New signals of vectorlike quarks at the LHC

Elias Bernreuther

UC San Diego

CIPANP 2025, Madison
June 12, 2025

based on *Eight top quarks and related signals at the LHC*
with Bogdan Dobrescu, in preparation

New fundamental fermions

- **All known fundamental fermions are chiral**

  Left-handed quarks and leptons are weak doublets, right-handed ones singlets

- Fourth generation of chiral fermions is essentially ruled out after LHC run 2

  Upper limit from Higgs couplings: $m_{t_4}, m_{b_4} \lesssim 0.7\ \mathrm{TeV}$

  Lower limit from direct searches: $m_{t_4}, m_{b_4} \gtrsim 1.7\ \mathrm{TeV}$

  CMS 2209.07327, ATLAS 2401.17165

New fermions have to be vectorlike

i.e. left- and right-handed fields have the same gauge charges

Motivations for vectorlike fermions

- Vectorlike fermions among the simplest possible additions to the SM
- Novel form of matter
- Appearing in many BSM models:
  - composite Higgs models
  - extra dimensions
  - extra $U(1)$'s
  - ...

Dobrescu, Hill, hep-ph/9712319;
Chivukula et al., hep-ph/9809470

Appelquist et al., hep-ph/0012100

Types of vectorlike fermions

Vectorlike leptons

Vectorlike quarks

- weak doublet or singlet
- down-type or up-type

Motivations for vectorlike fermions

- Vectorlike fermions among the simplest possible additions to the SM
- Novel form of matter
- Appearing in many BSM models:
  - composite Higgs models
  - extra dimensions
  - extra $U(1)$'s
  - ...

Dobrescu, Hill, hep-ph/9712319;
Chivukula et al., hep-ph/9809470

Appelquist et al., hep-ph/0012100

Types of vectorlike fermions

Vectorlike leptons

Vectorlike quarks

- weak doublet or singlet
- down-type or up-type

Vectorlike quarks: standard story

- Gauge eigenstates: **vectorlike up-type quark** $\chi_L, \chi_R = \left(\mathbf{3}, \mathbf{1}, \frac{2}{3}\right)$

SU(3)xSU(2)xU(1)

- Couplings of χ to third-generation SM quarks:

$$-m_{\chi\chi}\,\bar{\chi}_L\,\chi_R - m_{\chi i}\,\bar{\chi}_L\,u_R^i - y_{u3}\,\widetilde{H}\,\bar{q}_L^3\,u_R^3 + \mathrm{H.c.}$$

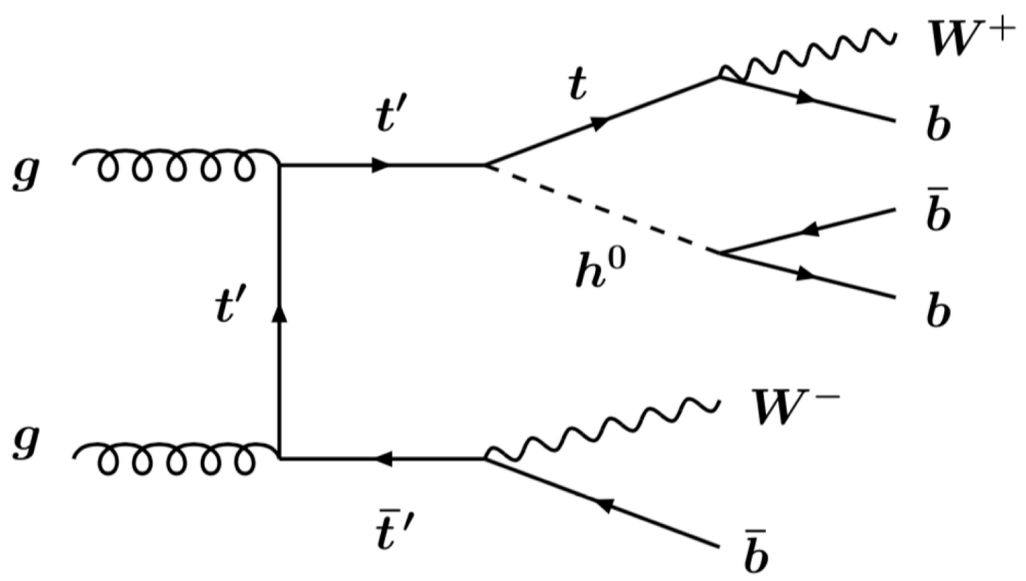
Mass mixing → **physical particles: t and t'**

- **Mass eigenstate t' decays via channels**

$$t' \to tZ,\ t' \to th,\ t' \to bW$$

ATLAS and CMS searches exclude these standard VLQs if $m_{t'} \lesssim 1.4$ TeV

CMS 2209.07327, ATLAS 2401.17165



Six tops from vectorlike quarks

Standard channels $\sim$ mixing angle s_L^2

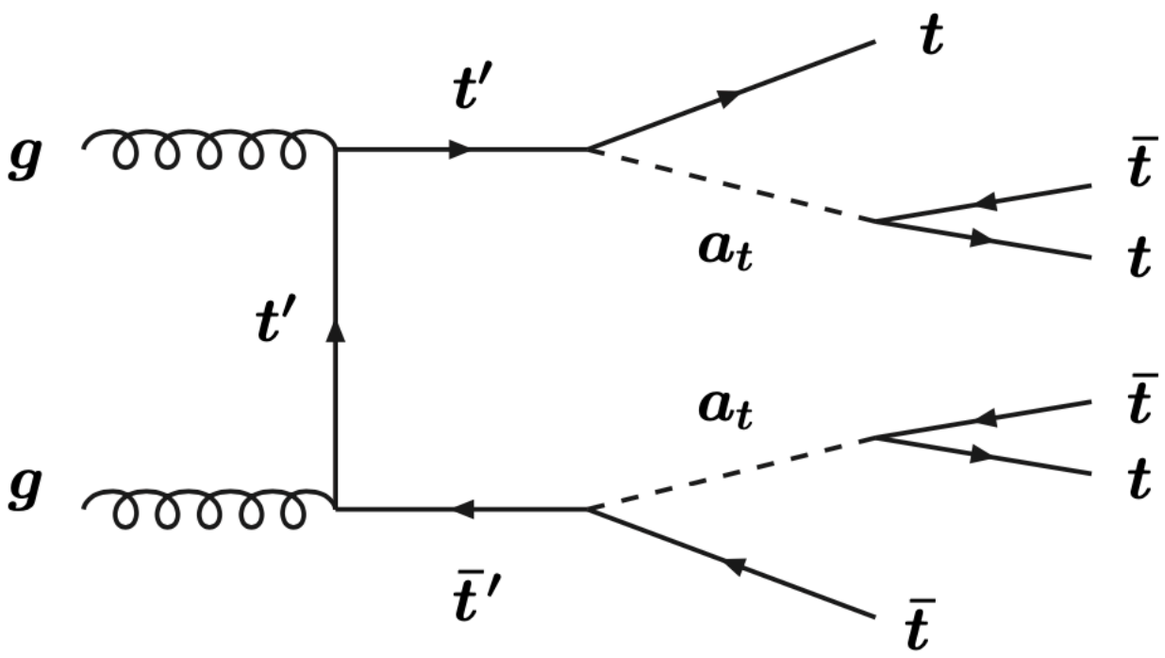
➡ If $s_L \ll 1$, **exotic decays may dominate**

Example: VLQ coupling to a pseudoscalar $\quad iy_o\, a_t\, \bar{t}\gamma_5 t'$

e.g. in models of quark and lepton compositeness

Dobrescu, 2112.15132

If $m_a > 350$ GeV, its **dominant decay is** $a_t \to t\bar{t}$



Final state $3W^+ 3W^- 6b$:

- up to 6 b jets
- up to 3 same-sign leptons

Current limit from recast of squark search: $m_{t'} \gtrsim 1$ TeV

Han et al., 1812.11286

Vectorlike quarks + complex scalar

Typical origin of pseudoscalar a_t: complex scalar ϕ

- Most general Yukawa interaction with singlet scalar:

$$-\phi\,\bar{\chi}_L\left(y_\chi\, e^{i\beta_\chi}\chi_R + y_o\, e^{i\beta_o}\, u_R^3\right) + \mathrm{H.c.}$$

$$y_\chi, y_o > 0 \quad \text{and} \quad 0 \le \beta_\chi, \beta_o < 2\pi$$

- After complex scalar acquires vacuum expectation value:

$$\phi = \left(v_\phi + \frac{1}{\sqrt{2}}\,\varphi_t\right)\exp\left(i a_t / v_\phi\right)$$

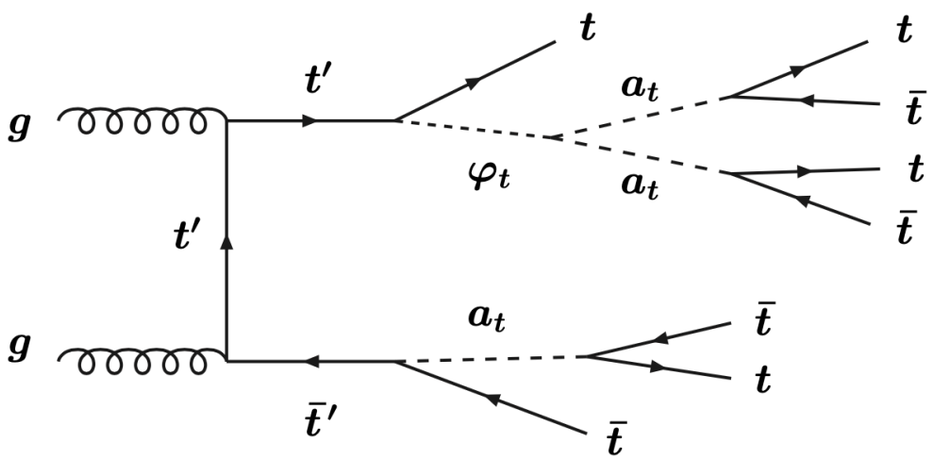
- **Trilinear coupling** $m_3\,\varphi_t a_t a_t$

➡ **Dominant decay of scalar φ_t:** $\varphi_t \to a_t a_t$ if $m_\varphi > 2m_a$

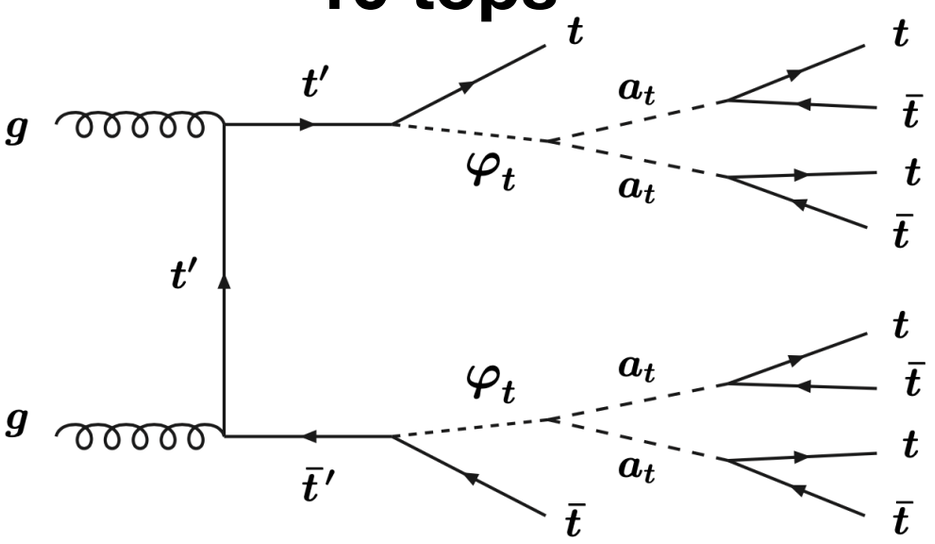
Eight or more tops from vectorlike quarks

Events with 6, 8 or 10 tops possible

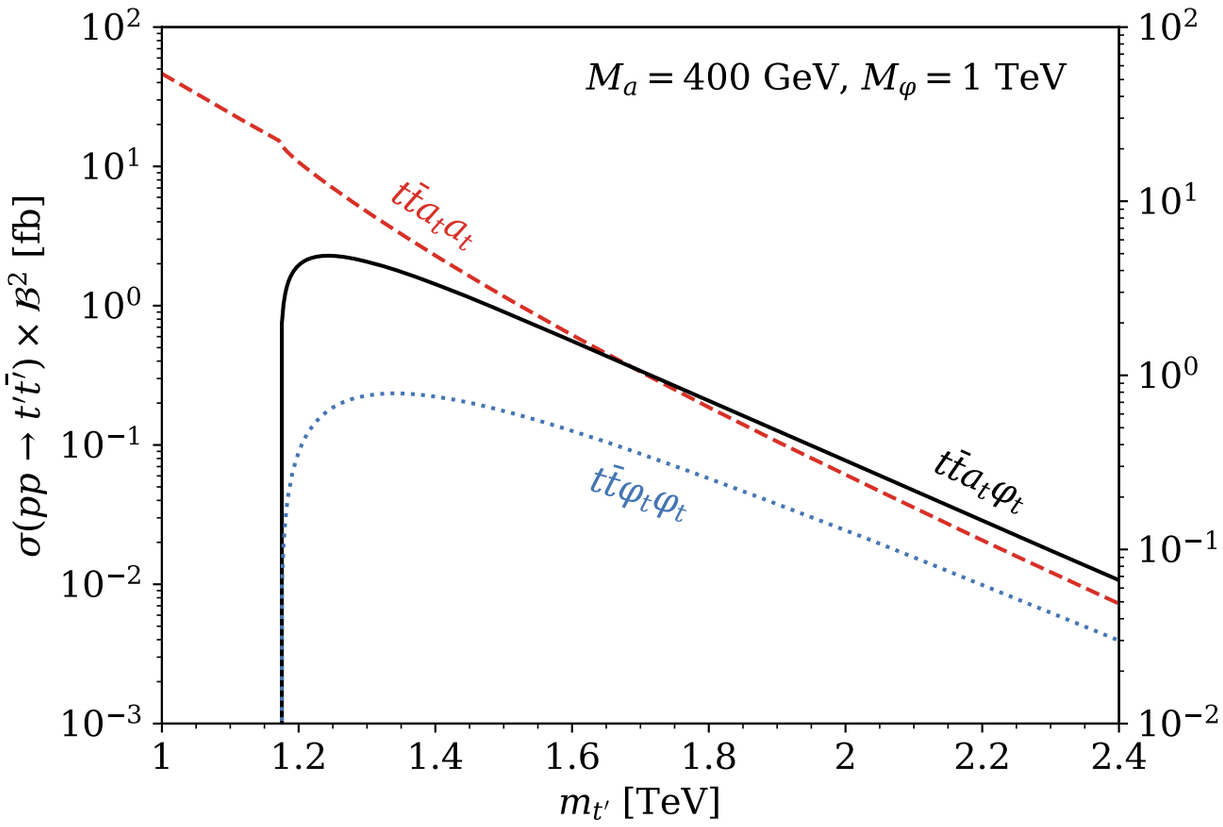
8 tops



10 tops



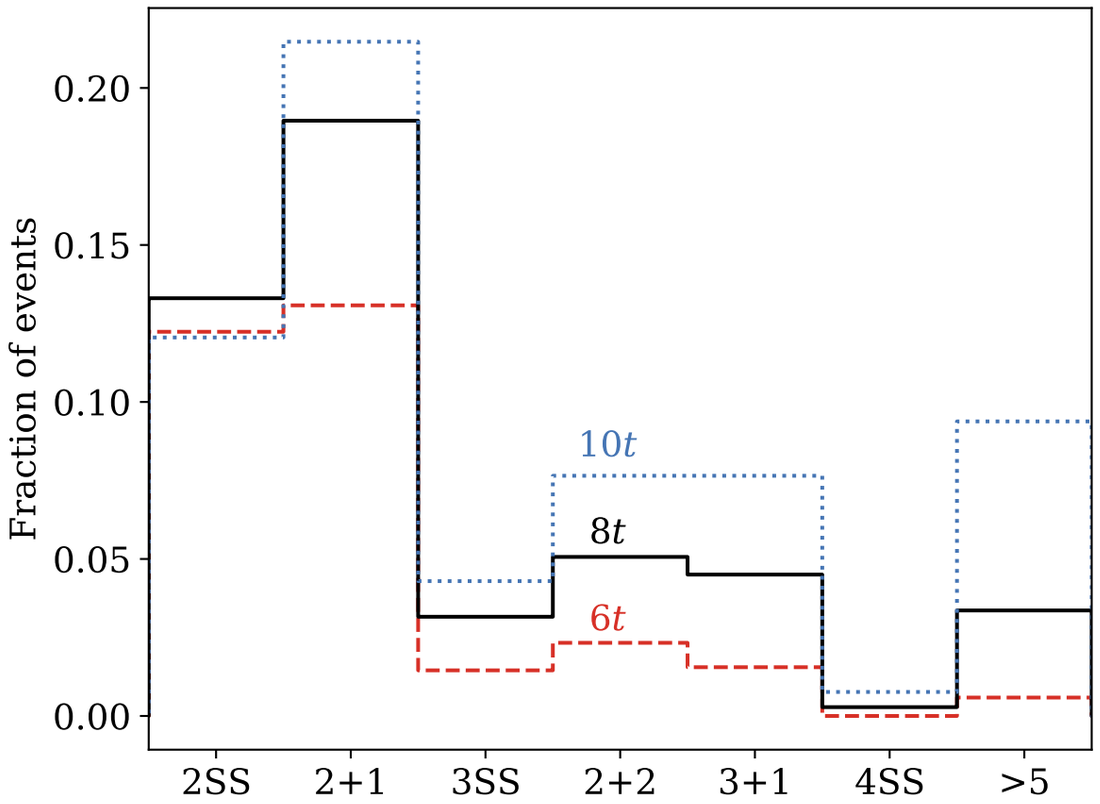
$$\frac{\mathrm{BR}(t' \to t\varphi_t)}{\mathrm{BR}(t' \to t a_t)} = \left(\frac{1 - m_\varphi^2/m_{t'}^2}{1 - m_a^2/m_{t'}^2} \right)^2$$

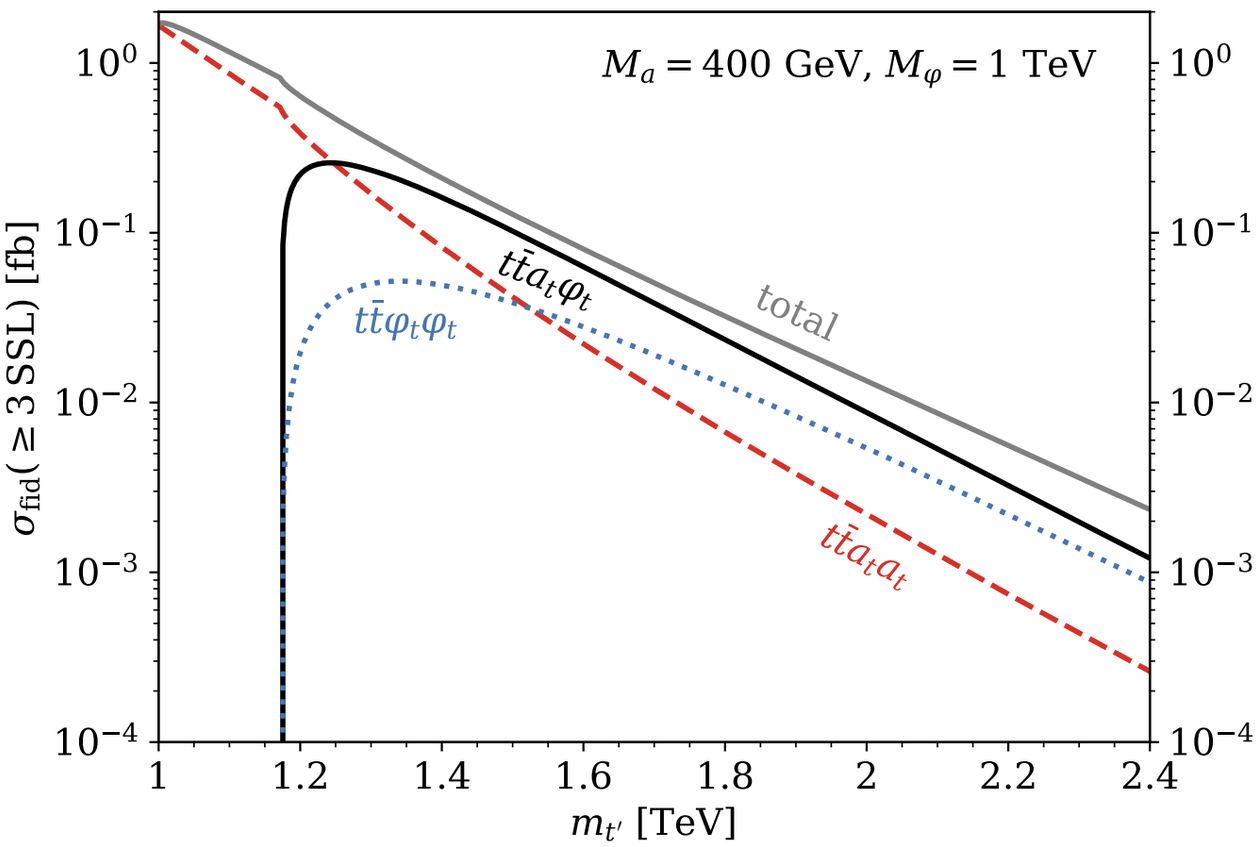


➡ 8 top signal may dominate over 6 tops for heavy t'

Eight or more tops from vectorlike quarks

- Large number of tops very challenging to reconstruct
- But can search for **large multiplicity of (same-sign) leptons**





- 8 top events are dominant contribution to 3 SSL events for $m_{t'} > 1.3$ TeV
- At least one 3SSL event at $300\ \text{fb}^{-1}$ up to $m_{t'} \approx 2.4$ TeV

Conclusions

- **New fermions have to be vectorlike** with respect to the SM gauge group
- **Existing ATLAS and CMS searches** set strong constraints on **mixing-induced decays** of VLQs into SM particles
- **Minimal and well-motivated extensions lead to exotic decays** not covered by existing searches, e.g. many top quarks
- **VLQ + complex scalar can lead to events with six, eight or ten tops**
- Eight tops is dominant signal in part of parameter space and produces **many (same-sign) leptons**