From dijet resonances to exotic signals at the LHC

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- **Dijet resonances**
- **Cascade decays of a leptophobic Z'**
- **Exotic decays of vectorlike quarks**

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Run I and the start of Run II at the LHC have confirmed many aspects of the Standard Model, and measured:

$$M_h = 125.09 \pm 0.24 \text{ GeV}$$ *(ATLAS + CMS, 1503.07589).*

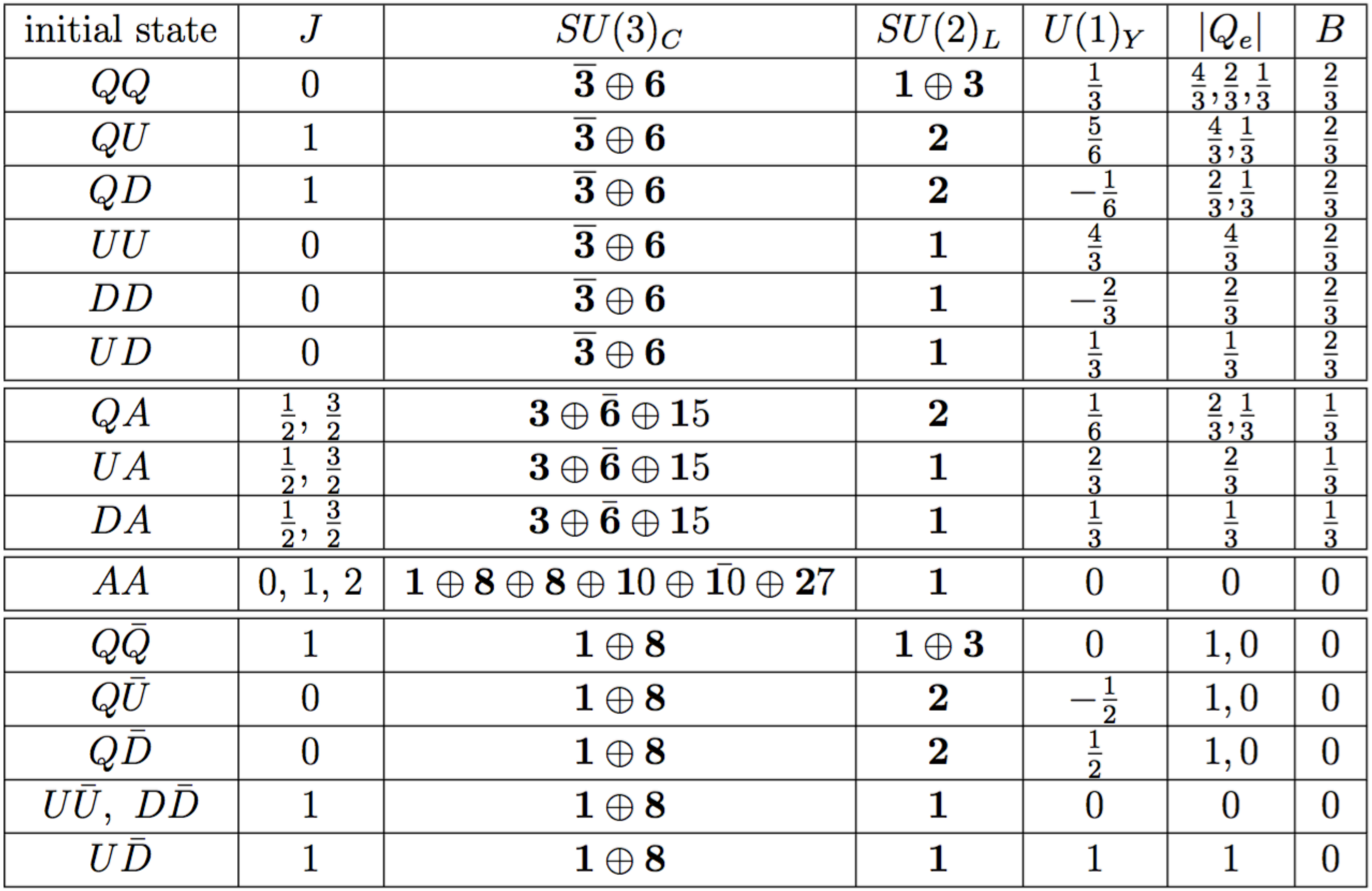
The LHC is probing the laws of nature at the shortest distances accessible by humans so far.

We do not know what the full Run II will find ...

Any s-channel resonance at the LHC should also give a dijet signal: if a parton collission produce it, then it can also decay back to those partons.

The resonance can be a particle of spin 0, 1/2, 1, ...

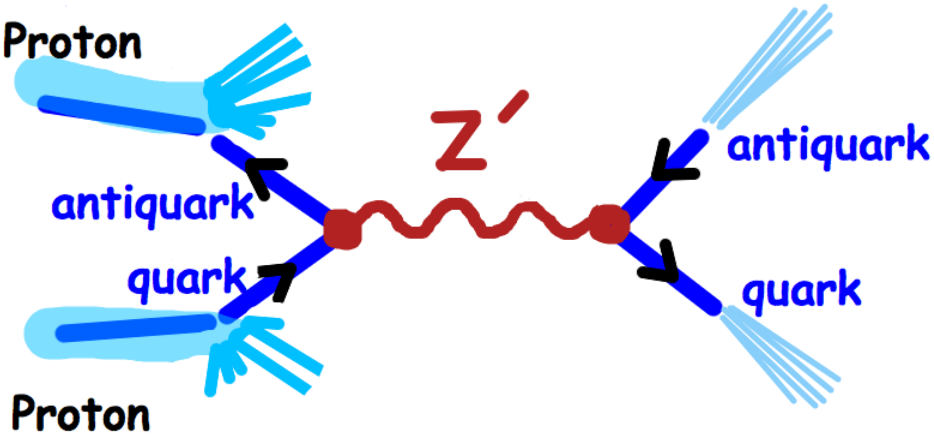
T. Han, I. Lewis, Z. Liu, 1010.4309:



initial state	J	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\lvert Q_e\rvert$	B
QQ	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}\oplus\mathbf{3}$	$\frac{1}{3}$	$\frac{4}{3},\frac{2}{3},\frac{1}{3}$	$\frac{2}{3}$
QU	1	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{2}$	$\frac{5}{6}$	$\frac{4}{3},\frac{1}{3}$	$\frac{2}{3}$
QD	1	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{2}$	$-\frac{1}{6}$	$\frac{2}{3},\frac{1}{3}$	$\frac{2}{3}$
UU	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{2}{3}$
DD	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$-\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
UD	0	$\bar{\mathbf{3}}\oplus\mathbf{6}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
QA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{2}{3},\frac{1}{3}$	$\frac{1}{3}$
UA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{3}$
DA	$\frac{1}{2},\frac{3}{2}$	$\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
AA	0, 1, 2	$\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10}\oplus\overline{\mathbf{10}}\oplus\mathbf{27}$	$\mathbf{1}$	0	0	0
$Q\bar{Q}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}\oplus\mathbf{3}$	0	1, 0	0
$Q\bar{U}$	0	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{2}$	$-\frac{1}{2}$	1, 0	0
$Q\bar{D}$	0	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{2}$	$\frac{1}{2}$	1, 0	0
$U\bar{U},\ D\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}$	0	0	0
$U\bar{D}$	1	$\mathbf{1}\oplus\mathbf{8}$	$\mathbf{1}$	1	1	0

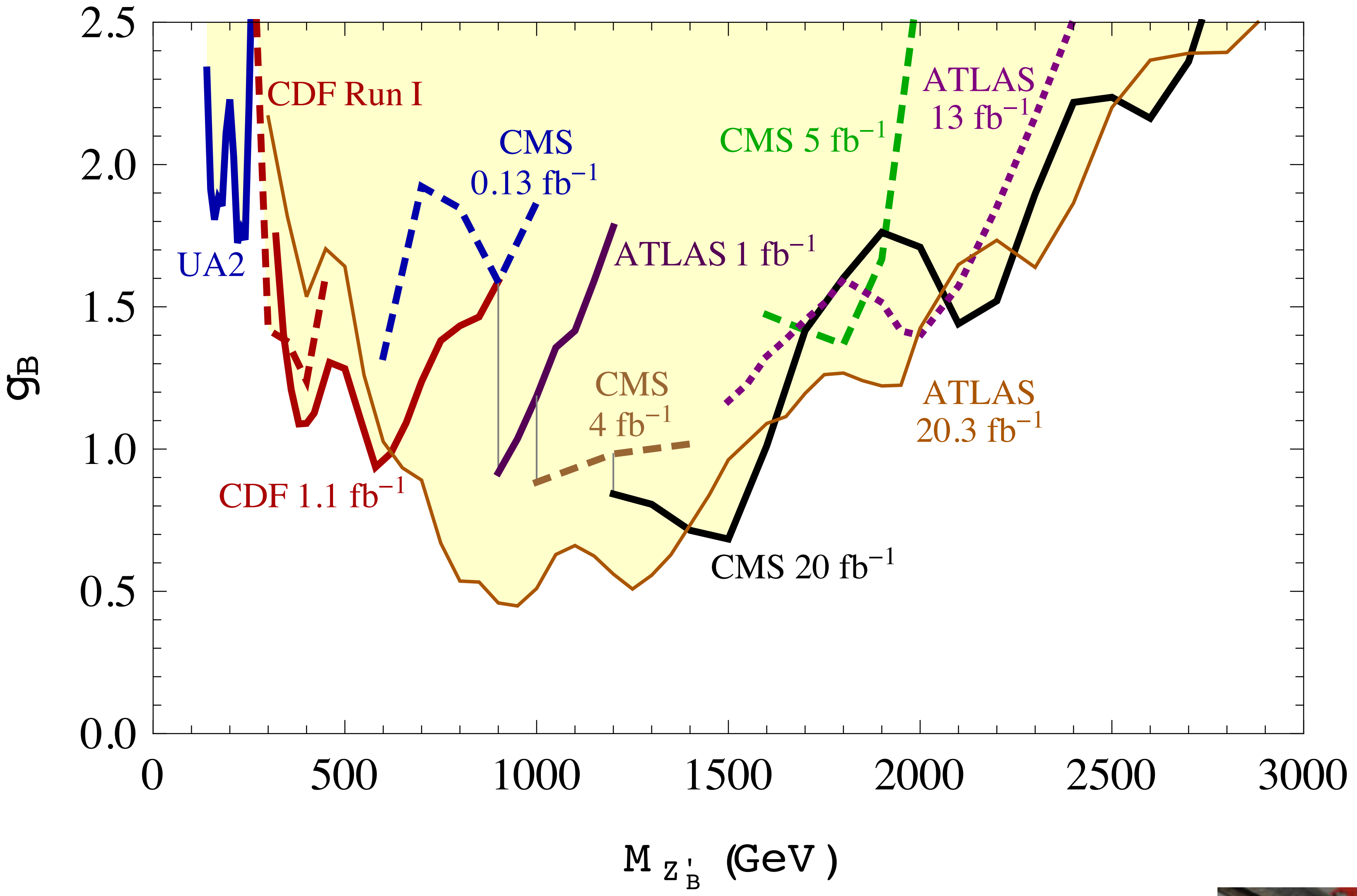
Hypothetical heavy particle of spin 1 and charge 0: Z' boson.

If Z' couples only to quarks (“leptophobic”), then it can be produced at hadron colliders and decays back to quark-antiquark pairs:



The two jets form a resonance that can show up above the background if $M_{Z'}$ is large enough and its couplings are large.

"Baryonic" Z'_B: same coupling (g_B) to all six quark flavors.



$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \overline{q}_L \gamma^\mu q_L + \frac{1}{3} \overline{q}_R \gamma^\mu q_R \right)$$

with Felix Yu:
1306.2629

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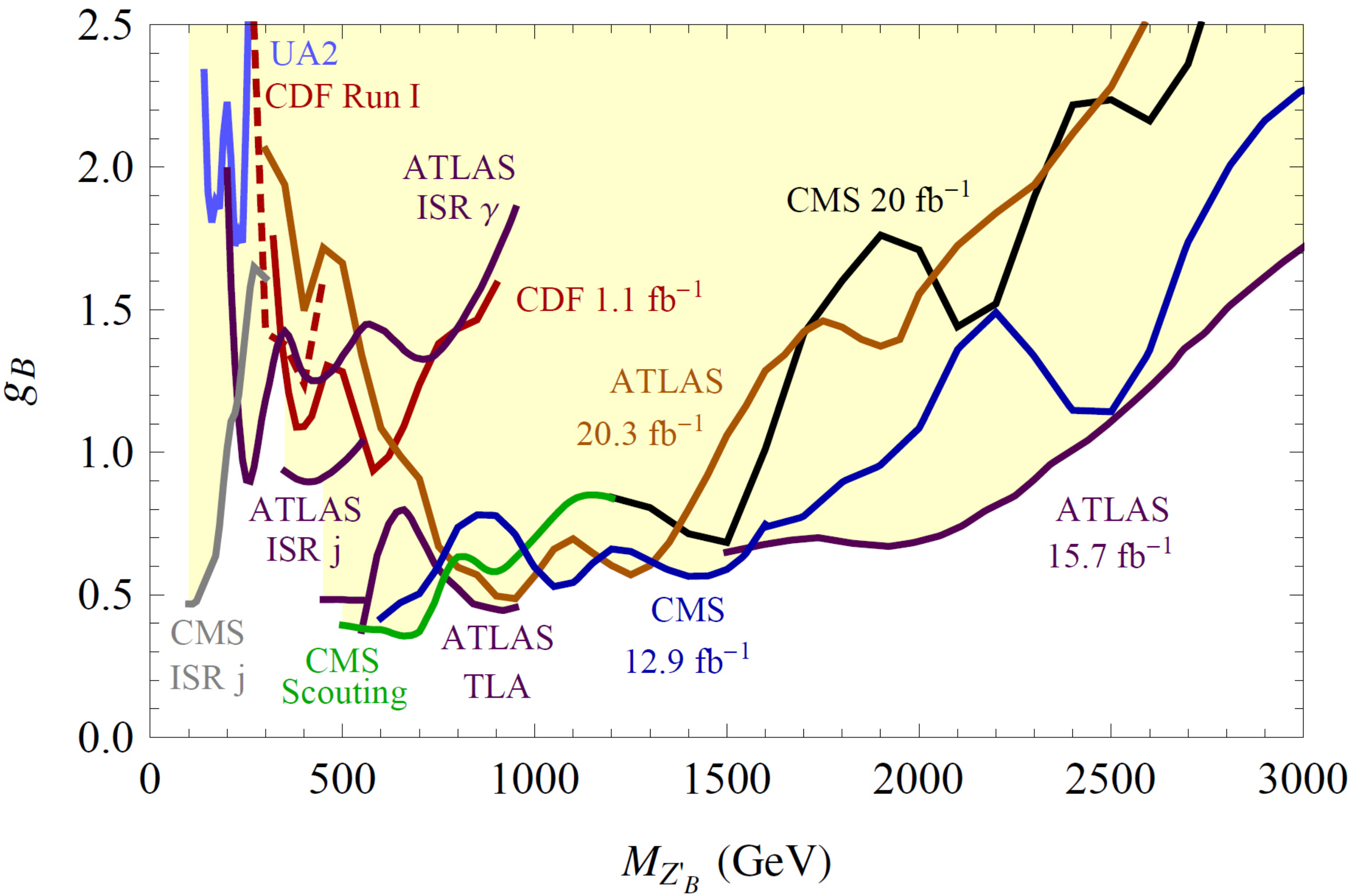

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with Felix Yu: 1306.2629

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

Z' is associated with a new gauge symmetry.

Simple choice: $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_B$

Theoretical requirements:

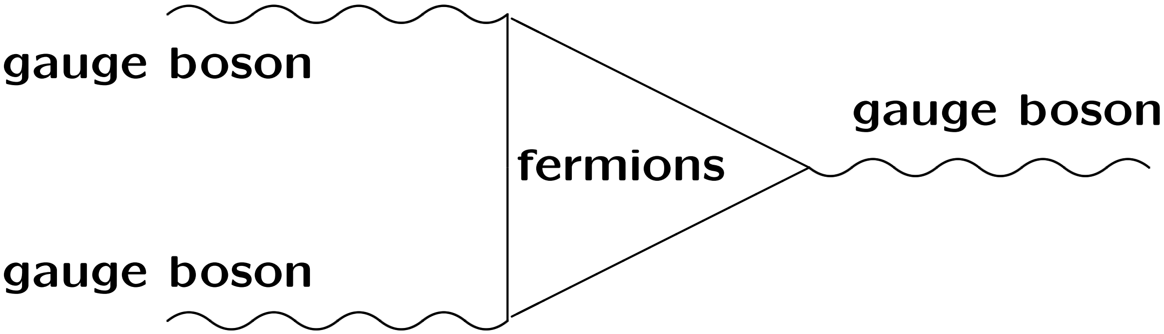
- **$U(1)_B$ must be spontaneously broken.**
  Simple choice: a new scalar field ϕ acquires a VEV.
- **All $U(1)_B$ gauge anomalies must cancel.**

Gauge anomaly cancellation

W. Bardeen, 1969, ...

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$$[SU(3)_c]^2U(1)_Y: \quad 2(1/6) + (-2/3) + (1/3) = 0$$

$$[SU(2)_W]^2U(1)_Y: \quad 3(1/6) + (-1/2) = 0$$

$$[U(1)_Y]^3: \quad 3\left[2(1/6)^3 + (-2/3)^3 + (1/3)^3\right] + 2(-1/2)^3 + (-1)^3 = 0$$

$$\ldots \qquad (u_L, d_L) \qquad u_R \qquad d_R \qquad (\nu_L, e_L) \qquad e_R$$

Any leptophobic Z' that couples to quarks requires new charged fermions to cancel the anomalies (or to mix with the SM quarks - not discussed here).

4th generation of chiral fermions is highly constrained (almost ruled out) by ATLAS and CMS searches for new quarks and Higgs measurements

⇒ The new fermions ("anomalons") must be

vectorlike with respect to $SU(3)_c \times SU(2)_W \times U(1)_Y$, and

chiral with respect to the new gauge group.

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	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1 $+2$
E_L E_R	1/2	$\mathbf{1}$	$\mathbf{1}$	-1	$+2$ -1
N_L N_R	1/2	$\mathbf{1}$	$\mathbf{1}$	0	$+2$ -1
ϕ	0	$\mathbf{1}$	$\mathbf{1}$	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.

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

Left-handed neutral anomalons in the mass eigenstate basis:

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

Right-handed ones:

$$\begin{pmatrix} N_{S_R} \\ N_{D_R} \end{pmatrix} = \begin{pmatrix} c'_N & s'_N \\ -s'_N & c'_N \end{pmatrix}\begin{pmatrix} N_R \\ L^\nu_R \end{pmatrix}$$

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

$$m_{E_D} - m_{N_D} \simeq \left(y^2_{EL} - y^2_{NL}\right)\frac{v^2_H}{2y_L\langle\phi\rangle} + \ldots$$

The decays of the four anomalon physical states depend on their mass ordering.

$U(1)_B$ 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.

Consider the following ordering $m_{E_S} > m_{E_D} > m_{N_D} > m_{N_S}$.

N_D has 2 decay modes: $N_S\, h^0$ and $N_S\, Z$.

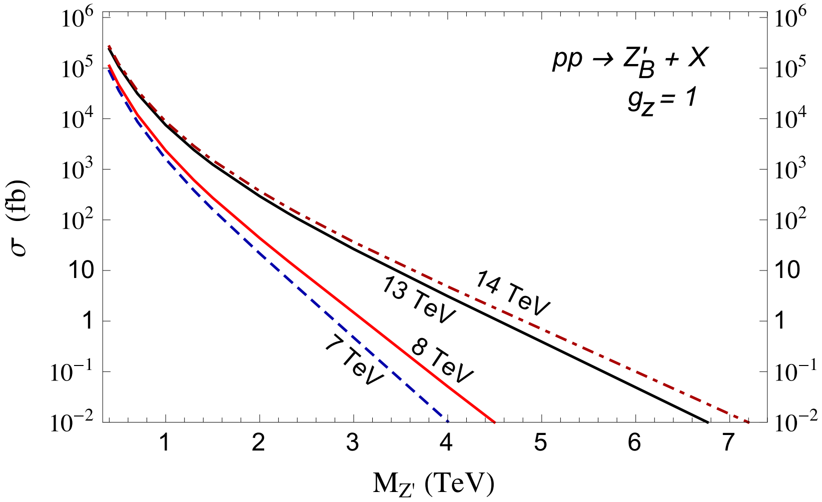
For $m_{N_D} - m_{N_S} \gg M_h$:

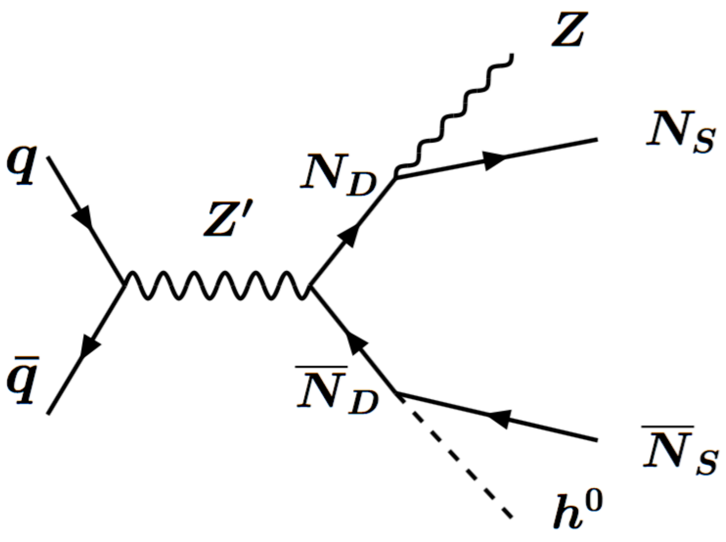
$$B(N_D \to N_S\, h^0) \approx B(N_D \to N_S\, Z) \approx \frac{1}{2}$$

assuming $M_\varphi > m_{N_D} - m_{N_S}$

Cascade decays via anomalons:

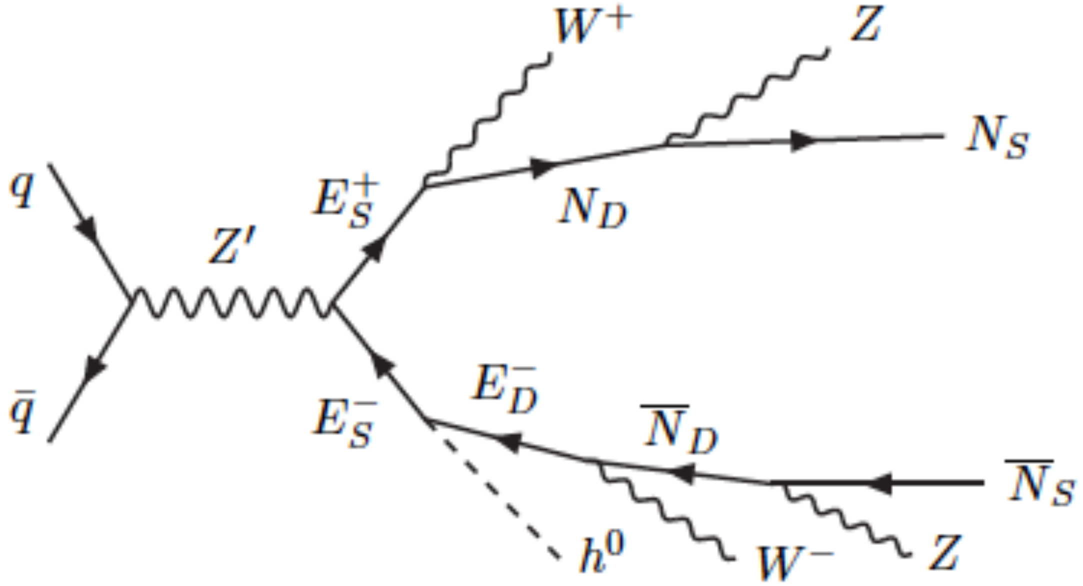
(1506.04435)





E_D has 2 decay modes: $N_D W$ and $N_S W$.

E_S has 3 main decay modes: $N_D W$, $E_D h^0$ and $E_D Z$.



Longer cascade decays:

$$Z' \to E_S^+ E_S^- \to E_D^+ E_D^- + 2(Z/h) \to N_D \bar{N}_D W W + 2(Z/h)$$

$$\to N_S \bar{N}_S W^+ W^- + 4(Z/h)$$

Other leptophobic Z' models:

Z'_{R12} model

(1506.04435)

The $U(1)_{R12}$-charged SM quarks and the fields beyond the SM:

field	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{R12}$
u_R , c_R	1/2	3	1	+2/3	+1
d_R , s_R				-1	-1
E_L , E'_L	1/2	1	1	-1	$+1$, -1
E_R , E'_R					0 , -2
N_R	1/2	1	1	0	$+2$
ϕ	0	1	1	0	$+1$

Z'_{R12} model predicts final states with missing energy,

$$Z'_{R12} \to E_1^+ E_1^- \to \; W^+ \bar{\nu}\, W^- \nu \;\;,\;\; W \nu\, Z \ell \;\;,\;\; W \nu\, h^0 \ell$$

or final states with one or more pairs of leptons,

$$Z'_{R12} \to E_1^+ E_1^- \to \; h^0 \ell\, Z \ell' \;\;,\;\; h^0 \ell\, h^0 \ell' \;\;,\;\; Z \ell\, Z \ell'$$

The leptons (ℓ and ℓ') may each be an e, a μ or a τ, with branching fractions that may violate lepton universality.

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.

χ is predicted in composite Higgs models (Chivukula et al, hep-ph/9809470),
little Higgs models (Arkani-Hamed et al, hep-ph/0206020), ...

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

'Standard' decay widths of t':

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

$$\Gamma(t' \to Zt) = \frac{s_L^2 c_L^2\, m_{t'}^3}{64\pi v_H^2}\left[1 - \frac{m_t^2}{m_{t'}^2} + O\left(\frac{m_t^4}{m_{t'}^4}\right)\right]$$

$$\Gamma(t' \to ht) = \frac{s_L^2 c_L^2 m_{t'}^3}{64\pi v_H^2}\left[1 + 5\frac{m_t^2}{m_{t'}^2} + O\left(\frac{m_t^4}{m_{t'}^4}\right)\right]$$

For $s_L \ll 1$, <u>exotic decays of vectorlike quarks</u> could dominate!

E.g., **4-fermion operator** $(\overline{\chi}_R l^3_L) i\sigma_2 (\overline{\tau}_R q^3_L) \quad \Rightarrow \quad t' \to \tau^+\tau^- t$

Example of UV completion: scalar leptoquark ξ,
which transforms as (3, 2, 7/6) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

Yukawa interactions of ξ:

$$\lambda_\chi \, (\overline{\chi}_R l^3_L)\xi - i\lambda_q \, \xi^\dagger \sigma_2 (\overline{\tau}_R q^3_L) + \lambda_t \, \xi^\dagger (\bar{l}^3_L t_R)$$

For $M_\xi > m_{t'}$, integrate ξ out:

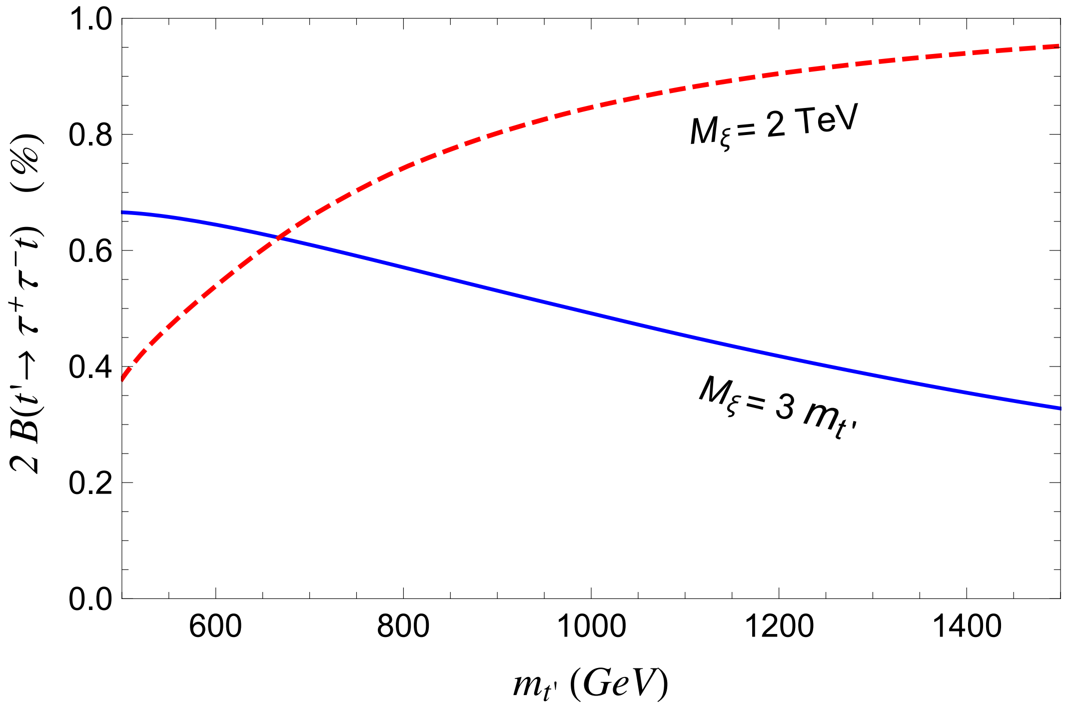
$$\frac{\lambda_t \lambda_\chi}{M_\xi^2} (\overline{\chi}_R l^3_L)^\top i\sigma_2 (\overline{\tau}_R q^3_L) - \frac{\lambda'_t \lambda_\chi}{M_\xi^2} \, (\bar{l}^3_L t_R)(\overline{\chi}_R l^3_L)$$

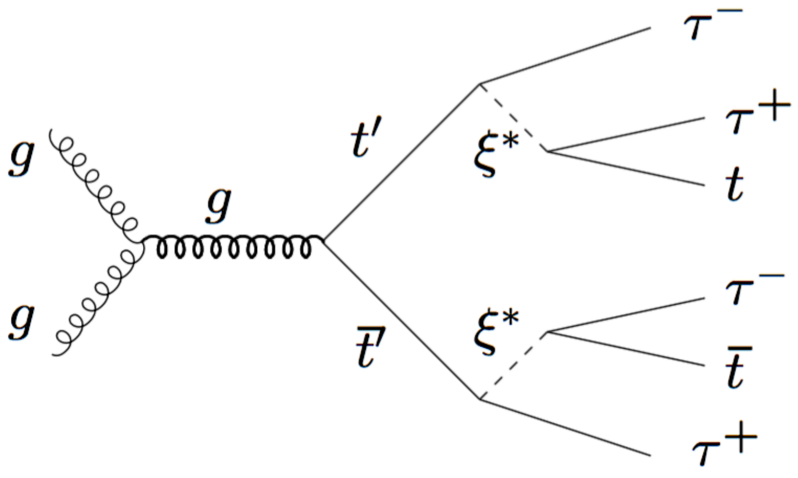
Exotic width:

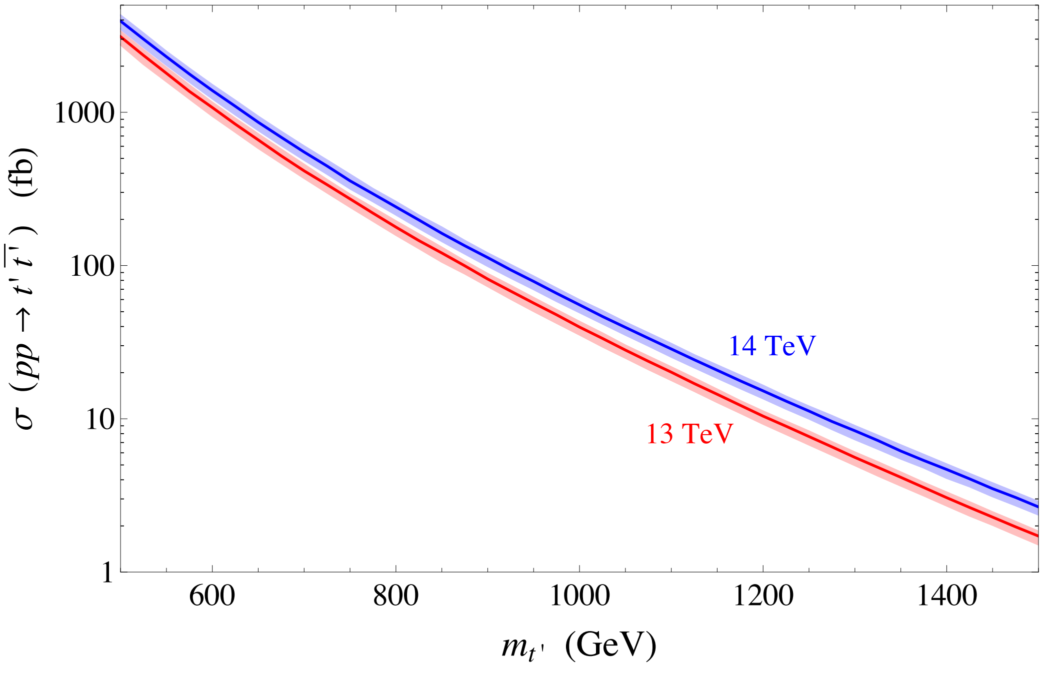
$$\Gamma(t' \to \tau^+\tau^- t) = \frac{\lambda_\chi^2(\lambda_t^2 + \lambda_t'^2)}{6144\pi^3 M_\xi^4} m_{t'}^5 \left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right].$$

χ-u^3 mixing induced at one loop:

$$s_L = \frac{y_\tau \lambda_\chi \lambda_q}{8\pi^2} \ln(\Lambda/M_\xi) \lesssim 6 \times 10^{-4} \quad \text{for} \quad \lambda_\chi\lambda_q \lesssim 1$$







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

Similar final states with τ replaced by μ or e ($t\bar{t} + 4\mu$, ...)

Other 4-fermion operators, *e.g.*,

$$\frac{\kappa_\chi \kappa_t}{M_\zeta^2}(\overline{\chi}^c_R d^3_R)(\overline{d}^3_R u^{3c}_R)$$

lead to a $t\bar{t} + 4b$ final states.

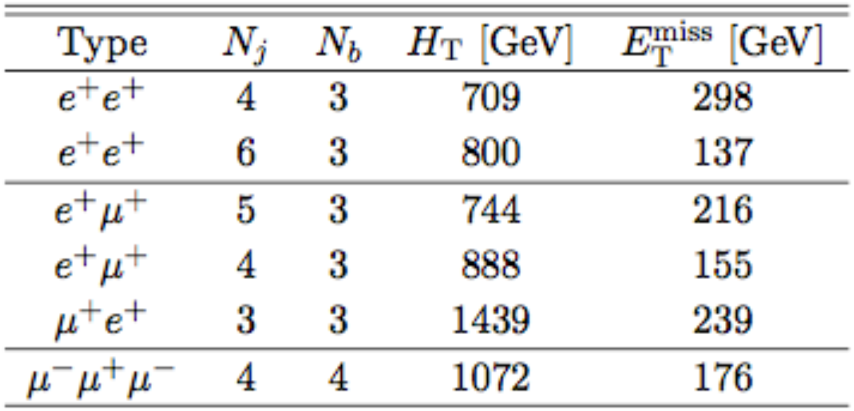
W' decays into heavy Higgs bosons

with Zhen Liu, 1507.01923

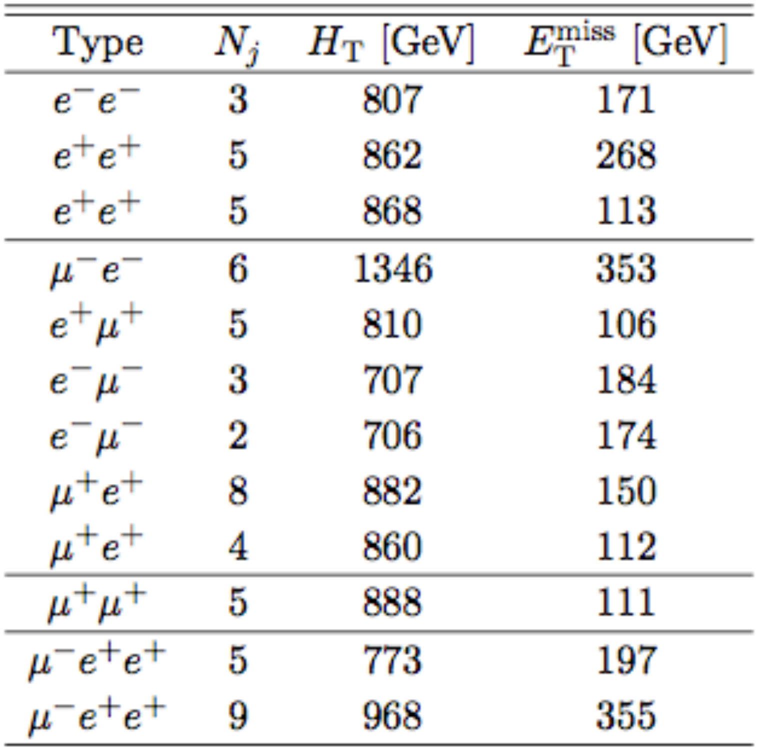
$$W' \to H^+H^0,\ H^+A^0 \to (t\bar{b})(t\bar{t}) \to 3W + 4b$$

ATLAS 1504.04605

$\ell^+\ell^+ + (\geq 3)b$ and $\ell^+\ell^+bb$



Type	N_j	N_b	H_T [GeV]	E_T^{miss} [GeV]
e^+e^+	4	3	709	298
e^+e^+	6	3	800	137
$e^+\mu^+$	5	3	744	216
$e^+\mu^+$	4	3	888	155
μ^+e^+	3	3	1439	239
$\mu^-\mu^+\mu^-$	4	4	1072	176



Type	N_j	H_T [GeV]	E_T^{miss} [GeV]
e^-e^-	3	807	171
e^+e^+	5	862	268
e^+e^+	5	868	113
μ^-e^-	6	1346	353
$e^+\mu^+$	5	810	106
$e^-\mu^-$	3	707	184
$e^-\mu^-$	2	706	174
μ^+e^+	8	882	150
μ^+e^+	4	860	112
$\mu^+\mu^+$	5	888	111
$\mu^-e^+e^+$	5	773	197
$\mu^-e^+e^+$	9	968	355

Excess explained for $M_{H^\pm} \approx M_{H^0} \approx M_{A^0} \approx$ 500–600 GeV

($M_{W'} \approx 1.9 - 2$ TeV)

Conclusions

- Run 2 of the LHC is exploring "Terra Incognita"

  → huge potential for surprises, data driven environment ...

Many additional searches (and novel techniques – jet substructure, quark vs. gluon jets, etc.) are necessary for probing new physics: vectorlike quarks, new gauge bosons, (pseudo)-scalars, ...

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

- Vectorlike fermions may have various exotic decays:

$$t' \to t\tau^+\tau^- \, , \; t\mu^+\mu^- \, , \; tb\bar{b} \, , \; ....$$