Signatures of new gauge bosons

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

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Run 1 and the start of Run 2 at the LHC have confirmed many aspects of the Standard Model, and measured:

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

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

We don't know what will be found with 3000 fb^{-1} of data ...

New gauge bosons

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

Z' **(particle of spin 1 and charge 0) is associated with a new gauge symmetry.**

Simple choices:

$$SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_z$$

$$SU(3)_c \times SU(2) \times SU(2) \times U(1)$$

$$SU(3)_c \times SU(3)_W \times U(1)$$

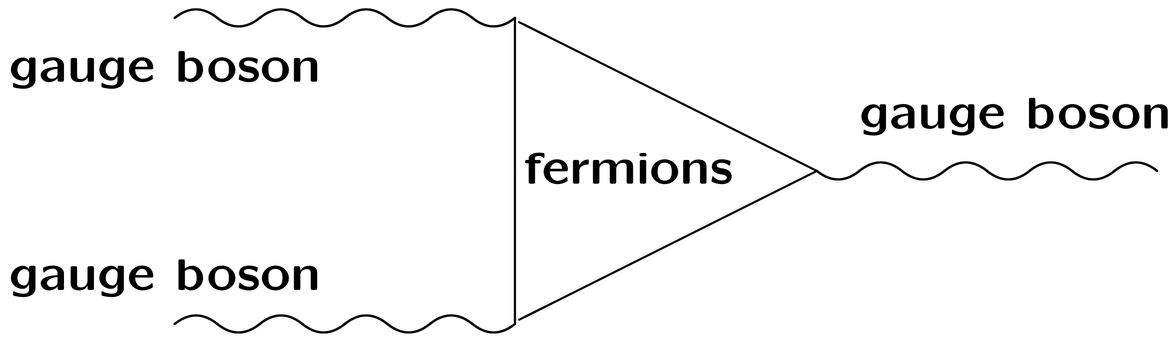
...

Gauge anomaly cancellation

W. Bardeen, 1969, ...

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Most Z' bosons that couple to quarks require new charged fermions to cancel the anomalies *(or to mix with the SM quarks).*

$\Rightarrow$ **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.**

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν_R'				$\cdot$	$\cdot$	$-1-x/3$	$\cdot$
ψ_L^l	1	2	-1	-1	$\cdot$	$-(1+x)/3$	$-2x/5$
ψ_R^l				$-x$	$\cdot$	$2/3$	$(-1+x/5)/3$
ψ_L^e	1	1	-2	-1	$\cdot$	$\cdot$	$\cdot$
ψ_R^e				$-x$	$\cdot$	$\cdot$	$\cdot$
ψ_L^d	3	1	$-2/3$	$\cdot$	$\cdot$	$-2/3$	$(1-4x/5)/3$
ψ_R^d				$\cdot$	$\cdot$	$(1+x)/3$	$x/15$

M. Carena, A. Daleo, B. Dobrescu, T. Tait, hep-ph/0408098

Leptophobic Z'

E.g., Z'_B couples to baryon number: $$\frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \overline{q}_L \gamma^\mu q_L + \frac{1}{3} \overline{q}_R \gamma^\mu q_R \right)$$

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.

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

Left-handed neutral anomalons in the mass eigenstate basis:

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

Right-handed ones:

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

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

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

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 $m_{E_s} > m_{E_D} > m_{N_D} > m_{N_s}$.

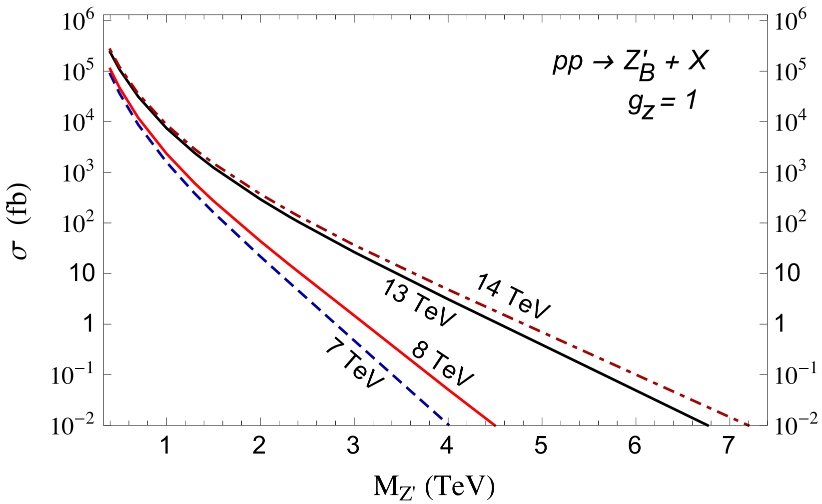
N_D has 2 decay modes: $N_S\, h^0$ and $N_S\, Z$.

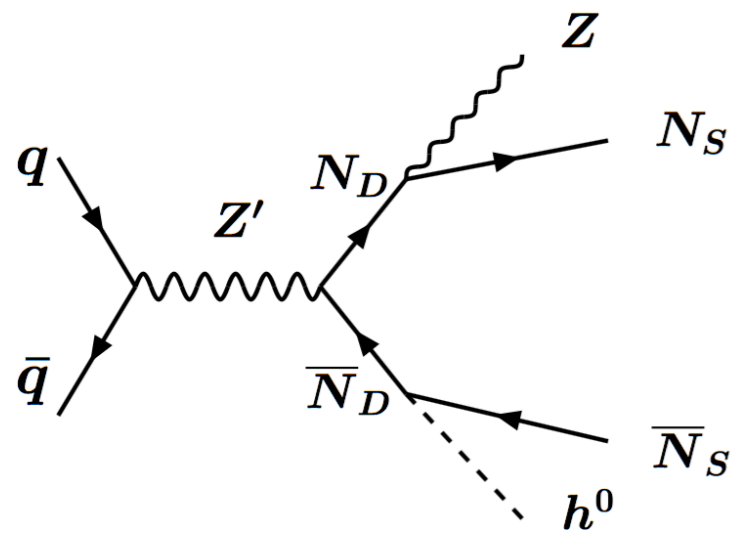
For $m_{N_D} - m_{N_s} \gg M_h$:

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

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

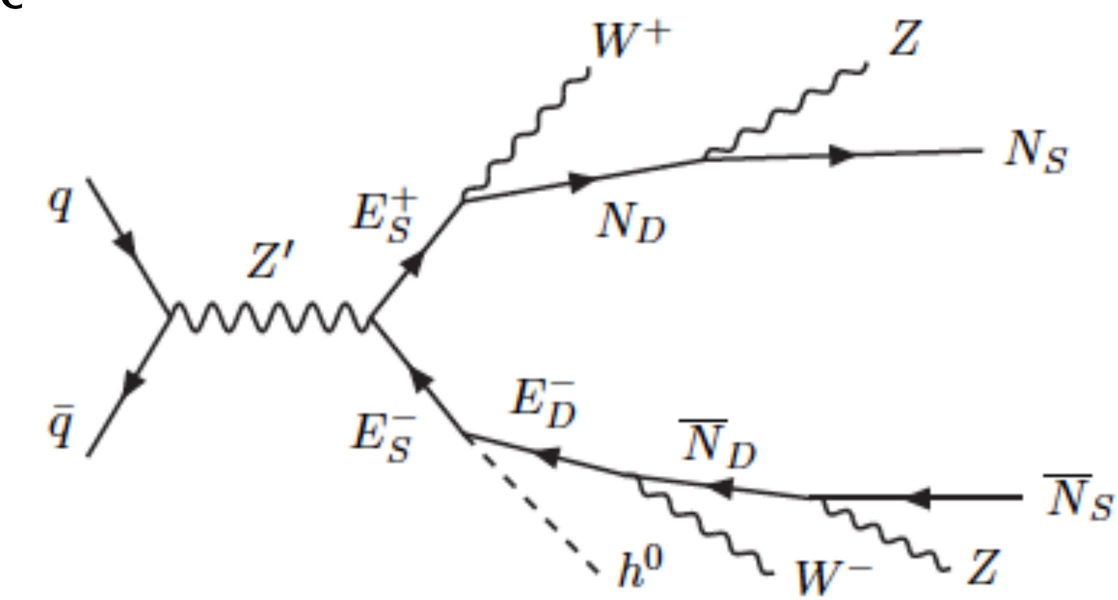
Cascade decays via anomalons: (1506.04435)





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

E_S has 3 main decay mode



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,**

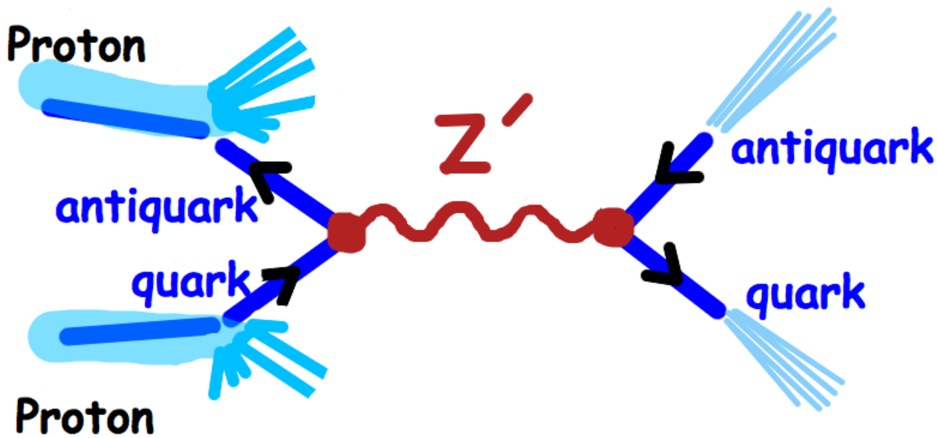
$$Z'_{R12} \to E_1^+ E_1^- \to \; W^+ \bar{\nu}\, W^- \nu \;\;,\;\; W \nu\, Z \ell \;\;,\;\; W \nu\, h^0 \ell$$

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.

If Z' couples to quarks, then it can be produced at hadron colliders and may decay 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.

Leptophobic Z': no tree-level couplings to leptons

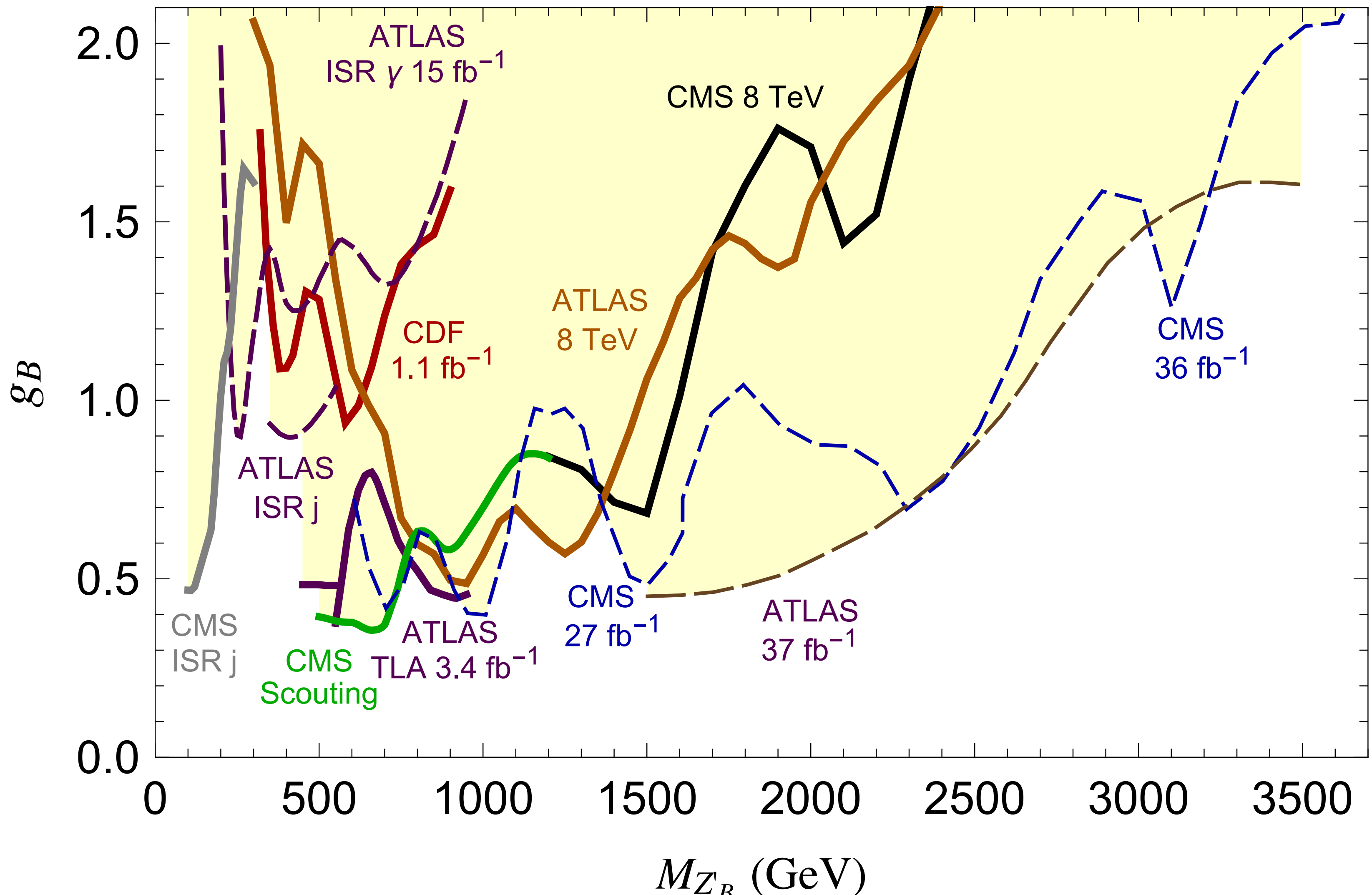
Any s-channel resonance at the LHC should also give a dijet signal: if a parton collission produce it, then it can also decay back to those partons.

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

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

initial state	J	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\|Q_e\|$	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	$\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \bar{\mathbf{10}} \oplus \mathbf{27}$	$\mathbf{1}$	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

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



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

with Felix Yu: 1306.2629

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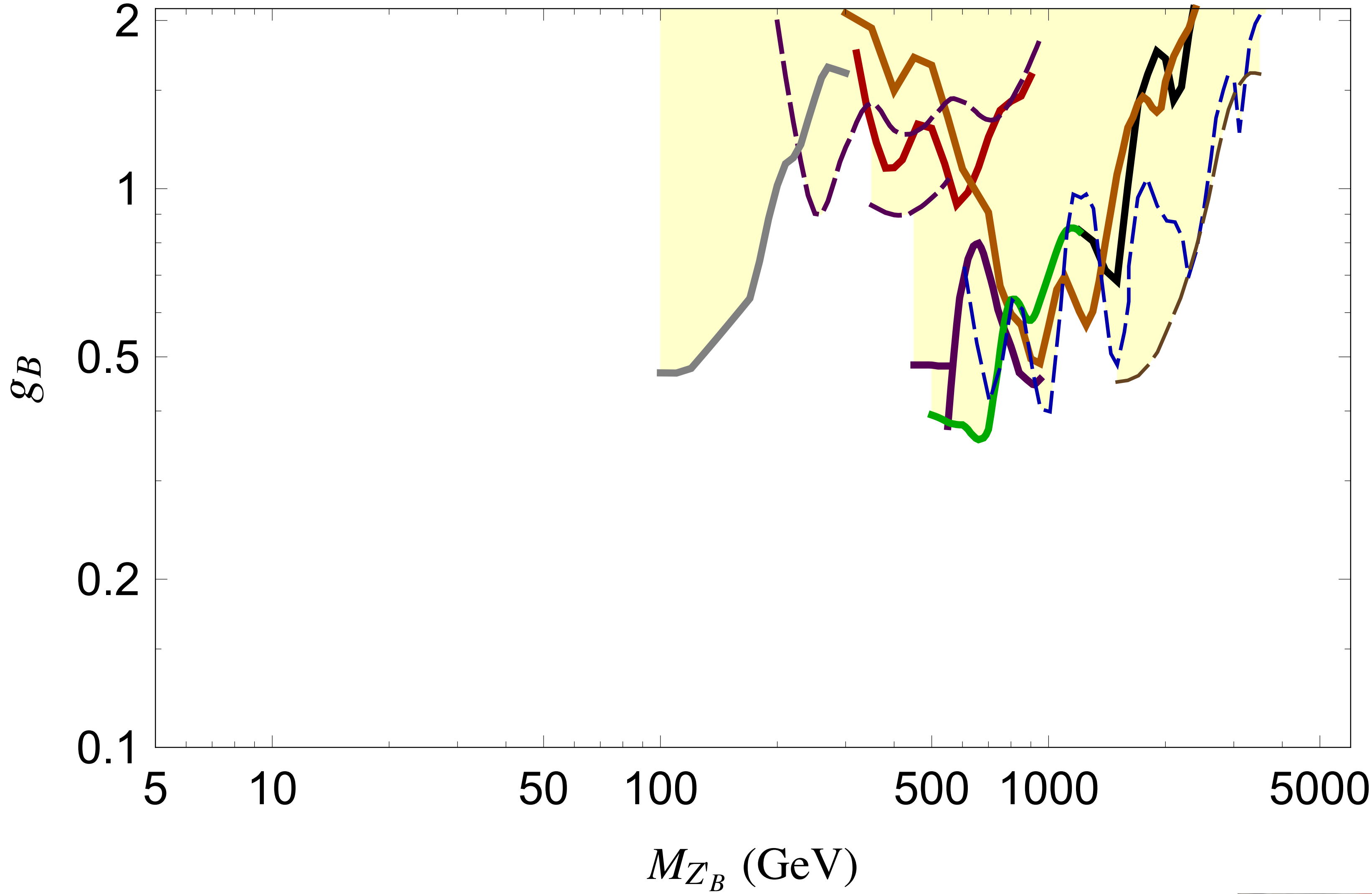

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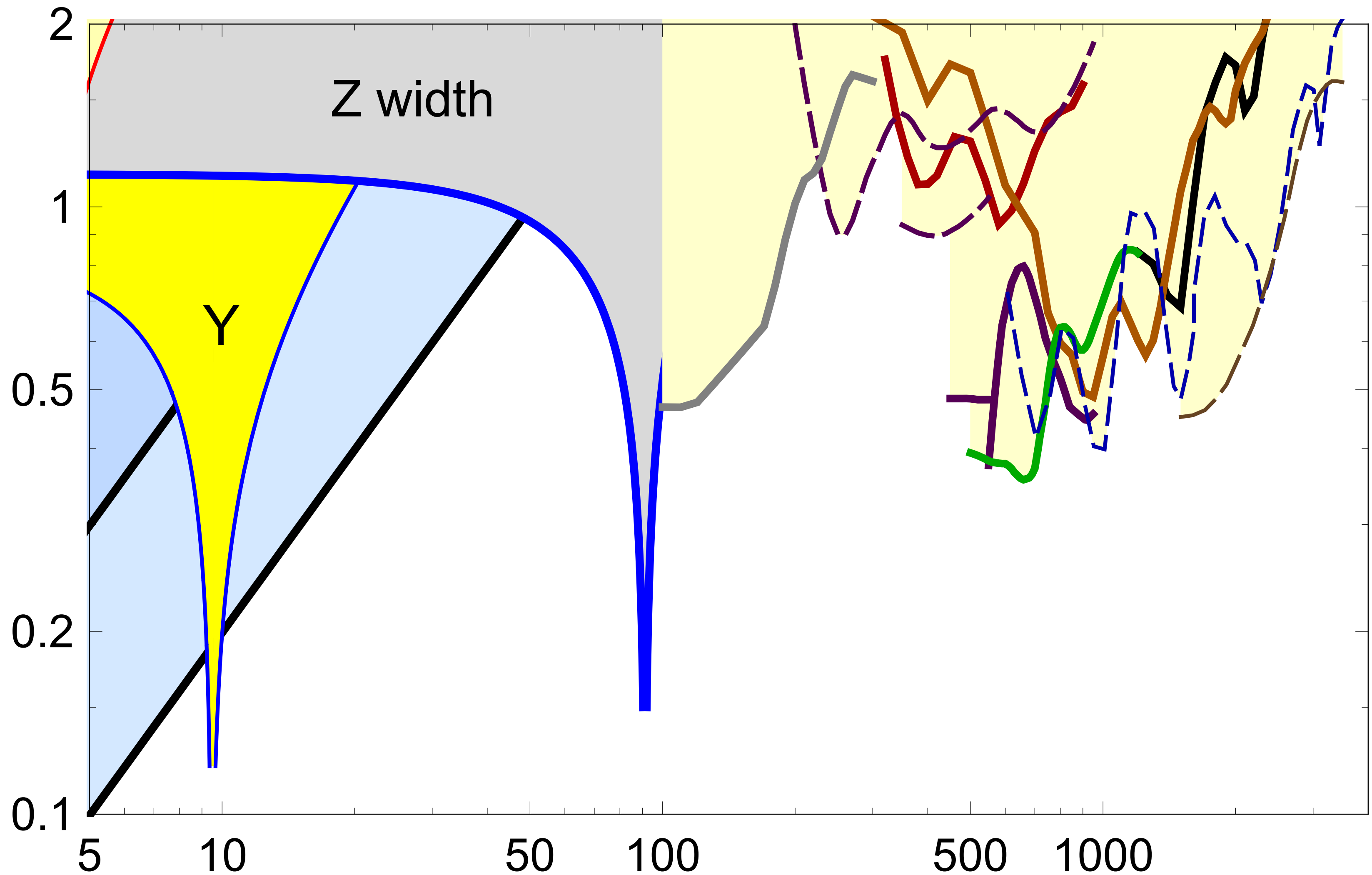


For low $M_{Z'}$, limits on anomalon masses impose a constraint on the gauge coupling. *(with Claudia Frugiuele, 1404.3947)*

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

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

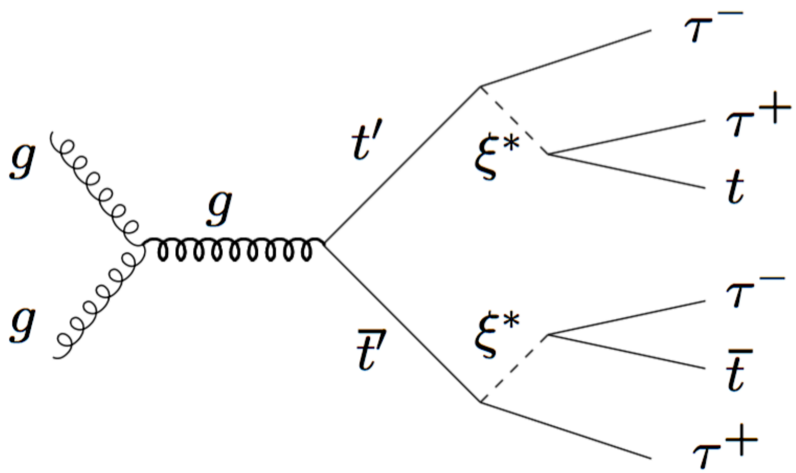
Example of UV completion: scalar leptoquark ξ,
which transforms as (3, 2, 7/6) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

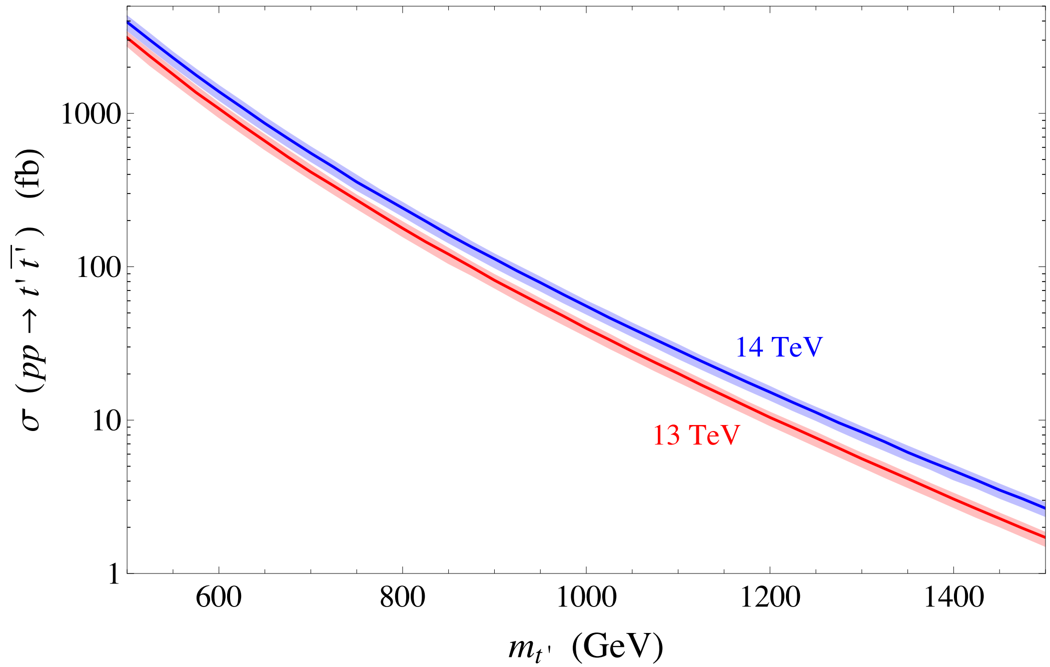
Yukawa interactions of ξ:

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

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

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





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.*,

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

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

Conclusions

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

  $\rightarrow$ 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:

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