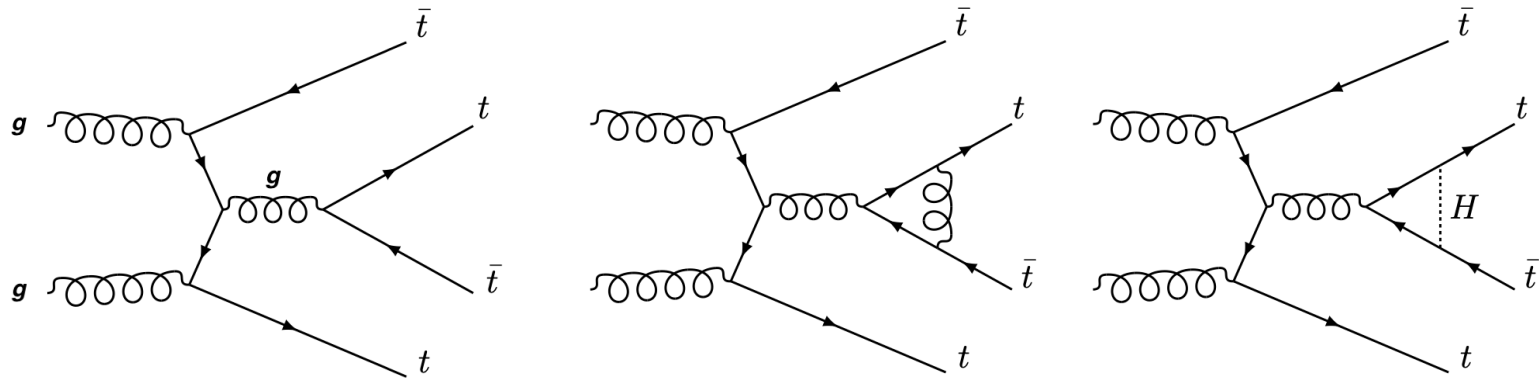# Predictions for 4 tops (more or less)
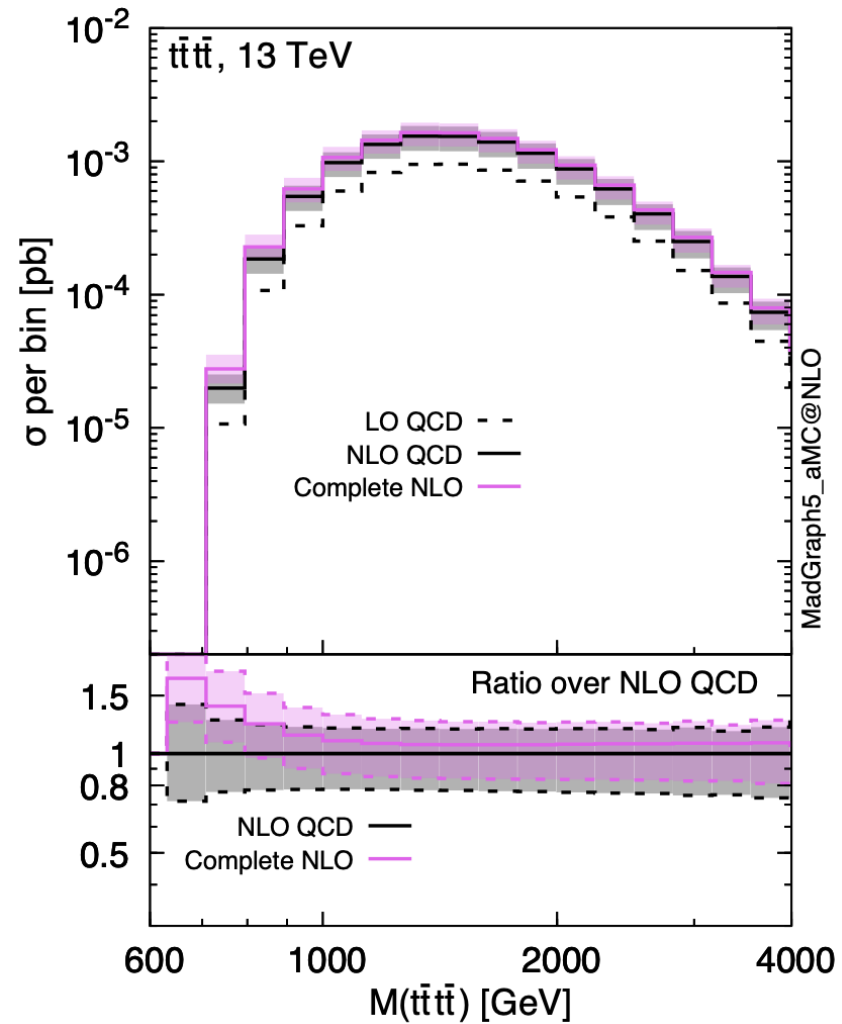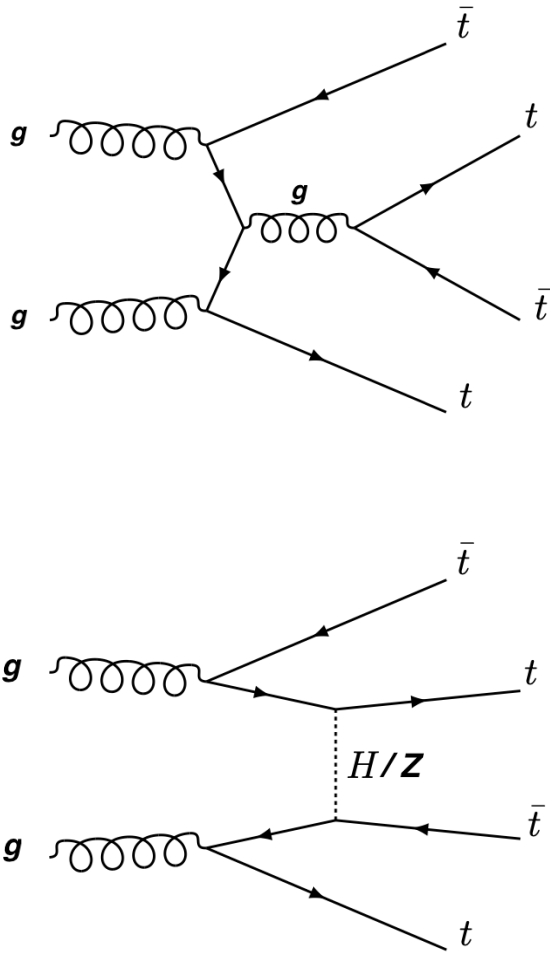
Bogdan Dobrescu *(Fermilab, Particle Theory Department)*

★ **SM prediction for $t\bar{t}t\bar{t}$ and 4 vs 3 tops**

★ **Extended Higgs sectors**

★ **Spin-1 resonances (W', Z', ...)**

★ **Vectorlike quarks**

July 13, 2023 − SMLHC conference

$t\bar{t}t\bar{t}$ production at the LHC in the SM

Frederix, Pagani, Zaro, 1711.02116

NLO(QCD+EW)+NLL' prediction at $\sqrt{s} = 13$ TeV:

$$\sigma(t\bar{t}t\bar{t})_{\mathrm{SM}} = 13.37\,^{+0.48}_{-1.52}\,(\mathrm{scale})\ \pm 0.92(\mathrm{pdf})\ \mathbf{fb}$$

Melissa van Beekveld, Anna Kulesza, Laura Moreno Valero, 2212.03259

Run 2 measurements:

$$\sigma(t\bar{t}t\bar{t})_{\mathrm{ATLAS}} = 22.5\,^{+4.7}_{-4.3}\,(\mathrm{stat})\,^{+4.6}_{-3.4}\,(\mathrm{syst})\ \mathbf{fb}$$

2303.15061

1.7 σ above SM

$$\sigma(t\bar{t}t\bar{t})_{\mathrm{CMS}} = 17.7\,^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.3}_{-1.9}\,(\mathrm{syst})\ \mathbf{fb}$$

2305.13439

1 σ above SM

3 versus 4 top signals:

ATLAS
$\sqrt{s}=13\text{TeV}, 140\text{ fb}^{-1}$
Obs: Exp:
— 68% CL   --- 68% CL
— 95% CL   --- 95% CL

✖ SM

✚ Best Fit

$\sigma_{t\bar{t}t}$ [fb]

$\sigma_{t\bar{t}t\bar{t}}$ [fb]

Obs. $-2\Delta \ln(L)$

CMS

4ℓ

3ℓ

$\sigma^{th.}_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}$ fb

arXiv:2212.03259

$2\ell\,$SS

Combined

Expected
Observed

$\sigma_{t\bar{t}t\bar{t}} / \sigma^{th.}_{t\bar{t}t\bar{t}}$

ATLAS signals:

$\ell^{\pm}\ell^{\pm}\, , \quad \geq 2b\, , \quad \geq 6j$

$\geq 3\ell\, , \quad \geq 2b\, , \quad \geq 6j$

CMS signals:

$\ell^{\pm}\ell^{\pm}\, , \quad \geq 2b\, , \quad \geq 6j$

$3\ell\, , \quad \geq 2b\, , \quad \geq 3j$
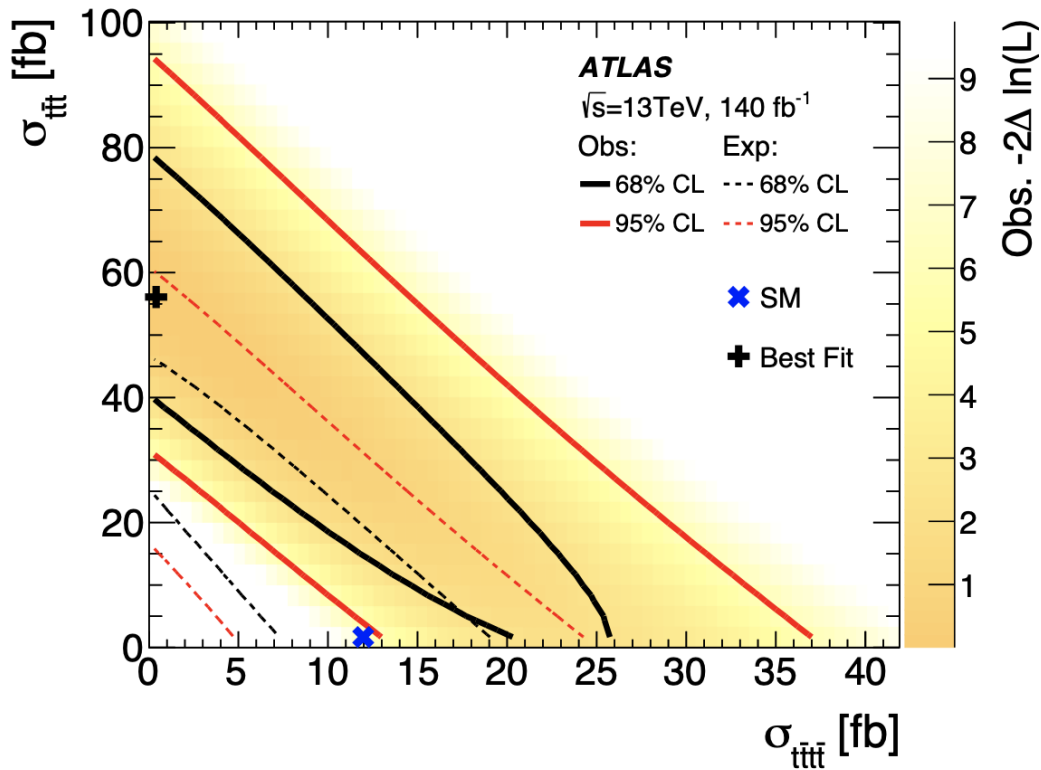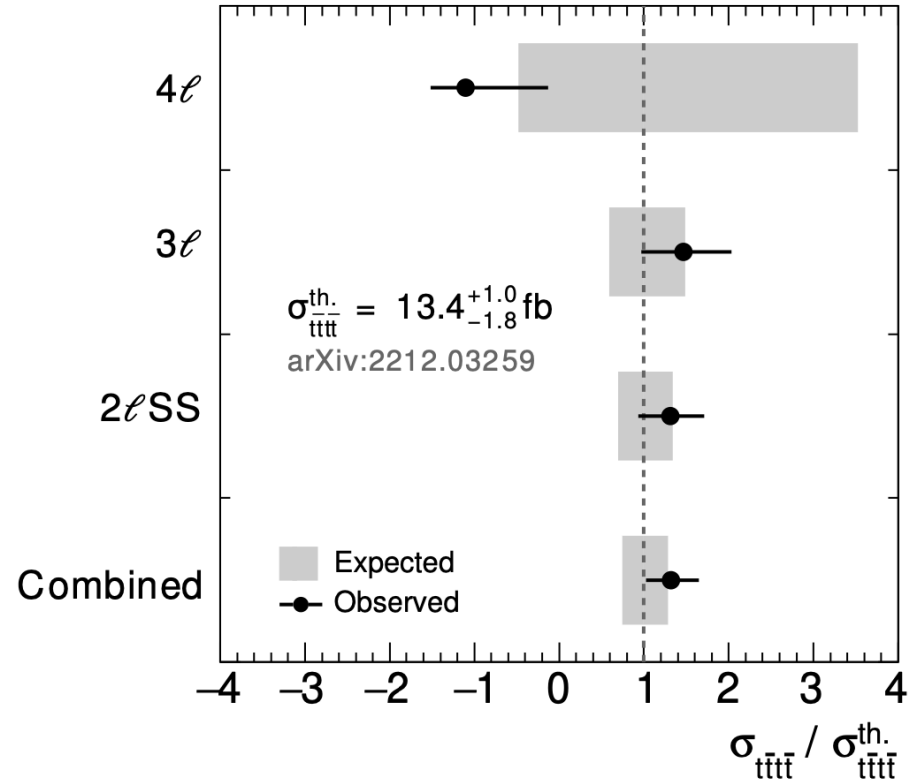
$4\ell\, , \quad \geq 1b$

Physics at scales in the $\sim 0.2 - 8$ TeV range may include:

- **extended Higgs sector**
  $\longrightarrow$ **new heavy spin-0 bosons (A^0, H^0, $H^\pm$, ...)**

- **extended gauge symmetries**
  $\longrightarrow$ **new heavy spin-1 bosons (Z', W', G', ...)**

- **composite Higgs** *(Chivukula et al, hep-ph/9809470)*
  $\longrightarrow$ **vectorlike partner of the top quark**

- **quarks and lepton compositeness** *(bound states of preons)*
  (BD 2112.15132; Ben Assi, BD, 2211.02211)
  $\longrightarrow$ **composite scalars** *(bound states of two SM fermions)*
  $\longrightarrow$ **composite vectorlike fermions**

- **...**

Two-Higgs-doublet Model $=$ SM $+$ 4 spin-0 particles: $A^0, H^0, H^{\pm}$
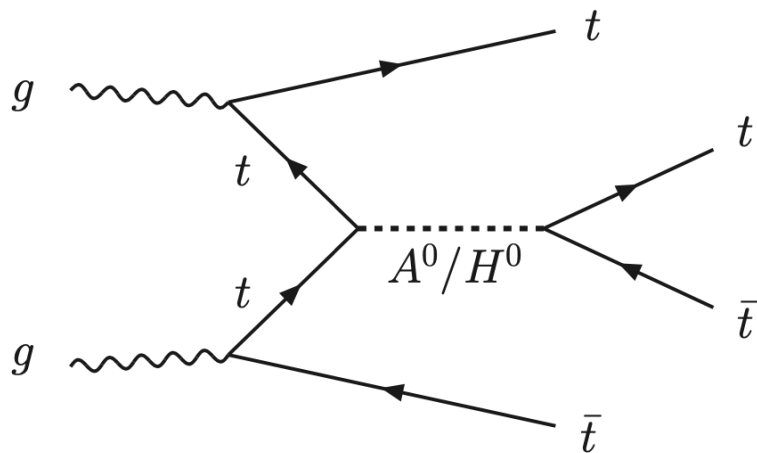
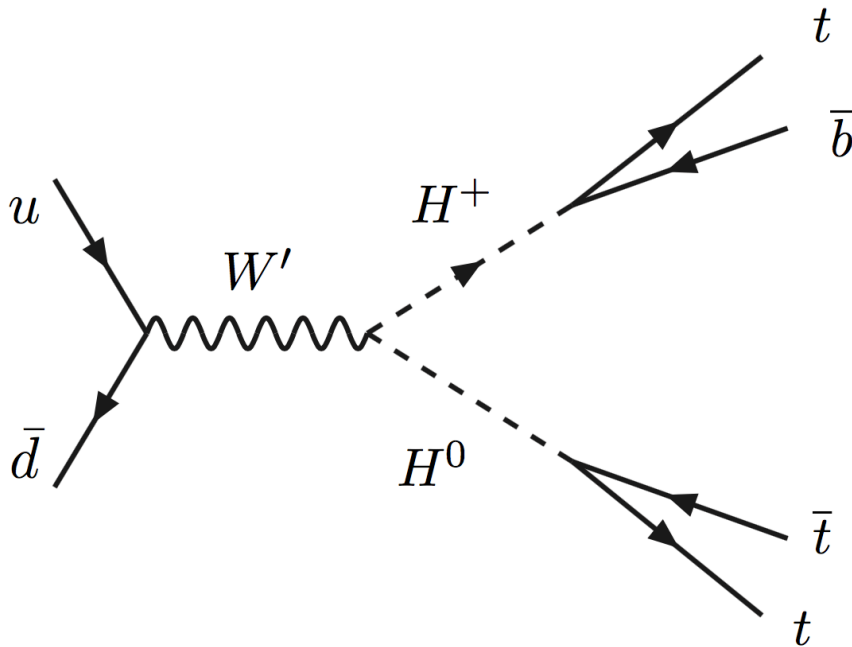**signal: $t\bar{t}$ resonance $+$ $t\bar{t}$ pair**
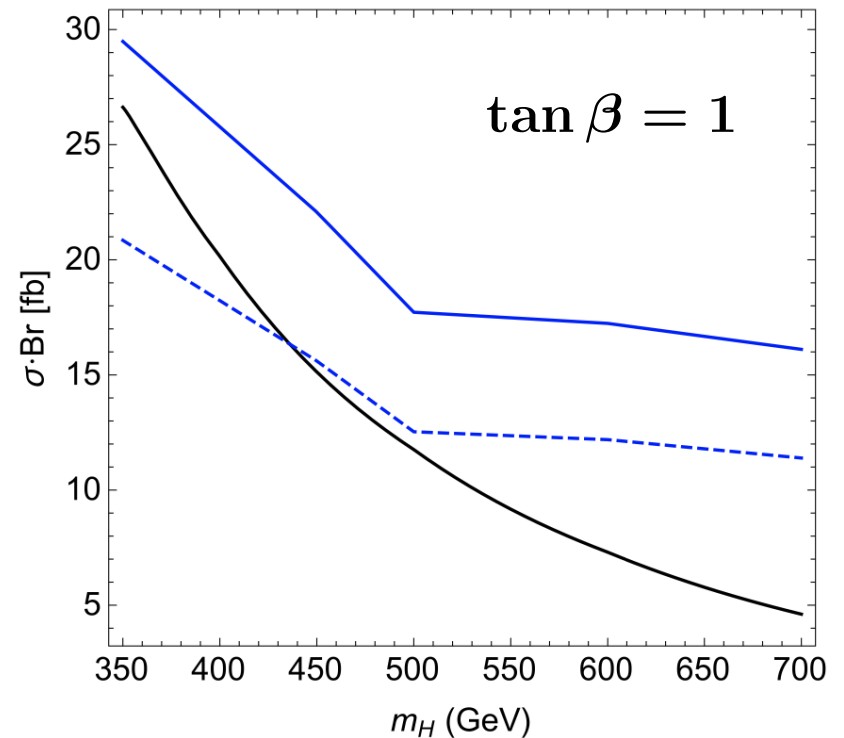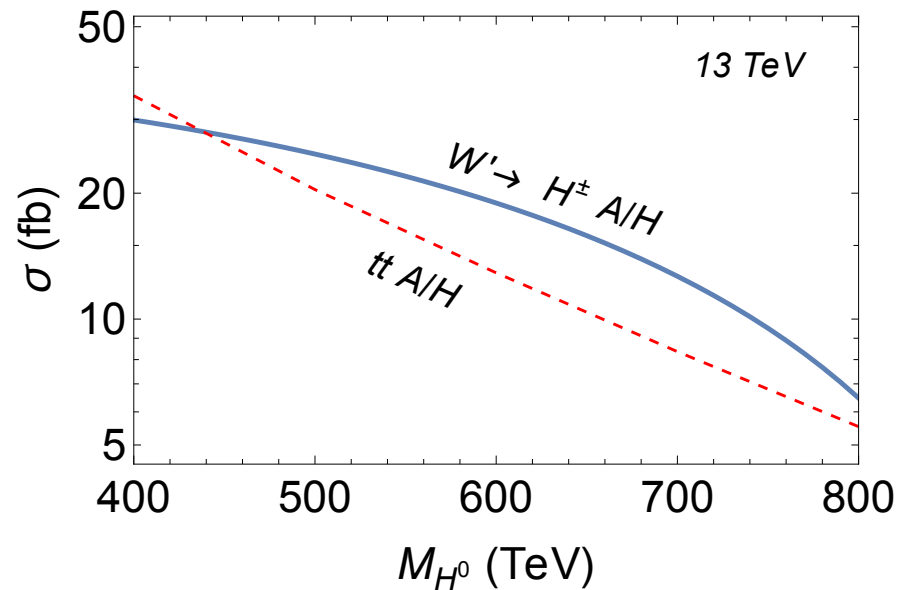
N. Craig et al, 1504.04630

Extended gauge symmetry

Embed the electroweak gauge group $SU(2)_L \times U(1)_Y$ in the "left-right" gauge symmetry: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

⋆ W' boson coupled to the SM right-handed fermions

⋆ Z' bosons with $M_{Z'} > M_{W'}$

⋆ symmetry breaking requires a second Higgs doublet: $A^0, H^0, H^\pm$

3 top signal!

BD, Z. Liu, 1507.01923

$$W' \to H^+ A^0, \ H^+ H^0 \to (t\bar{b})(t\bar{t}) \to 3W + 4b$$

- predicts about twice as many $\ell^+\ell^+$ events than $\ell^-\ell^-$ events

  and about twice as many $\ell^+\ell^+\ell^-$ events than $\ell^-\ell^-\ell^+$ events

- σ depends on $M_{W'}$, g_R; branching fraction depends on $M_{A^0}/M_{W'}$.

$$t\bar{t}A^0/H^0 \to t\bar{t}(t\bar{t}) \to 4W + 4b$$

- σ depends on M_{A^0} , $\tan\beta$

$$Z' \to H^0 A^0 \to (t\bar{t})(t\bar{t}) \to 4W + 4b$$

- σ depends on $M_{Z'}$, g_R; branching fraction depends on $M_{A^0}/M_{Z'}$.

- suppressed rate in left-right models $(M_{Z'} > M_{W'})$

- dominant channel in some models with $\mathsf{SM} \times U(1)'$ gauge group

4 or more tops from vectorlike quarks

Vectorlike (i.e. non-chiral) fermions — a new form of matter.

Masses allowed by $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry

$\Rightarrow$ naturally heavier than the t quark.

Unlike chiral fermions, vectorlike fermions have a decoupling limit:

$m \gg v_H \approx 174$ GeV $\rightarrow$ Standard Model is recovered.

Vectorlike quarks can be pair produced at the LHC due to their coupling to gluons.

Cross section depends only on their mass.
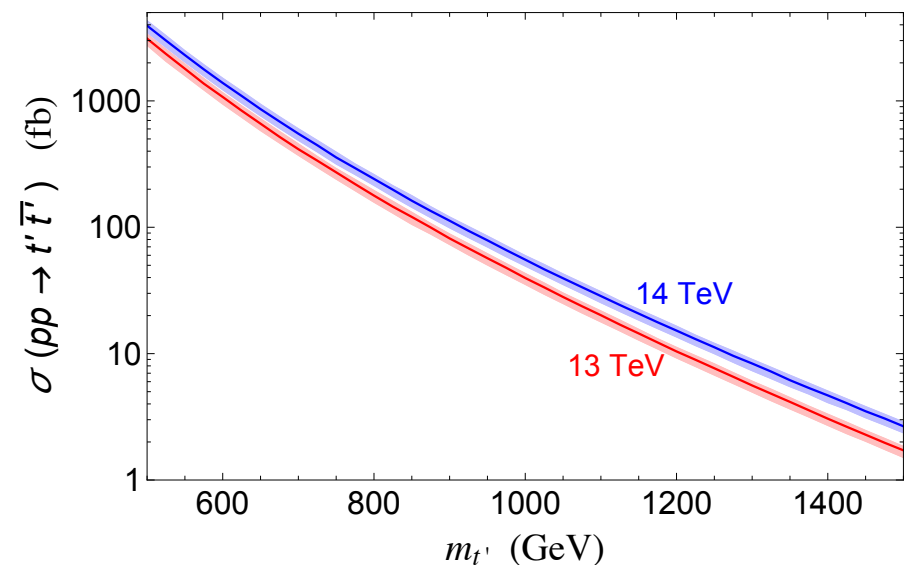
A vectorlike quark χ that transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the SM top quark.

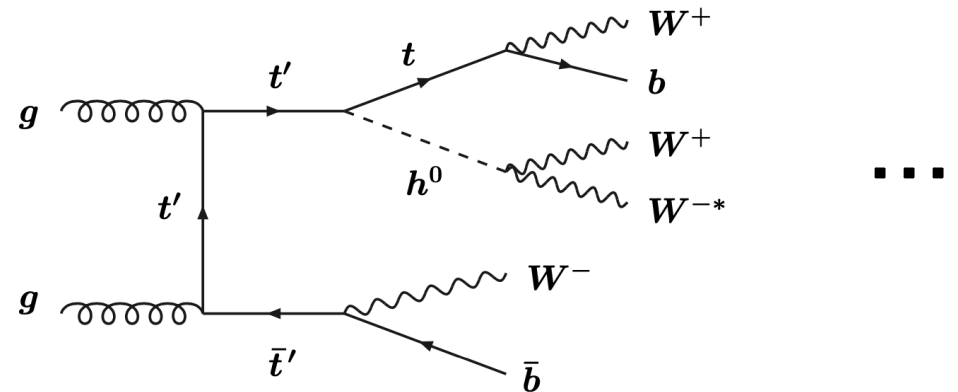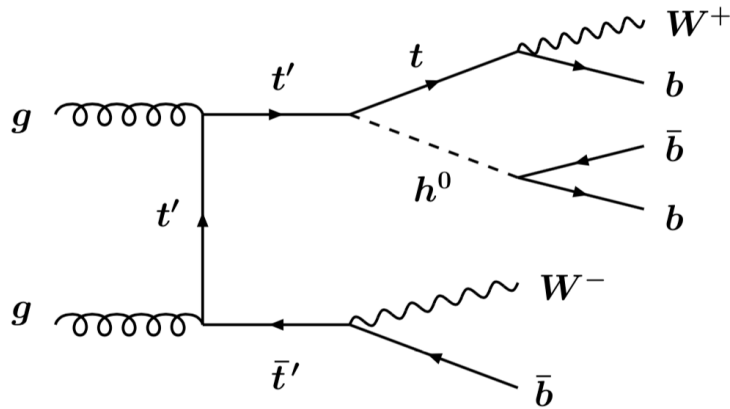*χ is predicted in composite Higgs models (Dobrescu, Hill, hep-ph/9712319),*

little Higgs models (Arkani-Hamed, Cohen, Georgi, hep-ph/0105239, ...),

...

Mass eigenstates: t **and** t'. **Mixing** $\sin\theta_L \equiv s_L$.

t' branching fractions: $B(t' \to W^+ b) = 1/2$, $B(t' \to h^0 t) = B(t' \to Zt) = 1/4$

T. Han, H. Logan, L. Wang, hep-ph/0506313

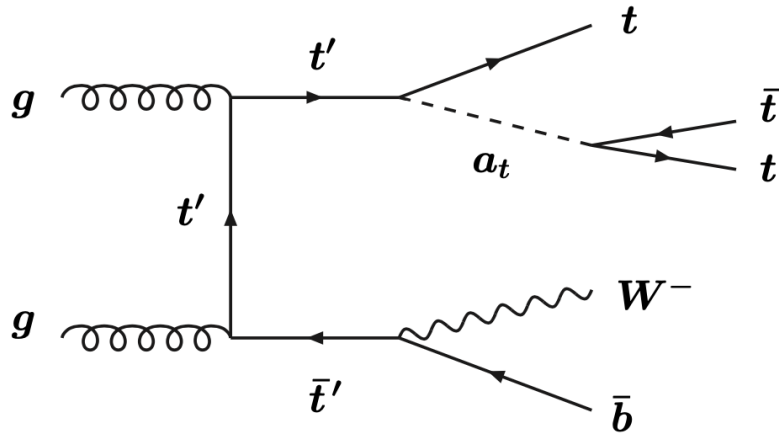**Current limit:** $m_{t'} \gtrsim 1.5$ **TeV**

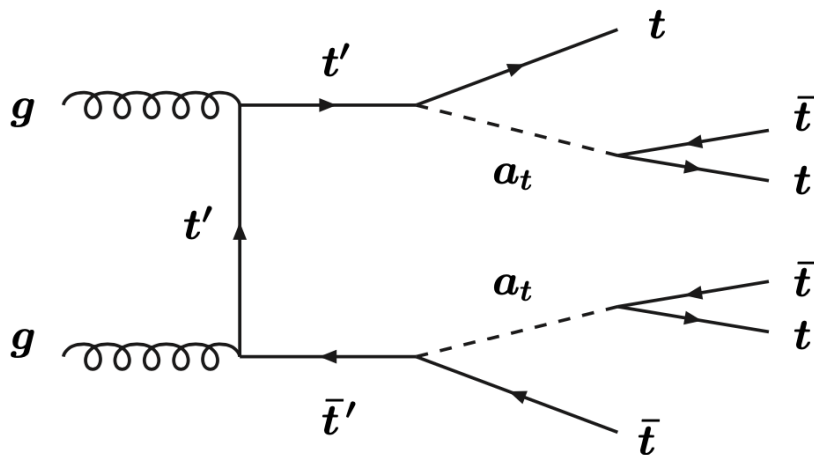*(ATLAS 1808.02343, CMS 2209.07327)*

mimicks the 4 top signal!

If vectorlike quark χ couples to a pseudoscalar a_t, $M_a < m_{t'} - m_t$, then there is competition between $t' \to t\, a_t$ and $t' \to W^+ b, h^0 t, Z t$

BD, Elias Bernreuther, 2304.08509

Signal: $3t + Wb$

a 4 top look-alike,

but W is boosted.

Signal: $6t$!

11

Conclusions

28 years after first observation of $t\bar{t}$ (CDF + D0),

ATLAS and CMS have observed $t\bar{t}t\bar{t}$ production!

Signal consistent with the SM (possible contamination from "3 tops"?)

Today's signal is tomorrow's background ... "4 top"-like signals predicted in many models:

- **Two-Higgs doublet model:** $t\bar{t}A^0$, $A^0 \to t\bar{t}$
- **Left-right symmetric models:** $W' \to H^+A^0 \to (t\bar{b})(t\bar{t})$
- **Vectorlike quarks:** $t'\bar{t}' \to th^0 Wb \to 4W + b\bar{b}$
- **Vectorlike quark + pseudoscalar:** $t'\bar{t}' \to ta_t Wb \to 3t + Wb$,

$$t'\bar{t}' \to ta_t\bar{t}a_t \to 6t$$

Exciting times ahead!

Bogdan Dobrescu (Fermilab)