New high-p_T probes of nonstandard physics

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- **Exotic decays of vectorlike quarks** *(with Felix Yu, 1612.01909)*
- **Cascade decays of a leptophobic Z'** *(1506.04435)*
- **W' decays into heavy Higgs bosons** *(with Andrea Peterson 1312.1999)*
- **Signatures of a Gluon-prime boson** *(with Yang Bai, 1012.5814)*
- **Loop decays: $Z' \to h^0\gamma$** *(with Patrick Fox and John Kearney, 1705.08433)*

July 28, 2017 – talk at the US ATLAS Workshop

Exotic decays of vectorlike quarks

with Felix Yu, 1612.01909

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.

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

'Standard' widths of t':

$$\Gamma(t' \to W^+ b) = \frac{s_L^2\, m_{t'}^3}{32\pi v_H^2}\left[1 + O\left(\frac{M_W^4}{m_{t'}^4}\right)\right]$$

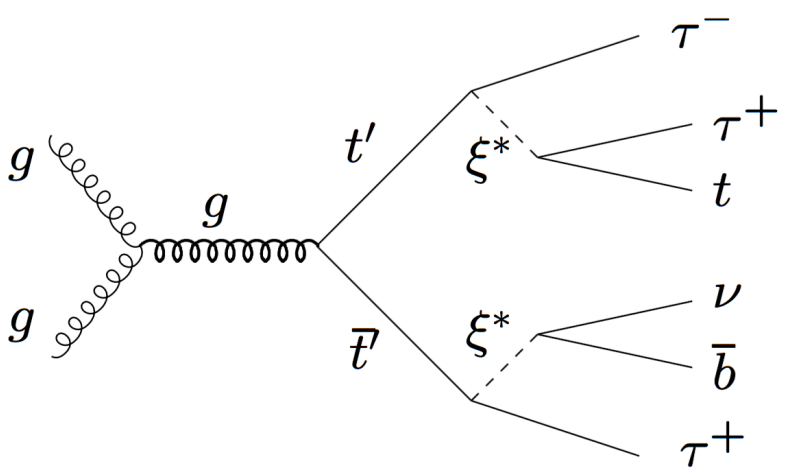
$$\Gamma(t' \to Zt) \approx \Gamma(t' \to ht) = \frac{s_L^2 c_L^2\, m_{t'}^3}{64\pi v_H^2}\left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

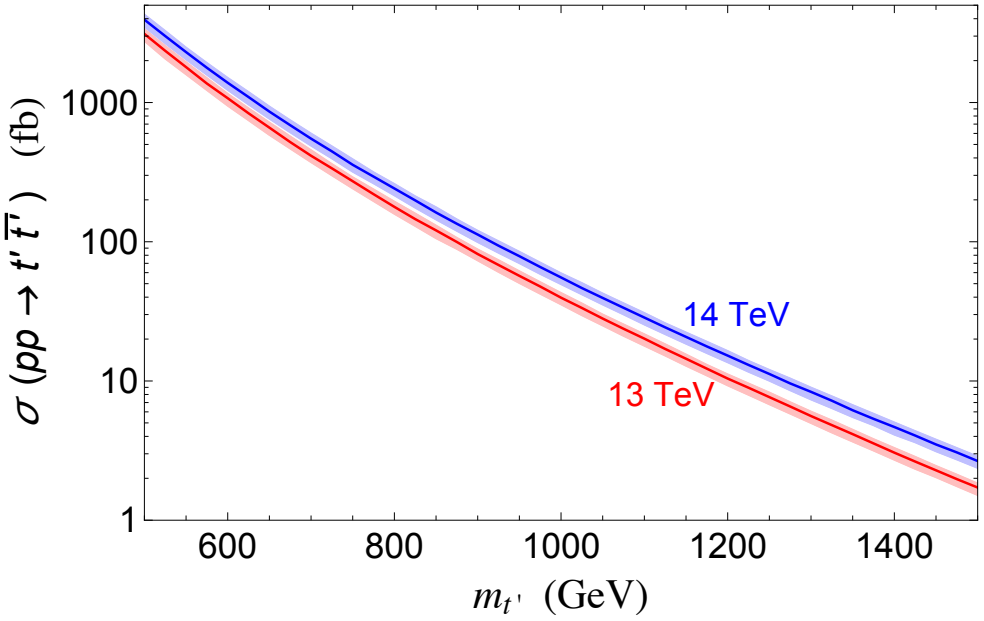
For $s_L \ll 1$, exotic decays of vectorlike quarks could dominate!

E.g., **4-fermion operator** $(\overline{\chi}_R l_L^3) i\sigma_2 (\overline{\tau}_R q_L^3) \Rightarrow t' \to \tau^+\tau^- t\ ,\ \tau^+\nu b$

Example of UV completion: scalar leptoquark ξ heavier than t'.

$m_{t'} \gg m_t$: t-tagged jet + 3τ + $b\nu$

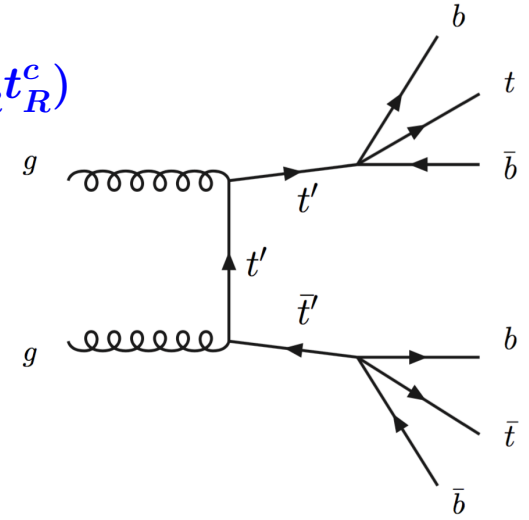




More LHC signatures: $t\bar{t}+4\tau$, $t\bar{t}\tau^+\tau^-\nu\nu$, $tb\tau+3\nu$ or $t\bar{t}+4\nu$.

Other 4-fermion operators, *e.g.*, $\frac{\kappa_\chi \kappa_t}{M_\zeta^2}(\overline{\chi}_R^c b_R^3)(\bar{b}_R^3 t_R^c)$

lead to a final state with $t\bar{t}+4b$



New gauge bosons

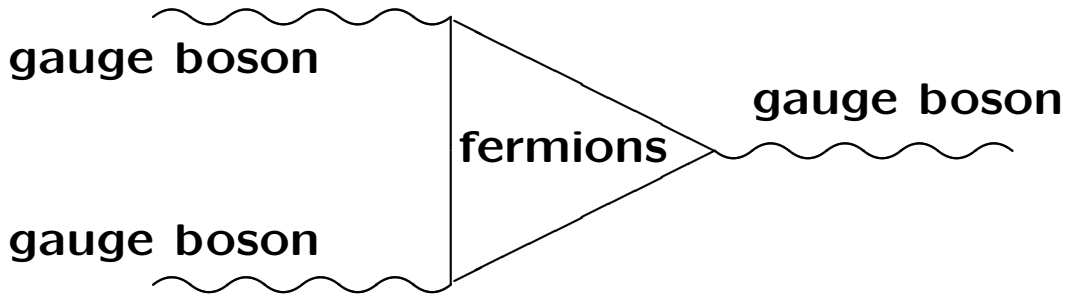
Spin-1 fields are well behaved in the UV provided that they are bound states (not discussed here) or gauge bosons.

New gauge bosons (Z', W', G', ...) require more particles:

- **The new gauge symmetry must be spontaneously broken.**
  Simple choice: a new scalar field ϕ acquires a VEV.

- **All $U(1)_B$ gauge anomalies must cancel**

$\Rightarrow$ *there must be new fermions ("anomalons"), which are vectorlike with respect to $SU(3)_c \times SU(2)_W \times U(1)_Y$, and chiral with respect to the new gauge group, with charges such that the sums over fermion triangle diagrams vanish.*



Flavor-universal leptophobic Z'

New fields carrying $U(1)_B$ charge in a minimal model:

B.A. Dobrescu, C. Frugiuele, 1404.3947

field	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
L_L L_R	1/2	1	2	$-1/2$	-1 $+2$
E_L E_R	1/2	1	1	-1	$+2$ -1
N_L N_R	1/2	1	1	0	$+2$ -1
ϕ	0	1	1	0	$+3$

There are two charged "anomalons", E and L^e, which can mix, and two neutral anomalons, N and L^ν, which can also mix.

$$\mathcal{L}_{N\text{mass}} = -\left(\overline{N}_R\,,\,\overline{L}^{\nu}_R\right)\begin{pmatrix} y_N\langle\phi\rangle & y_{NL}\,v_H \\ y_{LN}e^{i\theta_N}\,v_H & y_L\langle\phi\rangle \end{pmatrix}\begin{pmatrix} N_L \\ L^{\nu}_L \end{pmatrix} + \text{H.c.}$$

Left-handed neutral anomalons in the mass eigenstate basis:

$$\begin{pmatrix} N_{S_L} \\ N_{D_L} \end{pmatrix} = \begin{pmatrix} c_N & -s_N \\ s_N & c_N \end{pmatrix}\begin{pmatrix} N_L \\ L^{\nu}_L \end{pmatrix}$$

Small mass splitting between the charged and neutral physical states that are mostly part of the weak-doublet anomalon:

The decays of the anomalons depend on their mass ordering. **(1506.04435)**

$U(1)_B$ **symmetry is spontaneously broken down to** Z_3**.**

The anomalons have Z_3 **charge** $+1$

$\Rightarrow$ **lightest anomalon is stable (in the minimal model), can be a DM component if it is** N_S**.**

If $m_{E_S} > m_{E_D} \approx m_{N_D} > m_{N_S}$:

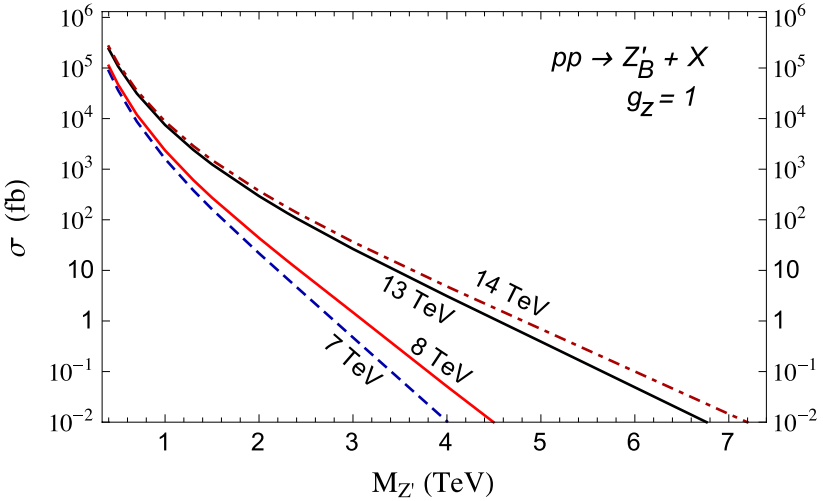
E_S decays into $N_D W$, $E_D Z$ or $E_D h^0$ ($N_S W$ has small BR)

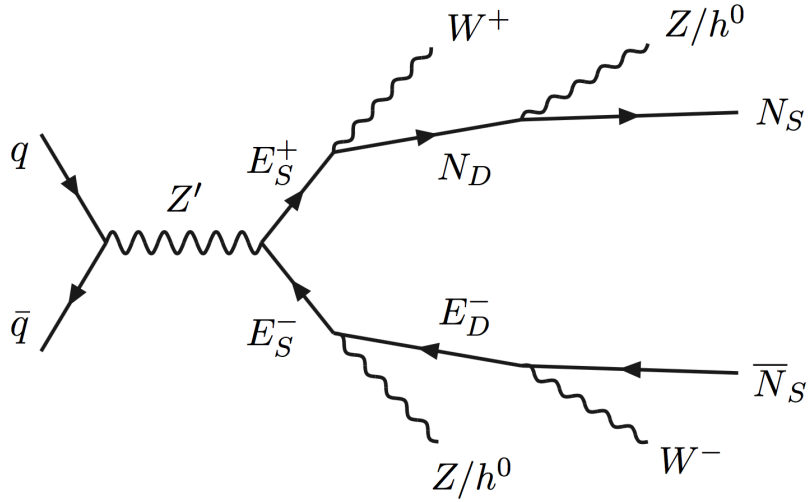
E_D decays mostly into $N_S W$

N_D decays into $N_S h^0$ or $N_S Z$ (equal BR's for $m_{N_D} - m_{N_s} \gg M_h$)

Cascade decays via anomalons:

(1506.04435)



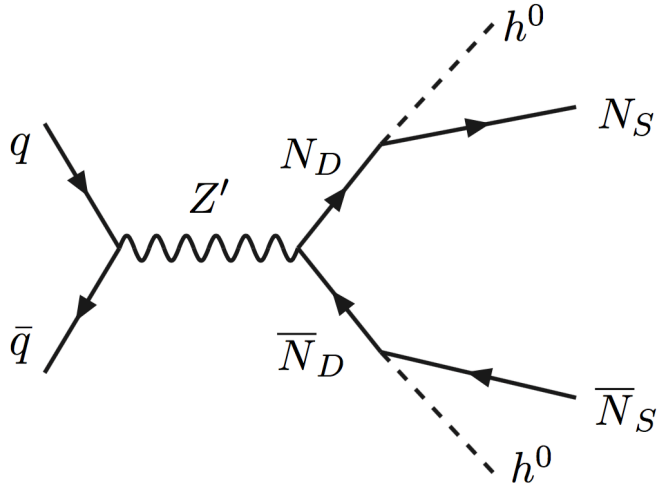


$M_{Z'} > 2M_{E_s} > 2M_{E_D}$: $W^+W^-ZZ + \not{E}_T$, or $W^+W^-Zh^0 + \not{E}_T$, or $W^+W^-h^0h^0 + \not{E}_T$

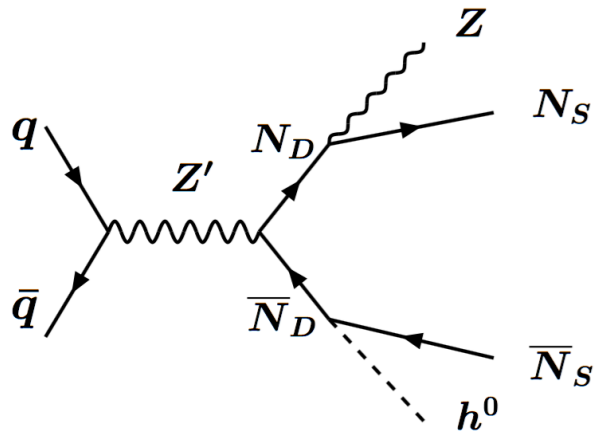
$M_{Z'} > 2M_{E_s} \gg 2M_{E_D}$: $4V$ or h^0-tagged jets + $\not{E}_T$

$M_{Z'} \gg M_{E_s}$: two (WZ) or (Wh^0)-tagged jets + $\not{E}_T$

For $M_{Z'} \gg M_{N_D}$ or $M_{N_D} \gg M_{N_S}$:



two h^0-tagged jets + $\not{E}_T$



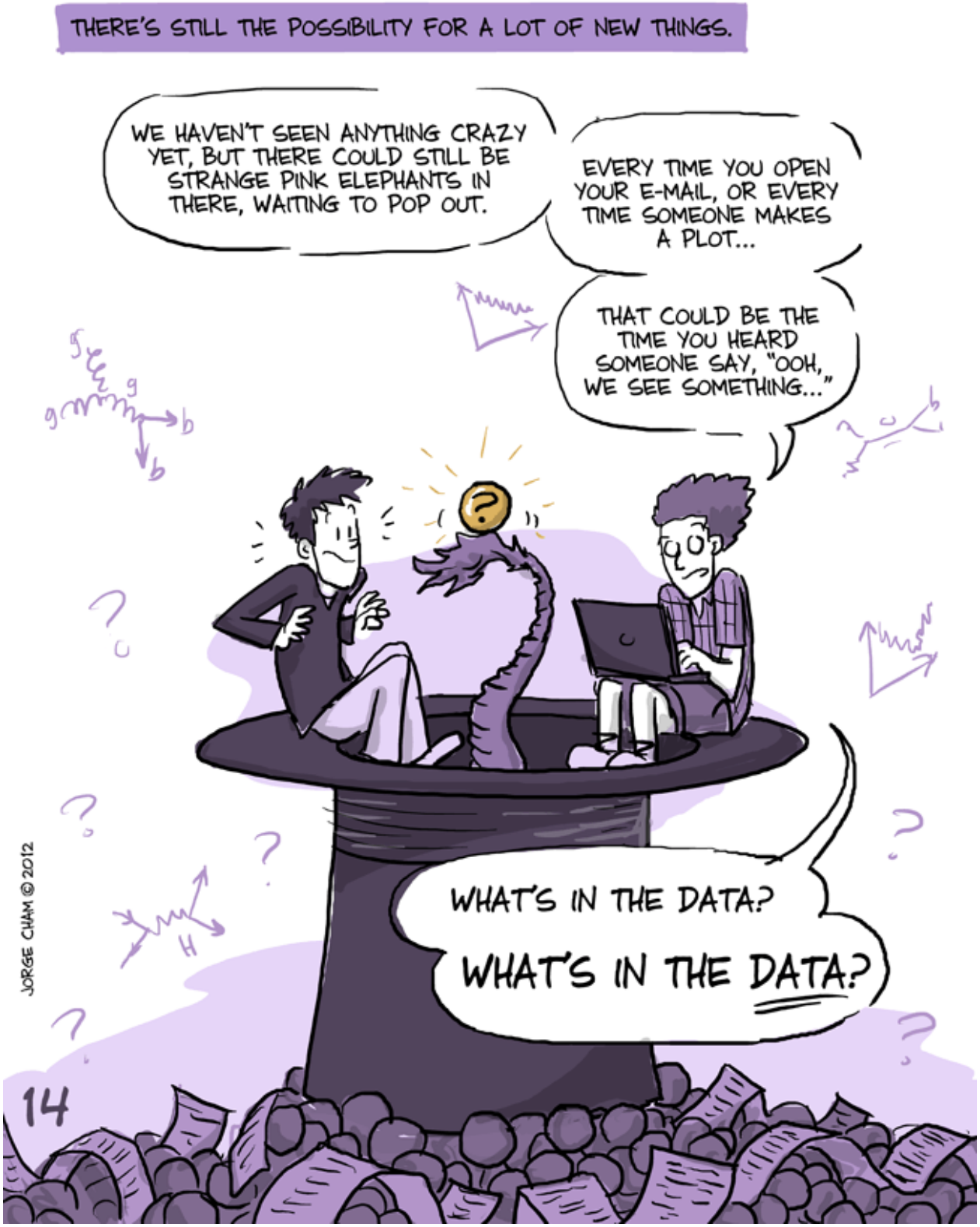
h^0-tagged jet + Z-tagged jet + $\not{E}_T$

Also: $ZZ + \not{E}_T$, or $W^+W^- + \not{E}_T$.

Many hiding places for new physics.

There are lots of new searches that ATLAS and CMS can and should do.

There is no substitute for dedicated searches.



phdcomics.com/higgs

W' decays into heavy Higgs bosons

(with Andrea Peterson 1312.1999)

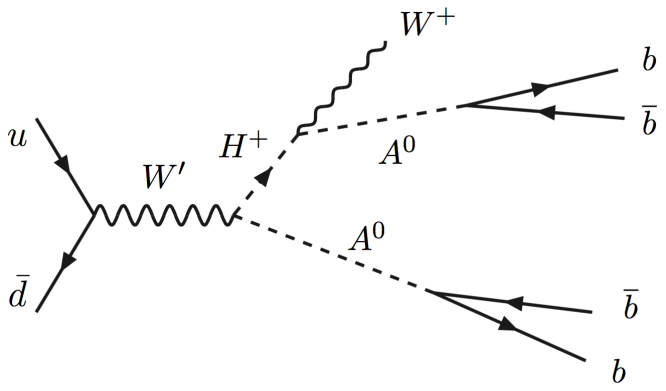
	$SU(3)_c$	$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
Δ	1	2	$\bar{2}$	0
Φ	1	2	1	$+\frac{1}{2}$
Q_L , L_L	3 , 1	2	1	$+\frac{1}{6}$, $-\frac{1}{2}$
u_R , d_R	3	1	1	$+\frac{2}{3}$, $-\frac{1}{3}$
e_R	1	1	1	$+1$

Meta-sequential W': same couplings to fermions as the W up to an overall parameter, $0.2 \lesssim \tan\theta \lesssim 1$.

Higgs sector includes H^+, H^0, A^0: odd states under Z_2 symmetry.

Dominant decay modes: $W' \to H^+ A^0$ and $H^+ H^0$ for $\tan\theta < 0.5$.

Lightest odd Higgs, A^0, may be stable *(signals:* $W + \not{E}_T$ *, or* $WZ + \not{E}_T$*),* **or could decay into a pair of the heaviest fermions (through small Z_2 breaking).**

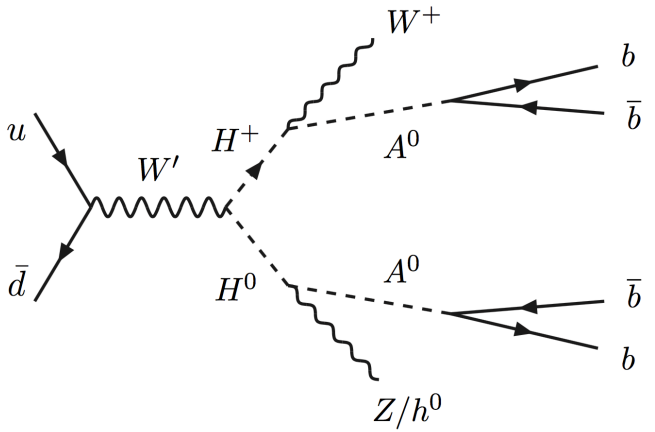


For $M_{W'} > M_{H^+} > M_{A^0}$:

two $(b\bar{b})$ resonances + W

For $M_{W'} \gg M_{H^+}$:

$(b\bar{b})$-tagged jet + $(b\bar{b}jj)$-tagged jet



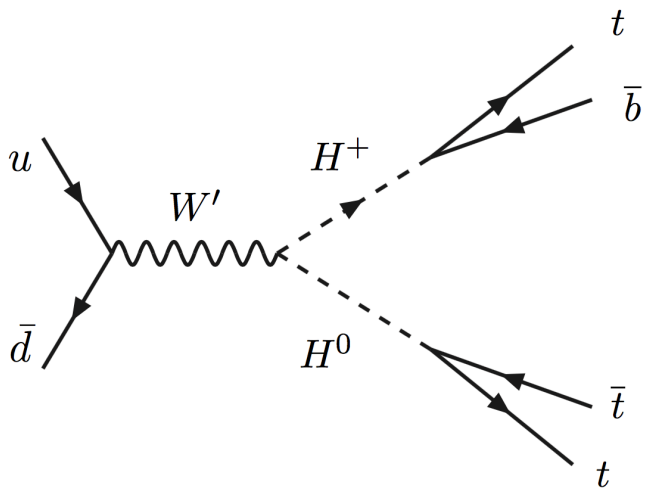
For $M_{W'} > M_{H^+} \gg M_{A^0}$:

two $(b\bar{b})$ resonances + W + (Z or h^0)

For $M_{W'} \gg M_{H^+}$: two $(b\bar{b}jj)$-tagged jets

Different W' model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Heavy Higgs bosons decay directly into a pair of the heaviest fermions:



For $M_{W'} \gg M_{H^+}$:

$(t\bar{b})$-tagged jet + $(t\bar{t})$-tagged jet

For $M_{W'} > M_{H^+} \gg m_t$:

three t-tagged jets + b

For $M_{W'} > M_{H^+} > m_t$:

$W^+W^+W^- + 4b$

(with Zhen Liu, 1507.01923)

Could be responsible for an interesting excess in the ATLAS searches for $\ell^+\ell^+ + (\geq 3)b$ and $\ell^+\ell^+bb$ (1504.04605)

G' decays into heavy scalars

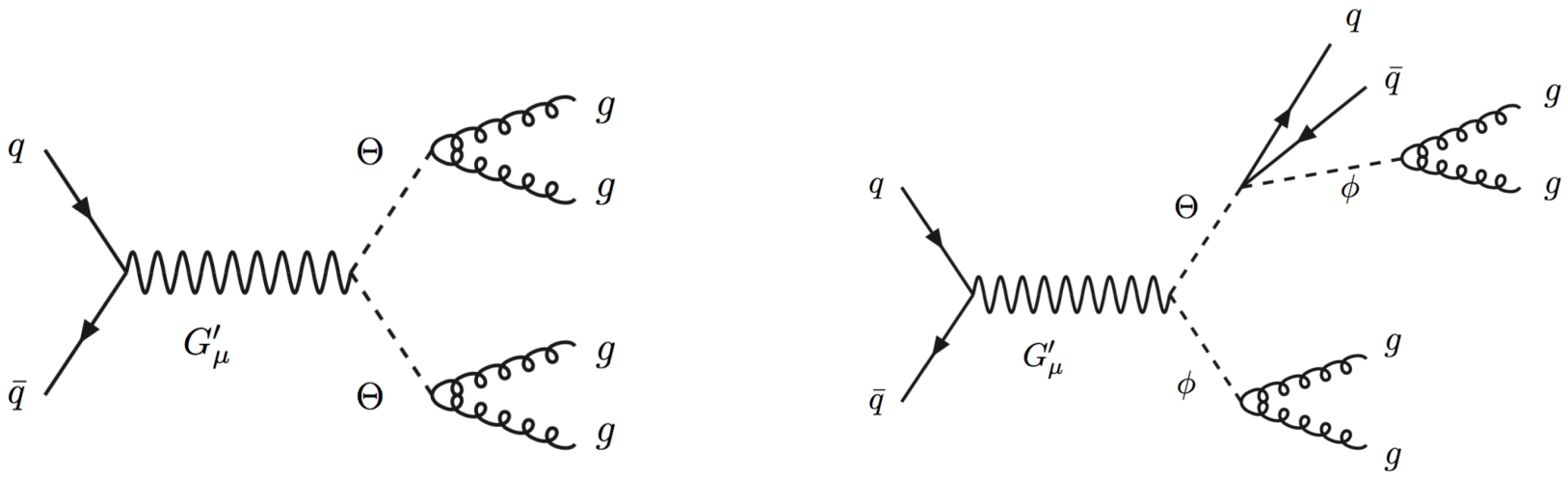
Heavy color-octet of spin-1: gluon-prime or coloron (G')

Renormalizable Coloron Model: *(with Yang Bai, 1012.5814)*

$SU(3)_1 \times SU(3)_2$ **gauge symmetry broken down to** $SU(3)_c$ **by the VEV of a** $(3, \bar{3})$ **scalar.** *Physical states:* G'*, a color-octet scalar* Θ*, a singlet pseudo-scalar* ϕ*.*

Signals for $M_\Theta < M_\phi$ **, or** $M_\Theta > M_\phi$**:**

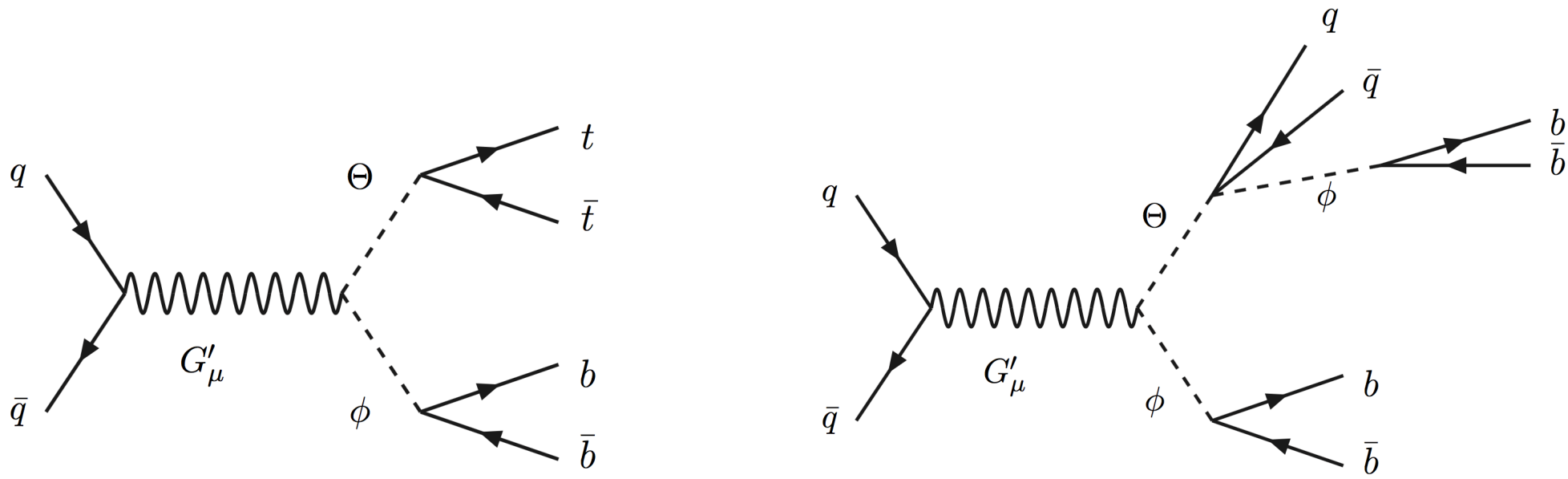
resonant dijet pairs , or $6j$ **(with two dijet resonances)**



Signal for long-lived ϕ**: two displaced** jj **resonances + 2 prompt jets**

More signatures in the Renormalizable Coloron Model:

Vectorlike quarks of multi-TeV mass may mediate other decays for the color-octet scalar Θ and the singlet pseudo-scalar ϕ.



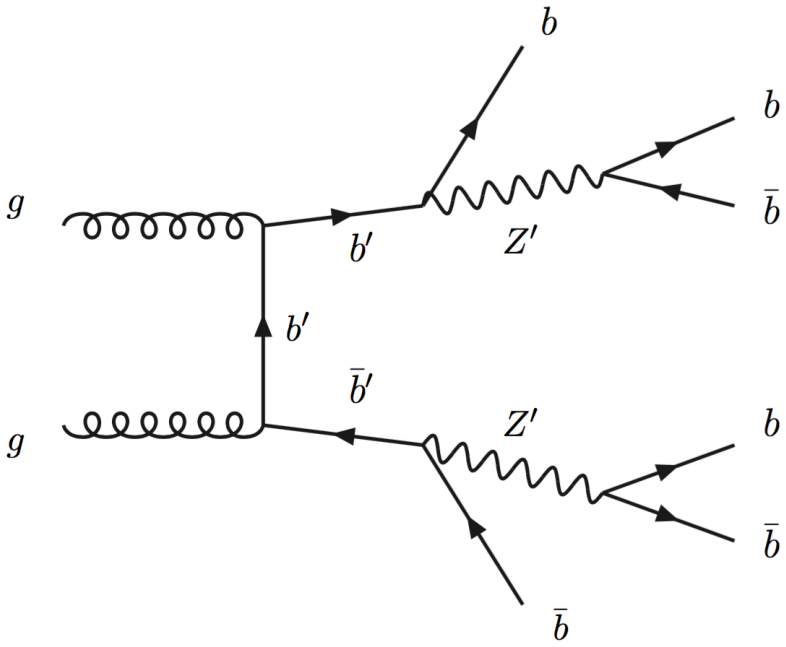
Signal for $M_{G'} > M_\Theta, M_\phi$: $t\bar{t} + b\bar{b}$, or two $b\bar{b}$ resonances + jets

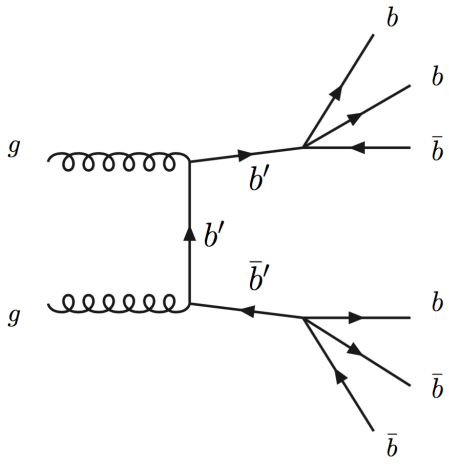
Signal for $M_{G'} \gg M_\Theta, M_\phi$: $(t\bar{t})$-"jet" + $(b\bar{b})$-"jet", or $(b\bar{b}jj)$-"jet" + $(b\bar{b})$-"jet"

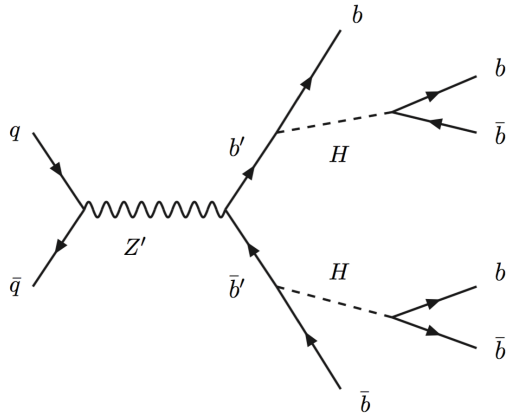
Signal for long-lived ϕ (and maybe Θ):

displaced $t\bar{t}b\bar{b}$, or two displaced $b\bar{b}$ resonances + prompt jj

b-philic Z': *(P. Fox, D. Tucker-Smith, 1509.00499)*



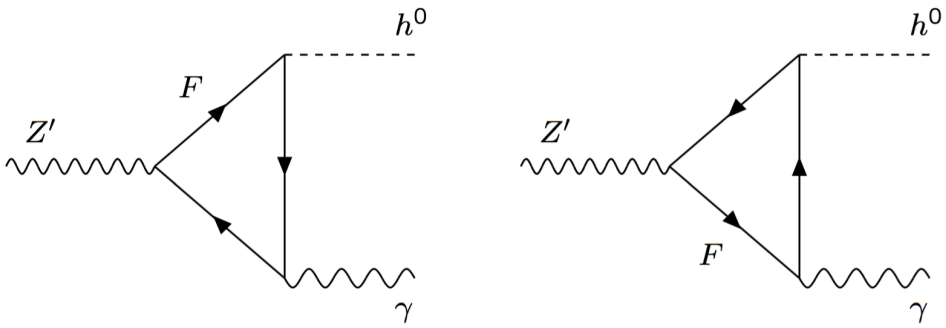




Paddy Fox: *"when you do a search for a certain topology, do also the related searches for other topologies in the same final state".*

Higgs-photon resonance: $Z' \to h^0\gamma$

B.A. Dobrescu, P.J.. Fox and J. Kearney, 1705.08433

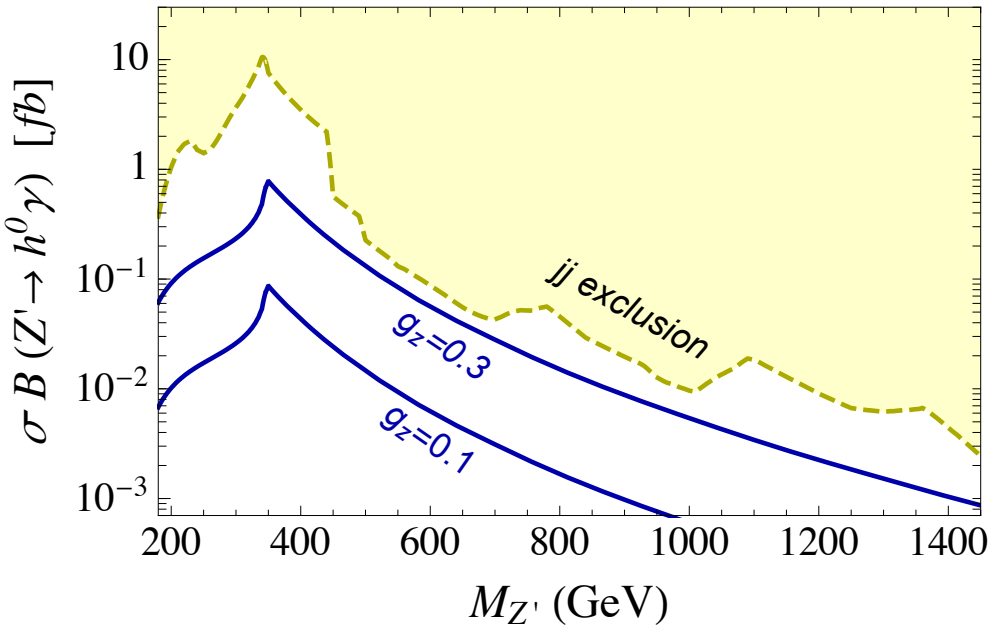


F *is the top quark or an anomalon.*

$$\frac{\Gamma(Z'_B \to h^0\gamma)}{\sum_q \Gamma(Z'_B \to q\bar{q})} \simeq \frac{\alpha\,|I(r_h, r_F)|^2 \left(1 - r_h^2\right)^3}{6\pi^3 \left(5 + \left(1 - r_t^2\right)\sqrt{1 - 4r_t^2}\right)}$$

$I(r_h, r_F)$ **is a loop integral of order one.**

$$r_h = \frac{M_h}{M_{Z'}}\,, \quad r_t = \frac{m_t}{M_{Z'}}$$



Conclusions

LHC is exploring "Terra Incognita" $\rightarrow$ huge potential for surprises

Many additional searches (and novel techniques – jet substructure, quark vs. gluon jets, etc.) necessary for probing new physics

- Vectorlike quarks may have exotic signatures: $t'\bar{t}' \rightarrow t\bar{b}\tau + \not{E}_T$ ...

- Z' boson may undergo cascade decays through anomalons, leading to final states with W, Z, Higgs bosons and $\not{E}_T$.

- W' boson may decay into heavy Higgs bosons, leading to final states with W, Z, Higgs bosons and heavy quarks.

- G' boson may decay into color-octet scalars, leading to multi-jet final states, or signals with $t\bar{t}$+jets, or displaced vertices...

- Z' bosons have interesting rare decays: $Z' \rightarrow h^0\gamma$, ...