Exotic signatures of new gauge bosons

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- **Dijet resonances** *(with Felix Yu)*

- **Cascade decays of a leptophobic Z'** *(1506.04435)*

- **Loop decays: $Z' \to h^0\gamma$** *(with Patrick Fox and John Kearney, 1705.08433)*

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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:

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

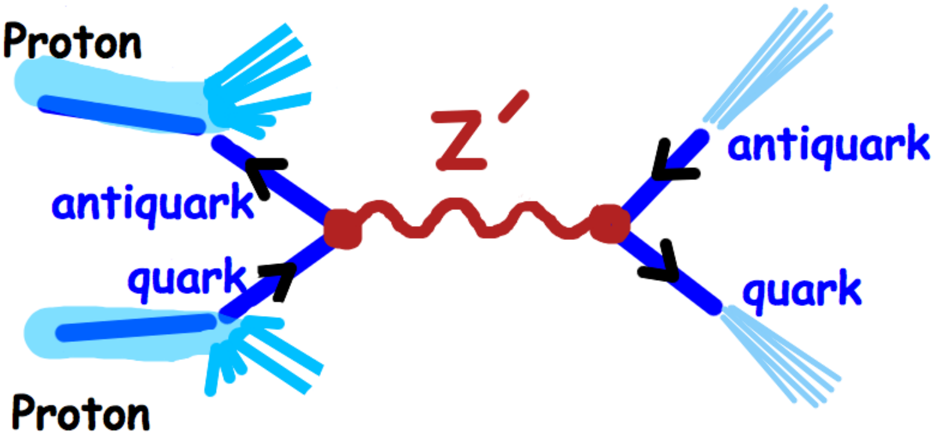
The LHC is probing the laws of nature at the shortest distances accessible by humans so far.

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 collision produces it, then it can also decay back to those partons.

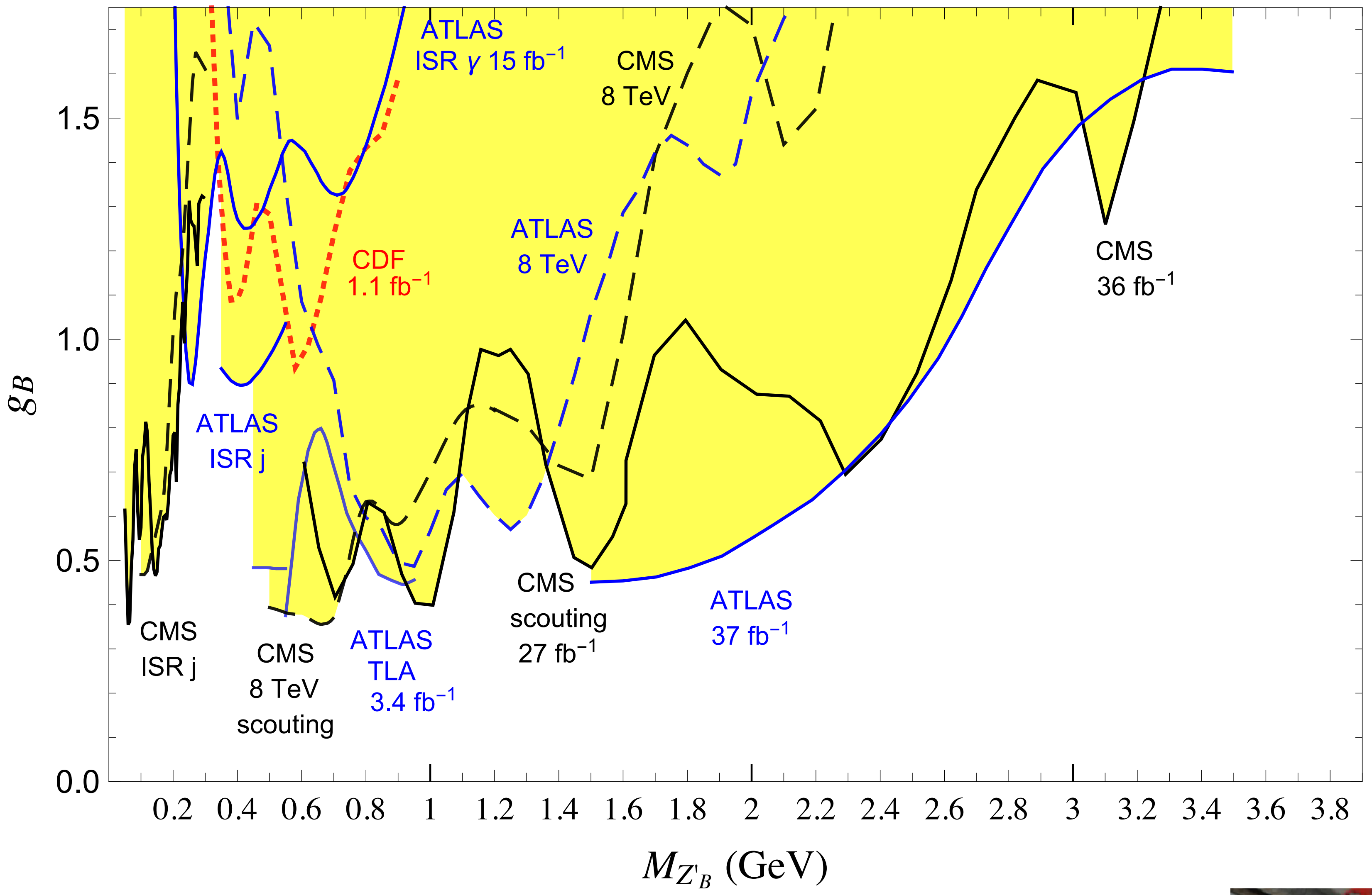
Hypothetical heavy particle of spin 1 and charge 0: Z' boson.

If Z' couples only to quarks ("leptophobic"), then it may be observed in dijet resonance searches at hadron colliders:



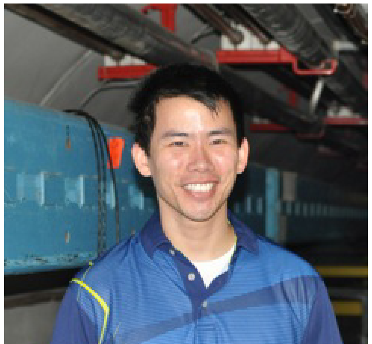
The two jets form a resonance that can show up above the background if $M_{Z'}$ is large enough and its couplings are large.

“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:
update to 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.

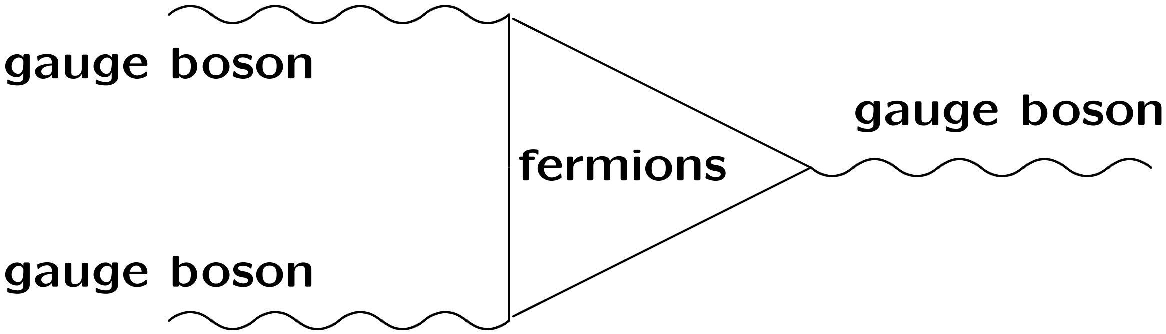
- **All $U(1)_B$ gauge anomalies must cancel.**

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:

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

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

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

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

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.

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

Left-handed neutral anomalons in the mass eigenstate basis:

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

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 $N_S\,Z$.

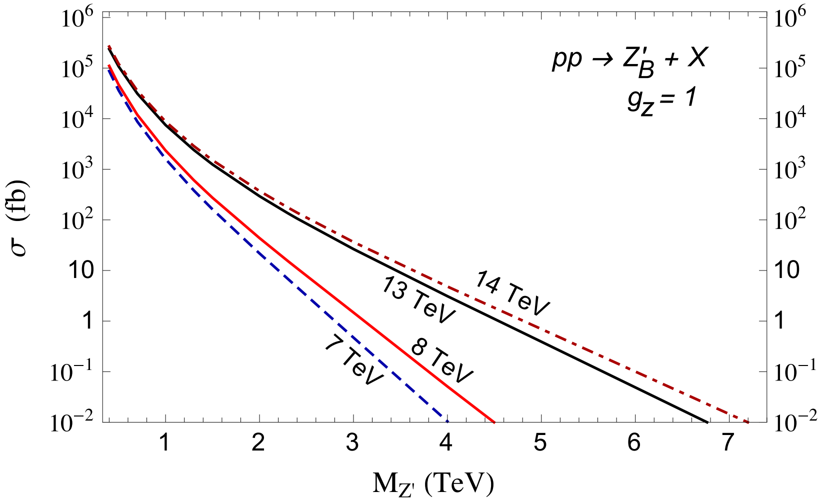
For $m_{N_D} - m_{N_S} \gg M_h$:

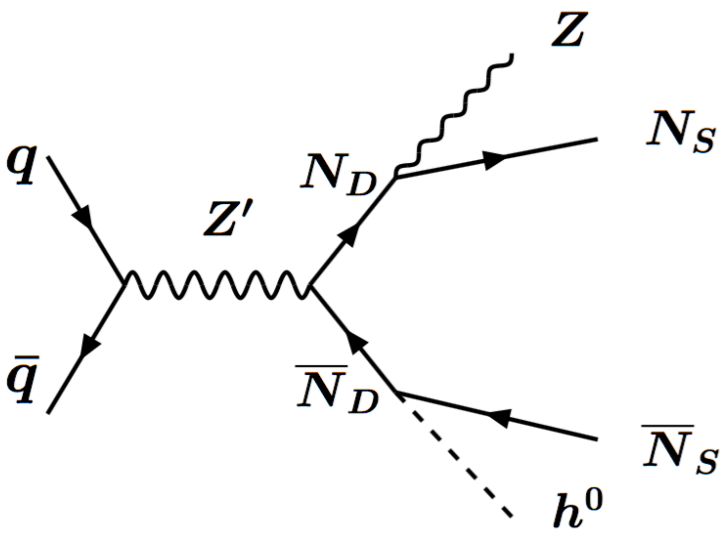
$$B(N_D \to N_S\,h^0) \approx B(N_D \to N_S\,Z) \approx \frac{1}{2}$$

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

Cascade decays via anomalons:

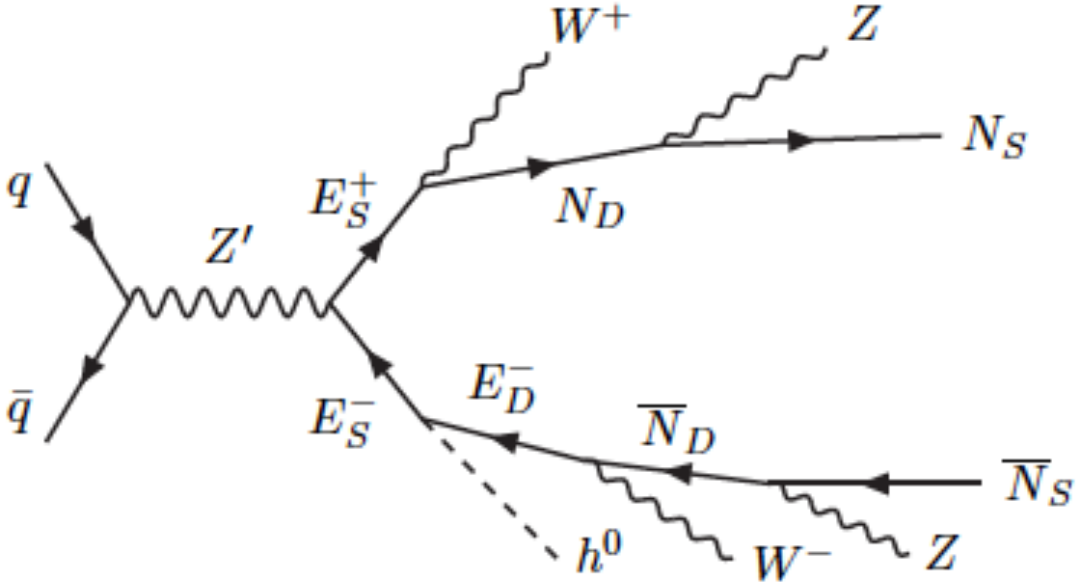
(1506.04435)





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,

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

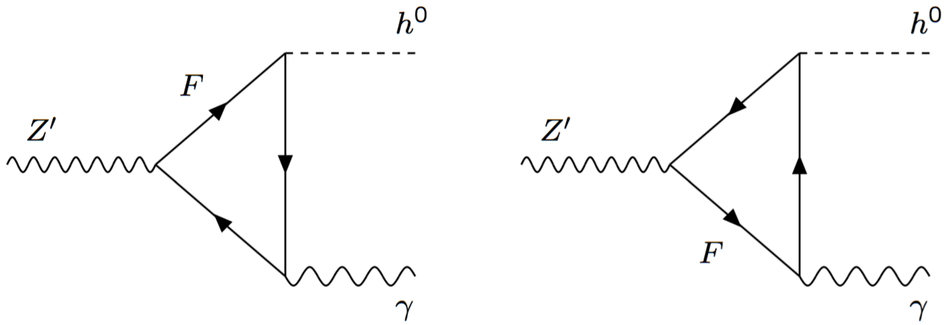
or final states with one or more pairs of leptons,

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

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

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

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

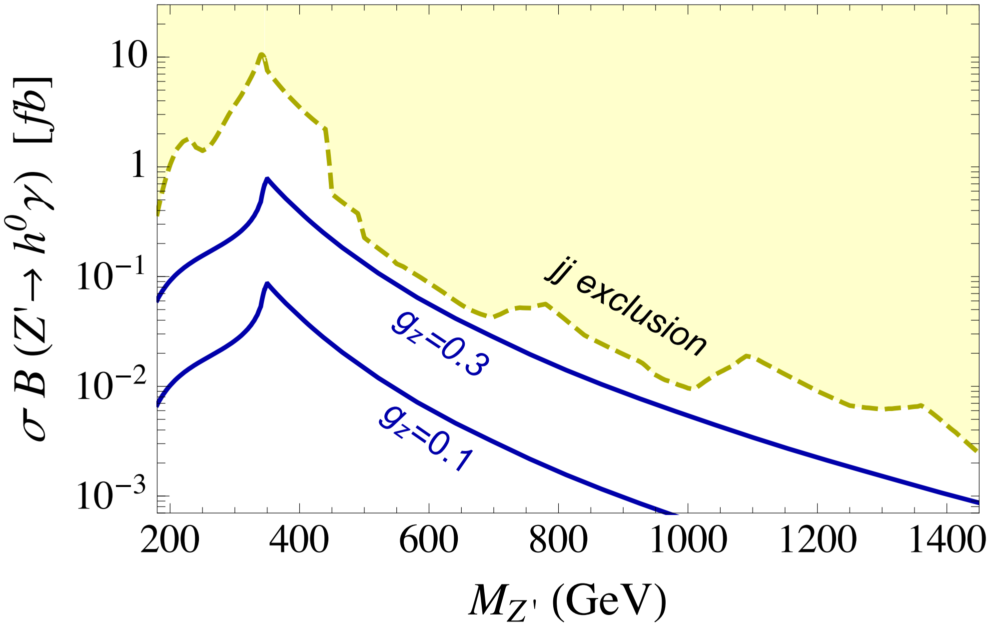


F *is the top quark or an anomalon.*

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

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

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



Conclusions

- 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 $\not{E}_T$.

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