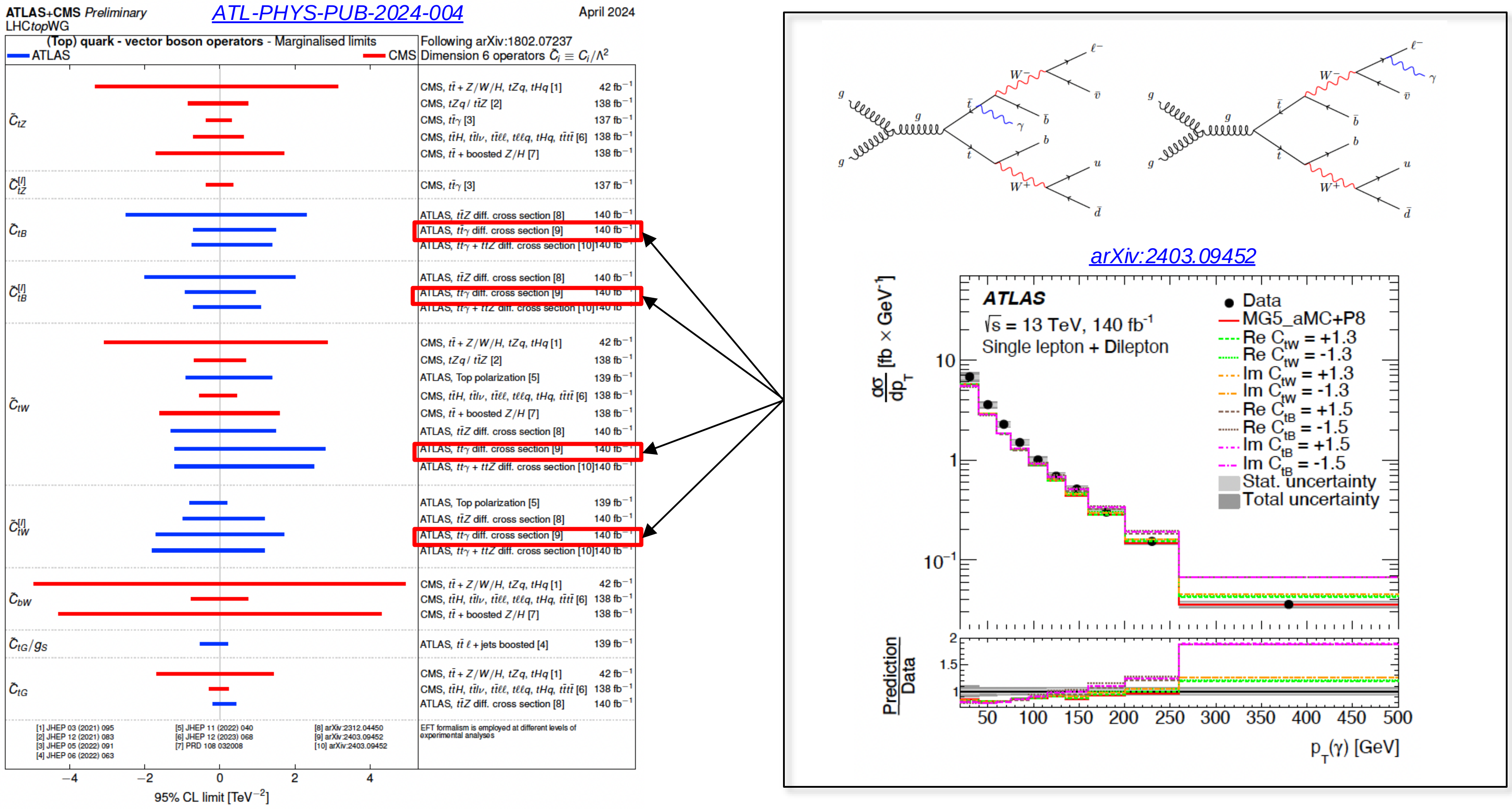
$$\mathcal{O}^i = f(c_1^i, c_2^i, ..., c_n^i)$$

set of observables — Dependence with the parameters (anomalous couplings, effect. operators coefficients)

and then perform a global fit to all observables, considering proper correlations of systematic uncertainties.

- This requires a coordinated effort among theorists and experimentalists (being followed up within LHCtopWG).

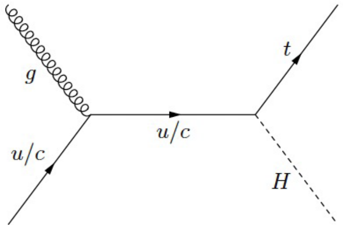
The SM Effective Field Theory (SMEFT)



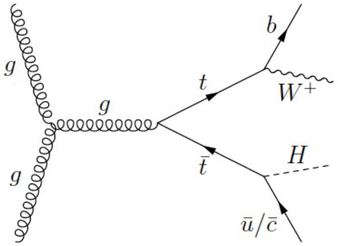
Top FCNC interactions

- Within the SM, neutral-current interactions are flavour-diagonal at tree level.
- Flavour-changing neutral-current interactions are loop-induced and tiny: BR(t→cg)~10^{-12}, BR(t→cγ)~10^{-14}, BR(t→cZ)~10^{-14}, BR(t→cH)~10^{-15}. Can be significantly enhanced in models beyond the SM.
- Example: Search for FCNC tHu and tHc interactions
  - Consider both tH production and tt decay.
  - Several analyses targeting different Higgs decay modes: H→γγ, H→ττ, H→WW/ZZ, H→bb, and their combination.

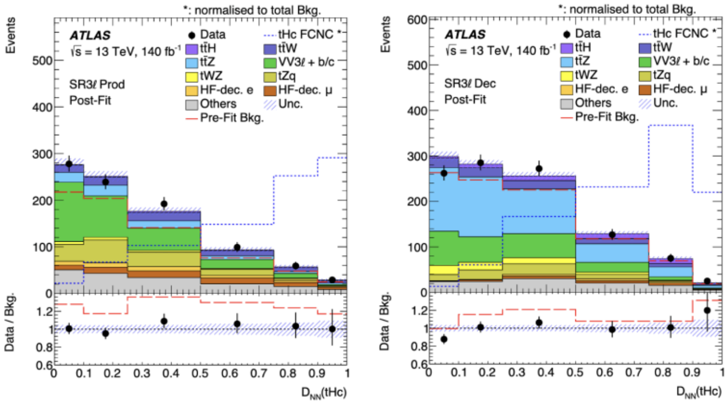
FCNC in production



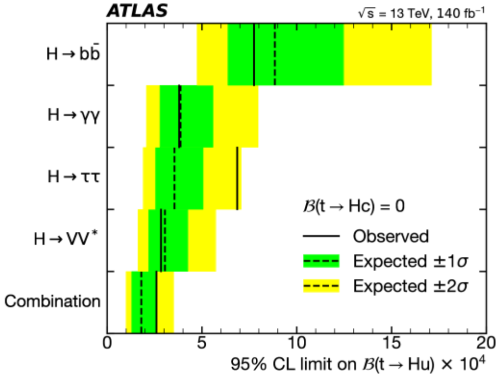
FCNC in decay



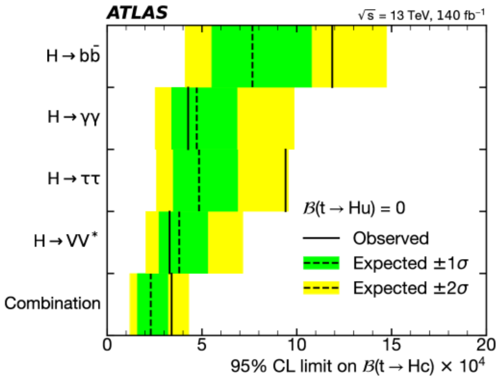
Search for H→ττ, WW, ZZ in 3L final states



arXiv:2404.02123

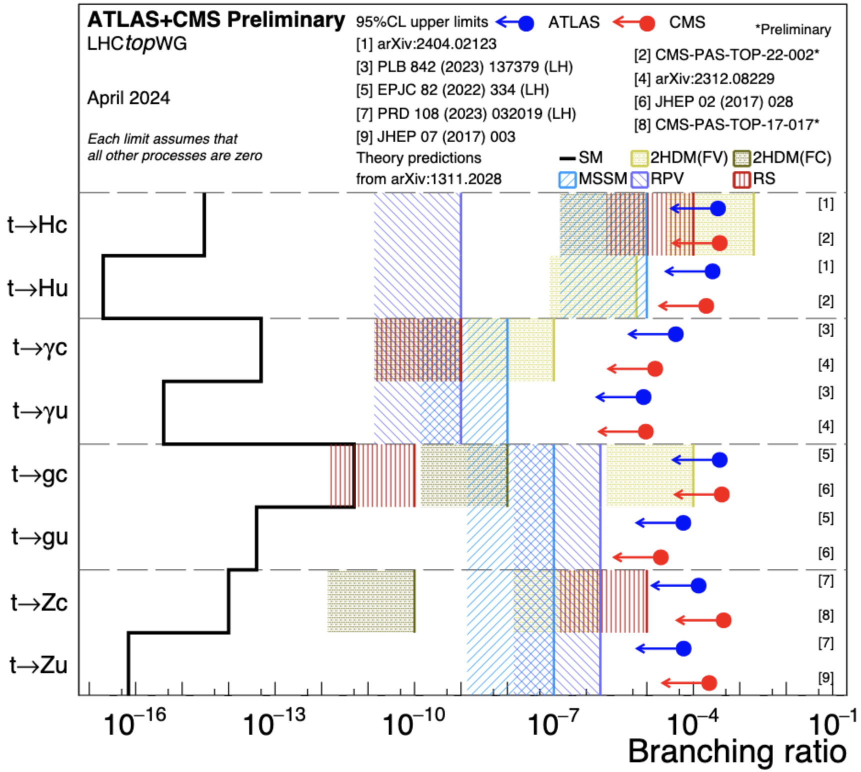


B(t→Hu) < 2.6(1.8)x10^{-4}

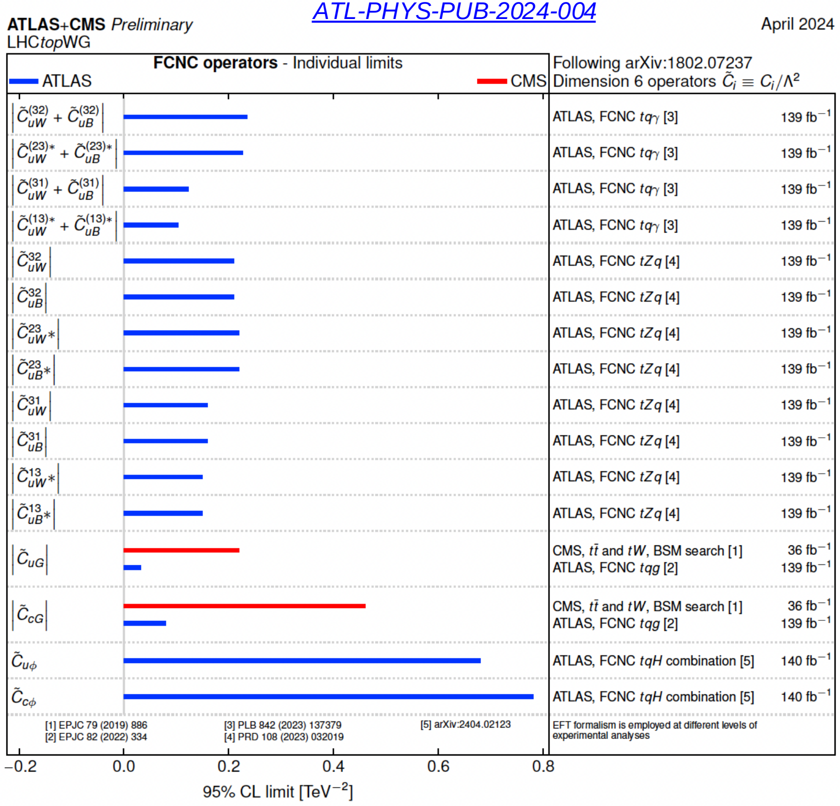


B(t→Hc) < 3.4(2.3)x10^{-4}

Summary of limits on FCNC top decays



ATL-PHYS-PUB-2024-004

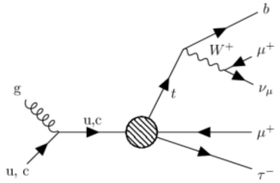


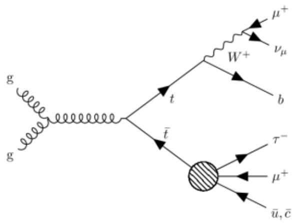
All other operators are set to zero

cLFV and BNV

cLFV

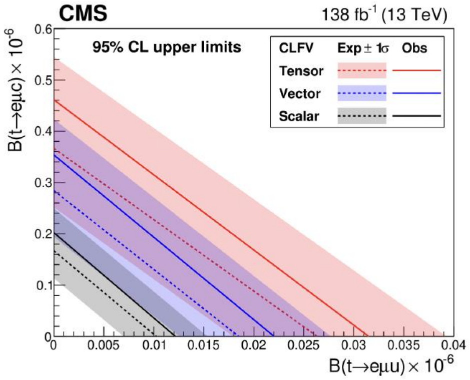
- Charged lepton flavour violation (cLFV) via neutrino oscillations is highly suppressed (BR~10^{-55}).
- Some BSM scenarios (leptoquarks, SUSY, 2HDM) can generate sizable cLFV.
- Consider trilepton events from single top production and tt decay modes.

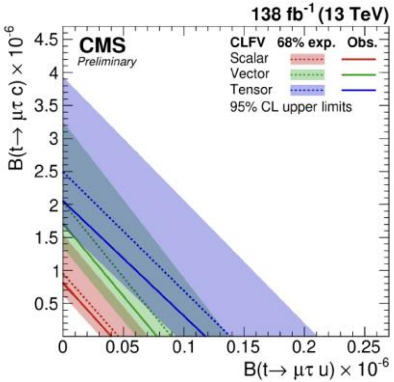




[arXiv:2312.03199](https://arxiv.org/abs/2312.03199)

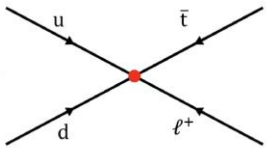
[CMS-PAS-TOP-22-011]()

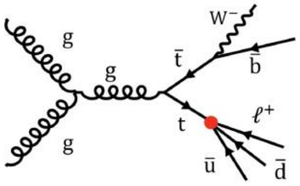


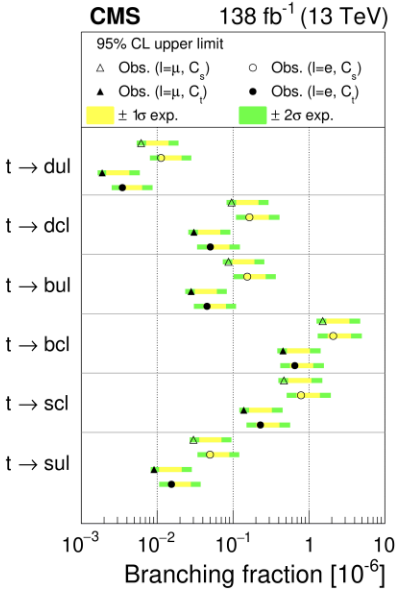


BNV

- Baryon number is conserved in the SM but is not a fundamental symmetry. It can be violated by BSM effects.
- Consider tqq'l vertex in 4-particle effective interaction
  ➔ also LNV.
- Consider dilepton events from single top production (dominant) and tt decay modes.







[arXiv:2402.18461](https://arxiv.org/abs/2402.18461)

Lepton-flavour universality in W decays

- Within the SM the couplings of charged leptons to W and Z are flavor-universal.
- Departures from lepton-flavour universality (LFU) are predicted by some BSM scenarios.
- Some of the most precise tests of LFU are performed using top decays.

Example: B(W→μν)/B(W→eν)

- Select tt events with eμ / ee / μμ and 1 or 2 b-tagged jets.
- Select inclusive Z events with ee / μμ.
- Measure the ratio:

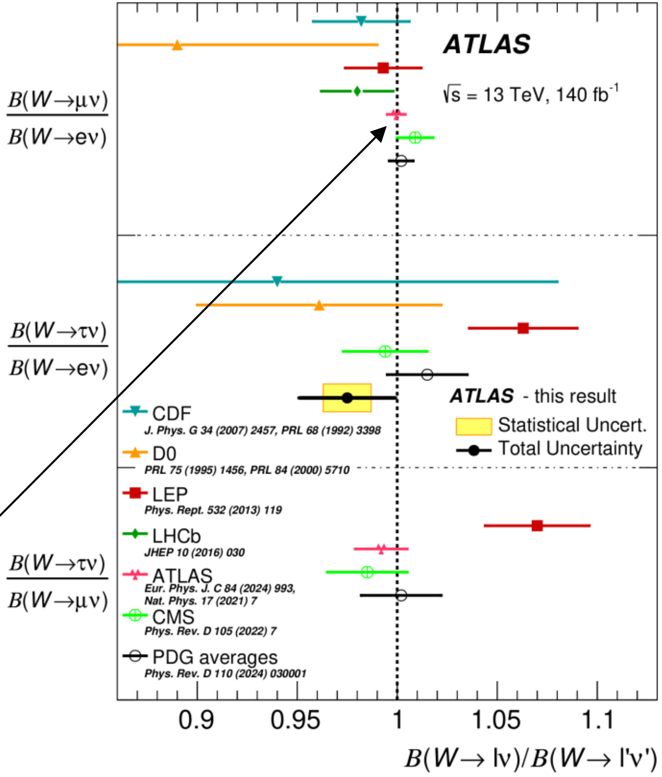
From LEP+SLD

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} \cdot \sqrt{\frac{\mathcal{B}(Z \to ee)}{\mathcal{B}(Z \to \mu\mu)}}$$

- Largely cancels lepton identification and luminosity uncertainties.

arXiv:2403.02133

$$\mathcal{B}(W \to \mu\nu)/\mathcal{B}(W \to e\nu) = 0.9995 \pm 0.0045$$



More precise than the previous World Average!

Summary

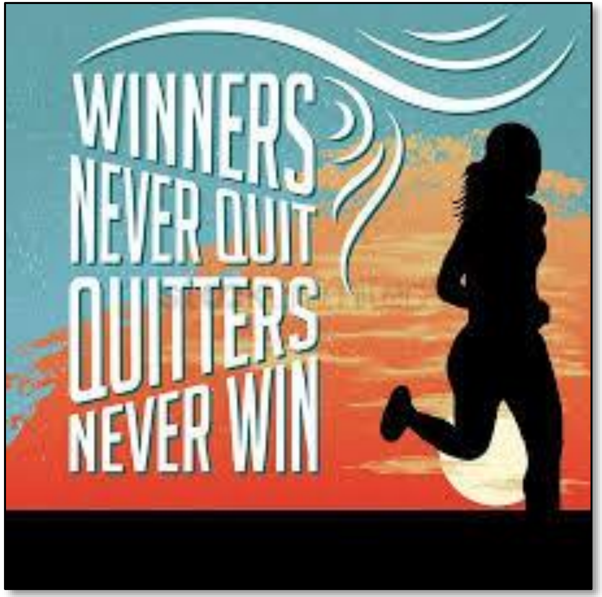
- Top quark physics is rich and exciting, and a central part the LHC physics program.

- Precise measurements of top quark production and properties allow for stringent tests of the SM, being at the same time sensitive to New Physics.
  - Many of the top measurements performed at the LHC are already dominated by systematics uncertainties. Reaching the ultimate precision requires a concerted effort from both the experimental and theory communities.
  - Some rare processes (e.g. 4-top production) become accessible with the increase of statistics in Run 2 and beyond.

- A broad program of direct searches for New Physics in top quark final states is underway and offers one of the most compelling opportunities for discovery at the LHC.
  - New experimental tools and analysis techniques yield sensitivity improvements well beyond luminosity scaling.

Summary

- Top quark physics is rich and exciting, and a central part the LHC physics program.
- Precise measurements of top quark production and properties allow for stringent tests of the SM, being at the same time sensitive to New Physics.
    - Many of the top measurements performed at the LHC are already dominated by systematics uncertainties. Reaching the ultimate precision requires a concerted effort from both the experimental and theory communities.
    - Some rare processes (e.g. 4-top production) become accessible with the increase of statistics in Run 2 and beyond.
- A broad program of direct searches for New Physics in top quark final states is underway and offers one of the most compelling opportunities for discovery at the LHC.
    - New experimental tools and analysis techniques yield sensitivity improvements well beyond luminosity scaling.
- So far, all results are compatible with the SM but we are barely scratching the surface, with x20 more integrated to be analysed by the end of the LHC!



Finding New Physics at the LHC may be more like running a marathon…

Exciting times ahead!