LHC tests of new theories

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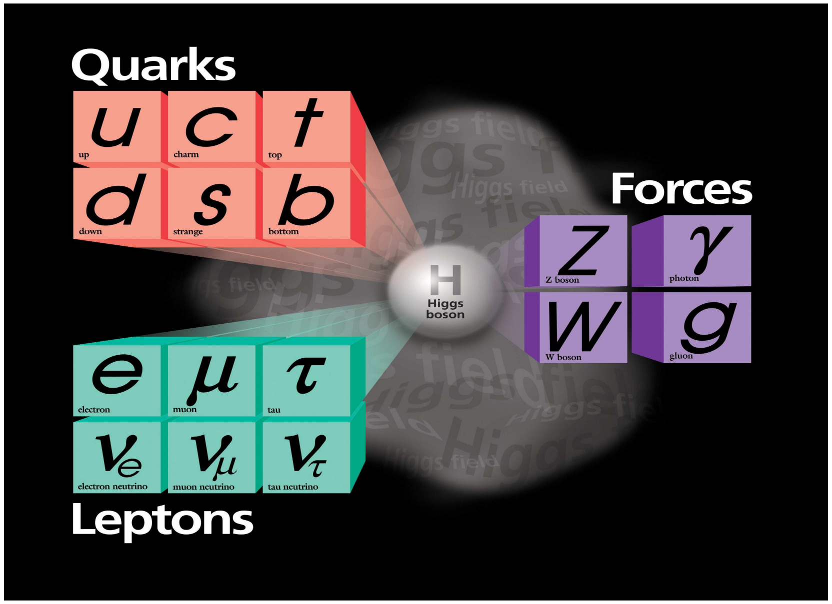


$+ \ ?$

June 11, 2015 – Fermilab Users Meeting

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

Run I has confirmed many aspects of the Standard Model, and measured $M_h = 125.09 \pm 0.24$ GeV *(ATLAS + CMS, 1503.07589).*

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

The observed elementary particles are

- **Scalar (spin 0): Higgs boson**

- **Chiral fermions (spin 1/2): 6 quarks and 6 leptons (left-handed doublets and right-handed singlets)**

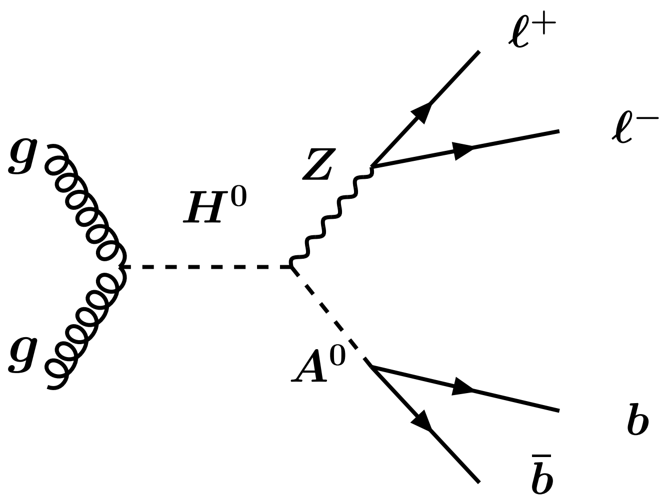
- **Gauge bosons (spin 1):** γ, W, Z, g.

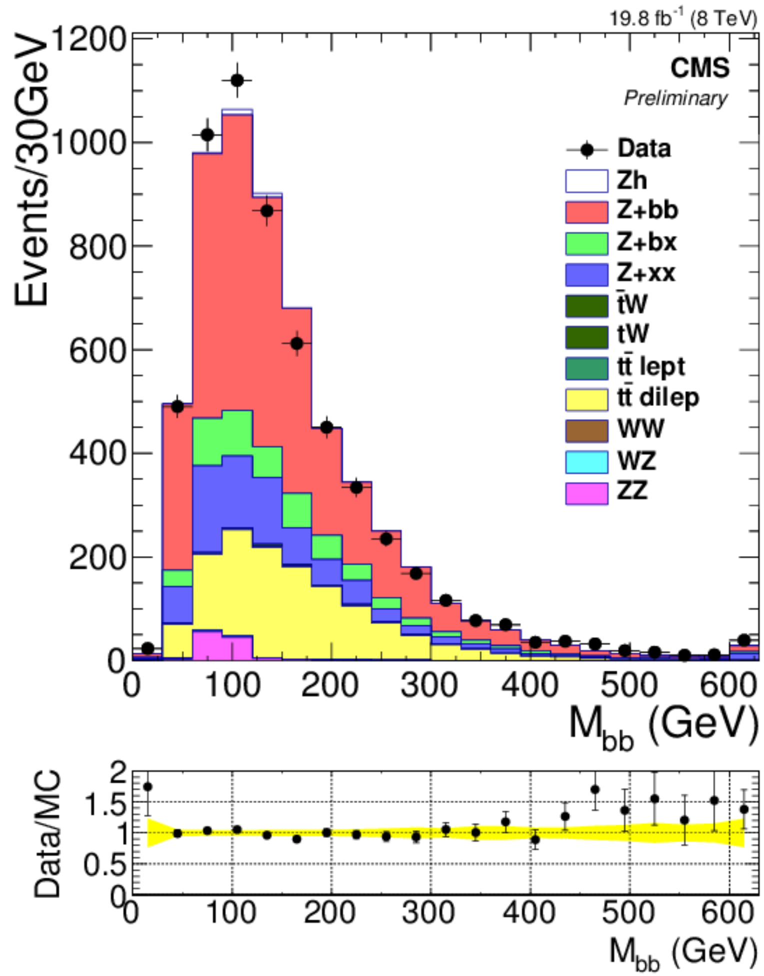
Simple assumption about new particles: heavier versions of the ones discovered so far!?

SM Higgs doublet has 4 degrees of freedom: h^0, longitudinal $Z, W^{\pm}$

A second Higgs doublet – heavier spin-0 particles: H^0, A^0, $H^{\pm}$.

(required in the MSSM, composite Higgs models, etc.)





CMS-PAS-HIG-15-001

Other processes:

$pp \to t\bar{b}H^- \to t\bar{b}\tau^-\nu$, ...

New fermions

All Standard Model fermions are chiral: their masses are not gauge invariant, and arise from the Higgs coupling.

Important legacy of Run I:

a 4th generation of chiral quarks and leptons has been ruled out by direct searches at the LHC.

Example:

$pp \to t'\bar{t}' \to (W^+b)(W^-\bar{b})$ **with** $B(t' \to Wb) = 100\%$

new limit: $m_{t'} > 770$ **GeV (ATLAS 1505.04306)**

already requires a nonperturbative coupling ...

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.

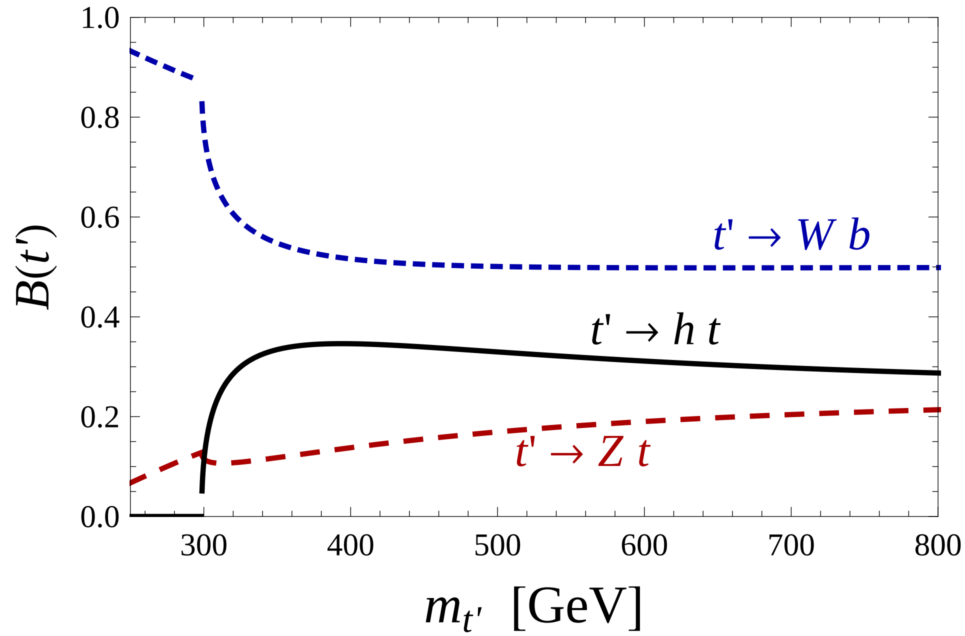
Unlike chiral fermions, the vectorlike fermions have a decoupling limit:

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

A vectorlike quark that transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the top quark.

Branching fractions of t':

$(\sin\theta_L = 0.1)$



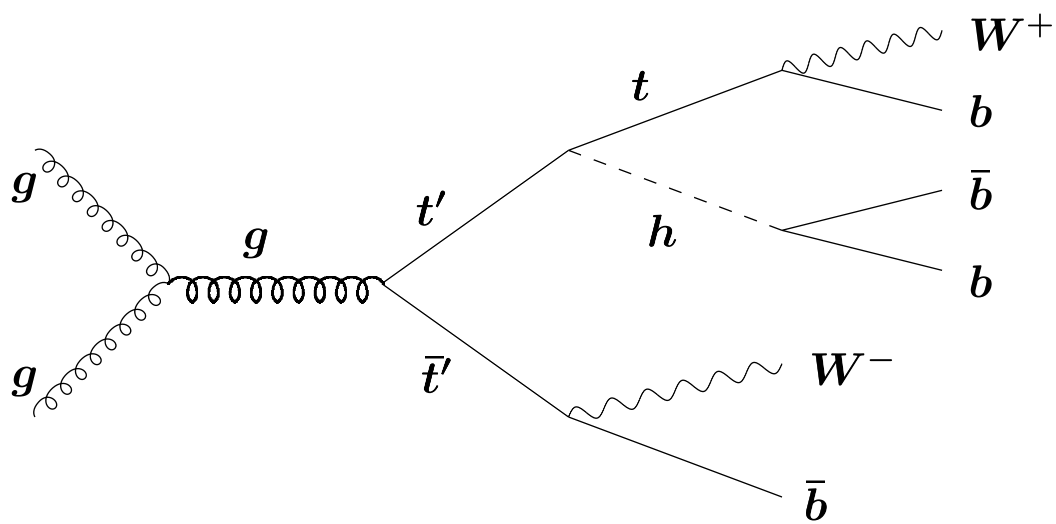
For $m_{t'} \gg m_t$:

decays into longitudinal W and Z $\longrightarrow$ $B(ht) = B(Zt) = B(Wb)/2$.

QCD production of $t'\bar{t}'$ pairs, followed by t' decays, leads to various final states:

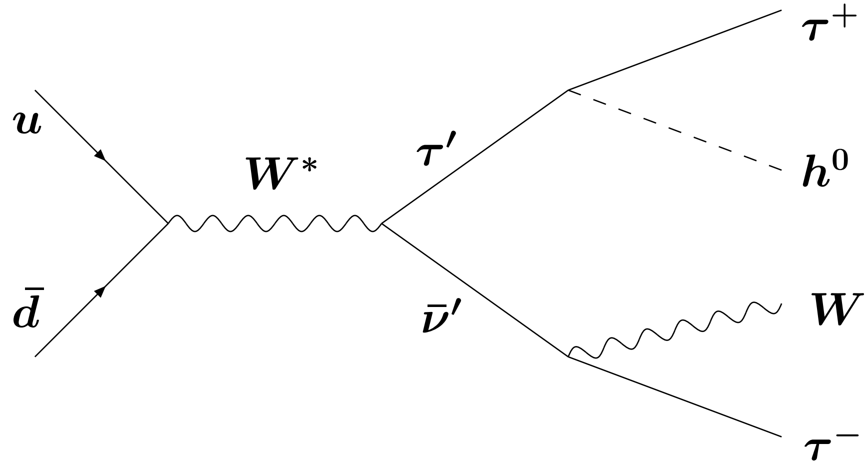
- $(W^+b)(W^-\bar{b})$ usual "t' search"
- $(Zt)(W^-\bar{b})$ or $(Z\bar{t})(W^+b)$
- $(ht)(W^-\bar{b})$ or $(h\bar{t})(W^+b)$, with $h \to b\bar{b}$ or $h \to W^+W^-$
- ...

Example:



ATLAS and CMS limits on vectorlike quarks: $m \gtrsim 700$ GeV

Vectorlike leptons



Lower limits on vectorlike lepton masses ~ 270 GeV *(1312.5329)*

(stronger limits if the decays are into e or μ instead of τ)

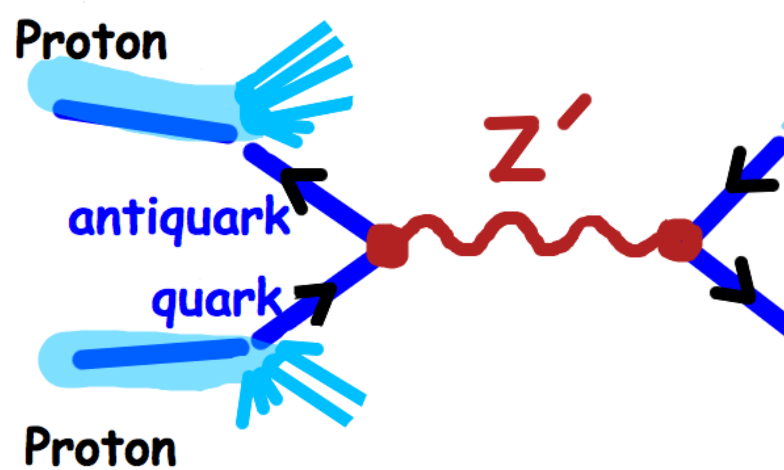
Run II will be sensitive to significantly higher masses in these and other electroweak processes.

New gauge bosons

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

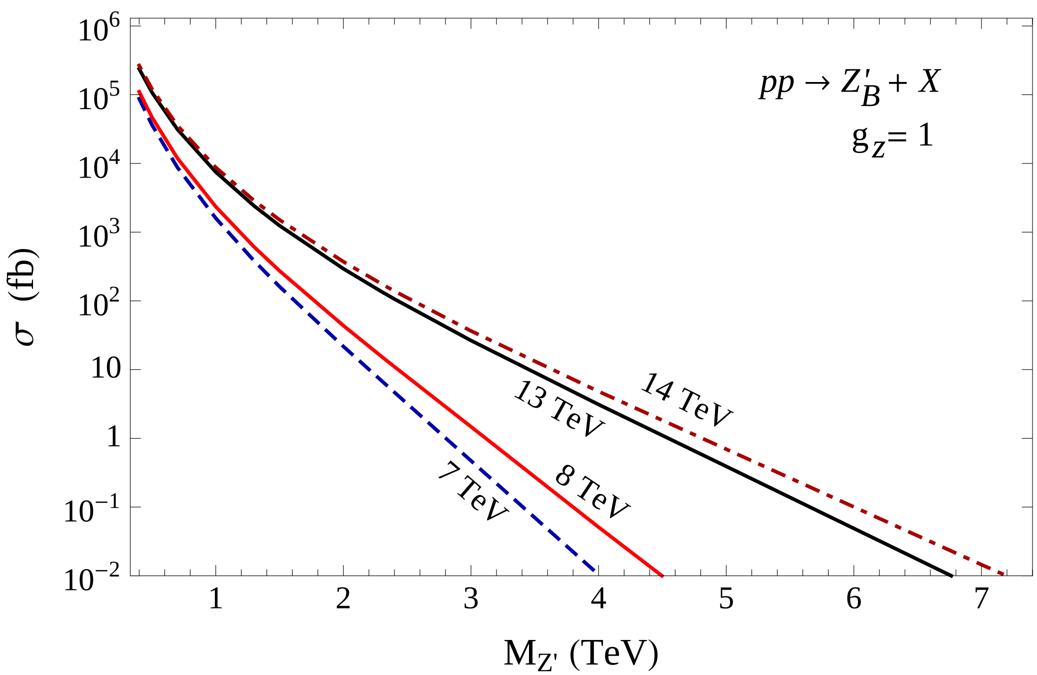
If couplings to quarks are flavor-independent:

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



then s-channel production

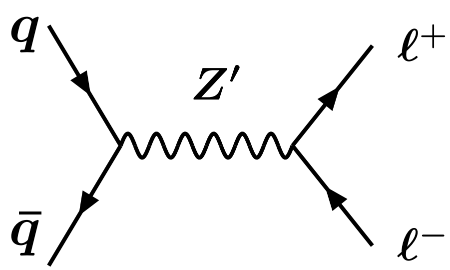
of Z'_B at the LHC for $g_z = 1$:

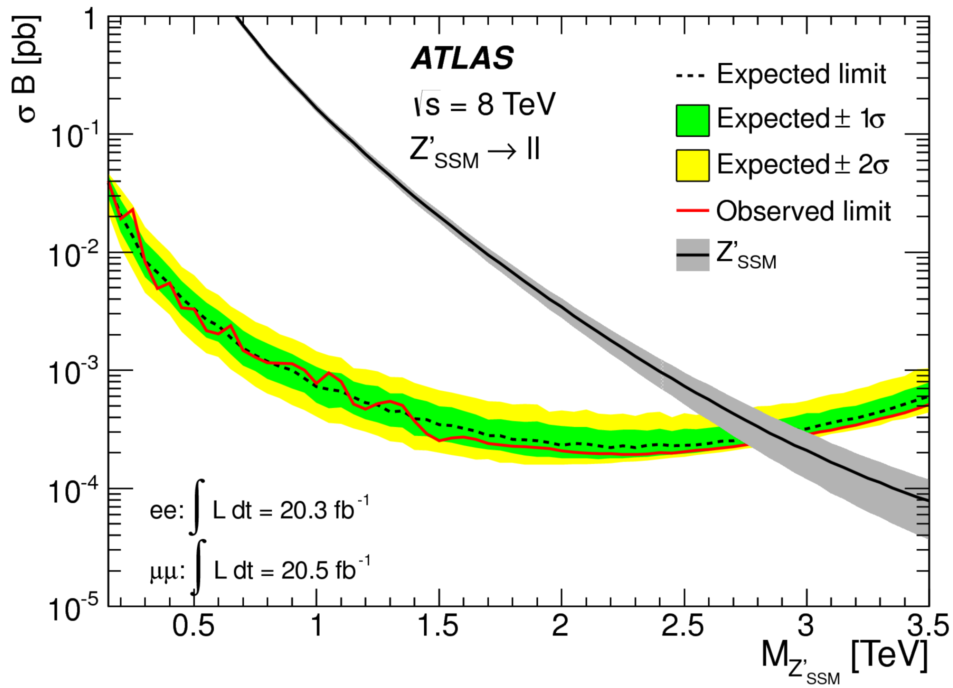


Cross section scales as g_z^2

if $g_z \lesssim O(2)$.

If Z' couples to leptons, then stringent limits on g_z from dilepton resonance searches ($g_z < 0.1$ for $M_{Z'} \approx 2$ TeV):





If Z' couples only to quarks ("leptophobic"), then it decays to quark-antiquark pairs $\rightarrow$ limits on g_z are loose (large background)

$g_z < 1.3$ for $M_{Z'} \approx 2$ TeV *(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.

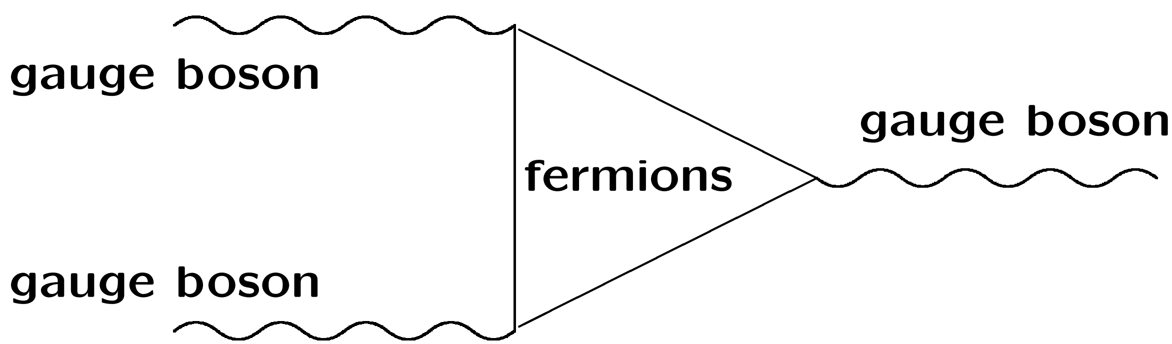
- **All $U(1)_B$ gauge anomalies must cancel.**

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:

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

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

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

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

Any leptophobic Z' that couples to quarks requires new charged fermions to cancel the anomalies.

(or to mix with the SM quarks - Fox et al, 1104.4127)

$\Rightarrow$ **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.**

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

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	$+3$

Mass mixing of the two charged anomalons (E and L^e) $\rightarrow$ E_D, E_S

Two neutral anomalons (N and L^ν), mixing $\rightarrow$ N_D, N_S

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

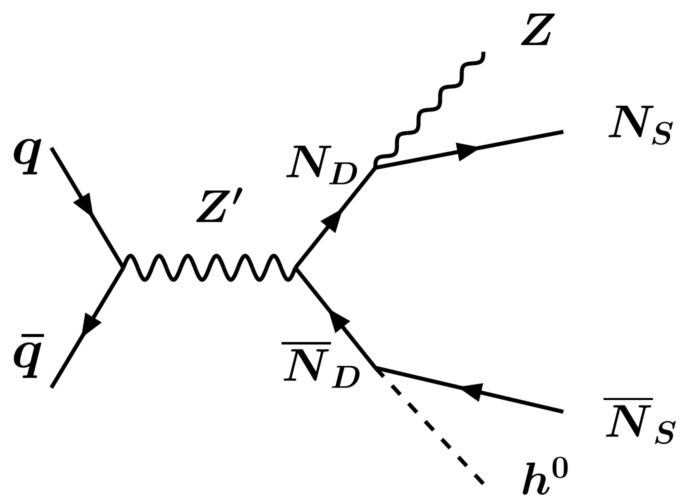
$U(1)_B$ symmetry is spontaneously broken down to a Z_3 subgroup

The anomalons have Z_3 charge $+1$

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

For $m_{E_S} > m_{E_D} > m_{N_D} > m_{N_S}$:

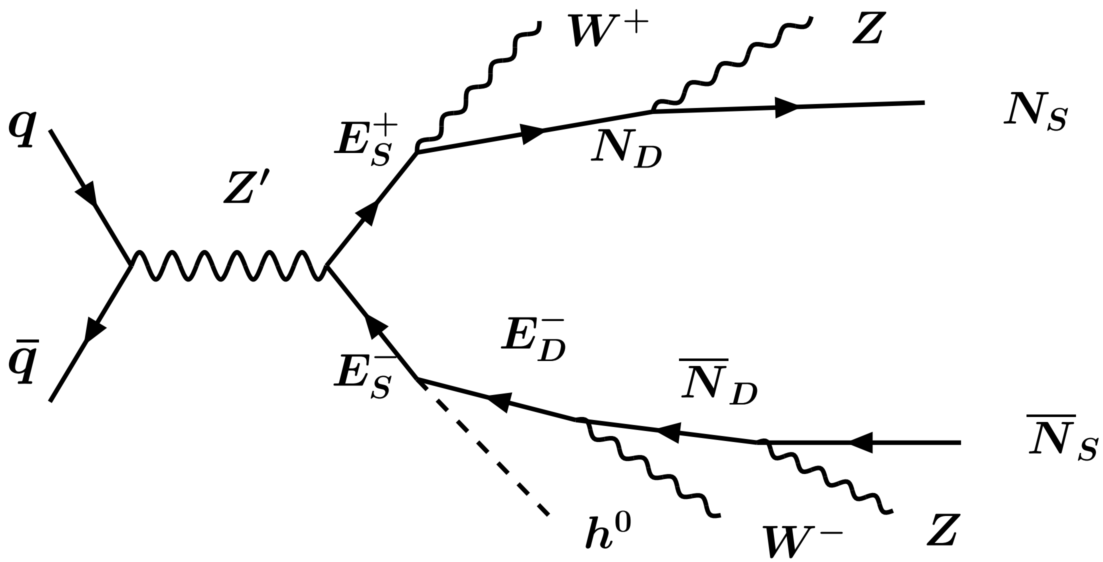
N_D anomalon has 2 decay modes: $N_S\, h^0$ and $N_S\, Z$.



E_D anomalon can decay into $N_D\, W$ or $N_S\, W$.

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

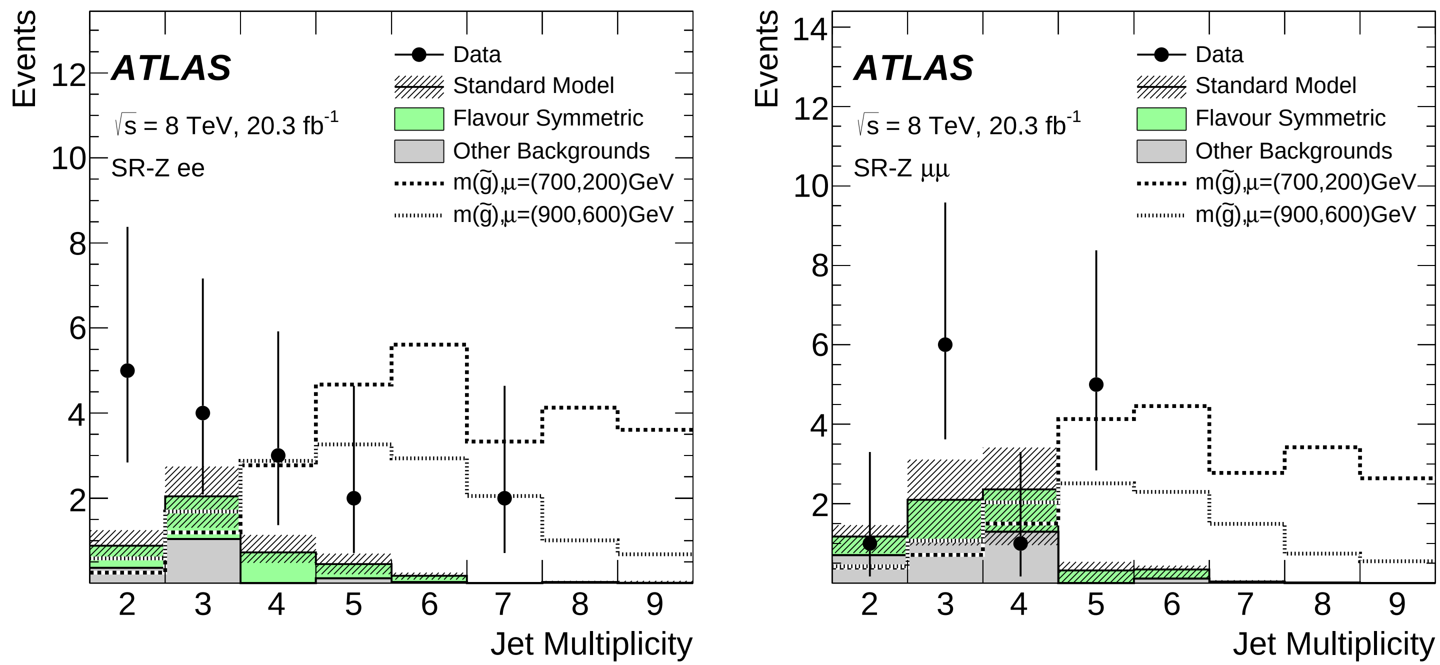
Long cascade decays:



Leptophobic Z' leads to final states with leptons!

Signatures with a $Z \to \ell^+\ell^-$, missing energy and jets.

ATLAS 1503.03290 – events with $H_T > 600$ GeV (3σ excess)



Jet multiplicity is more consistent with the Z' interpretation than with supersymmetry.

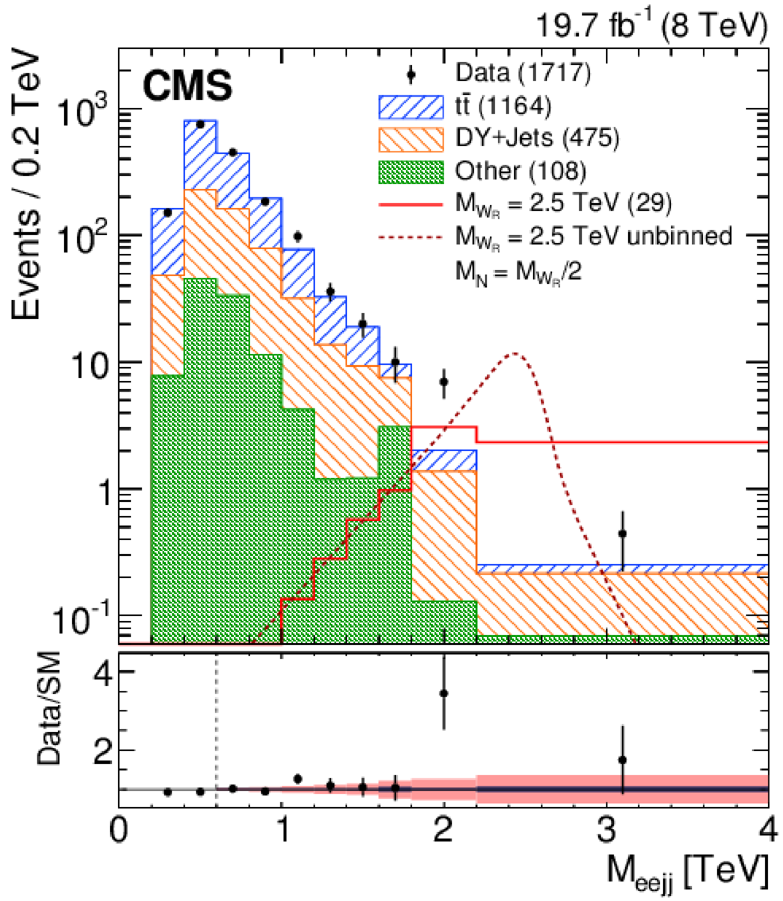
$\underline{W' \text{ boson:}}$ **hypothetical particle of spin 1 and charge ± 1, requires an extra $SU(2)$ gauge group.**

CMS search for $W'_R \to eN_R \to e^+e^-jj$:

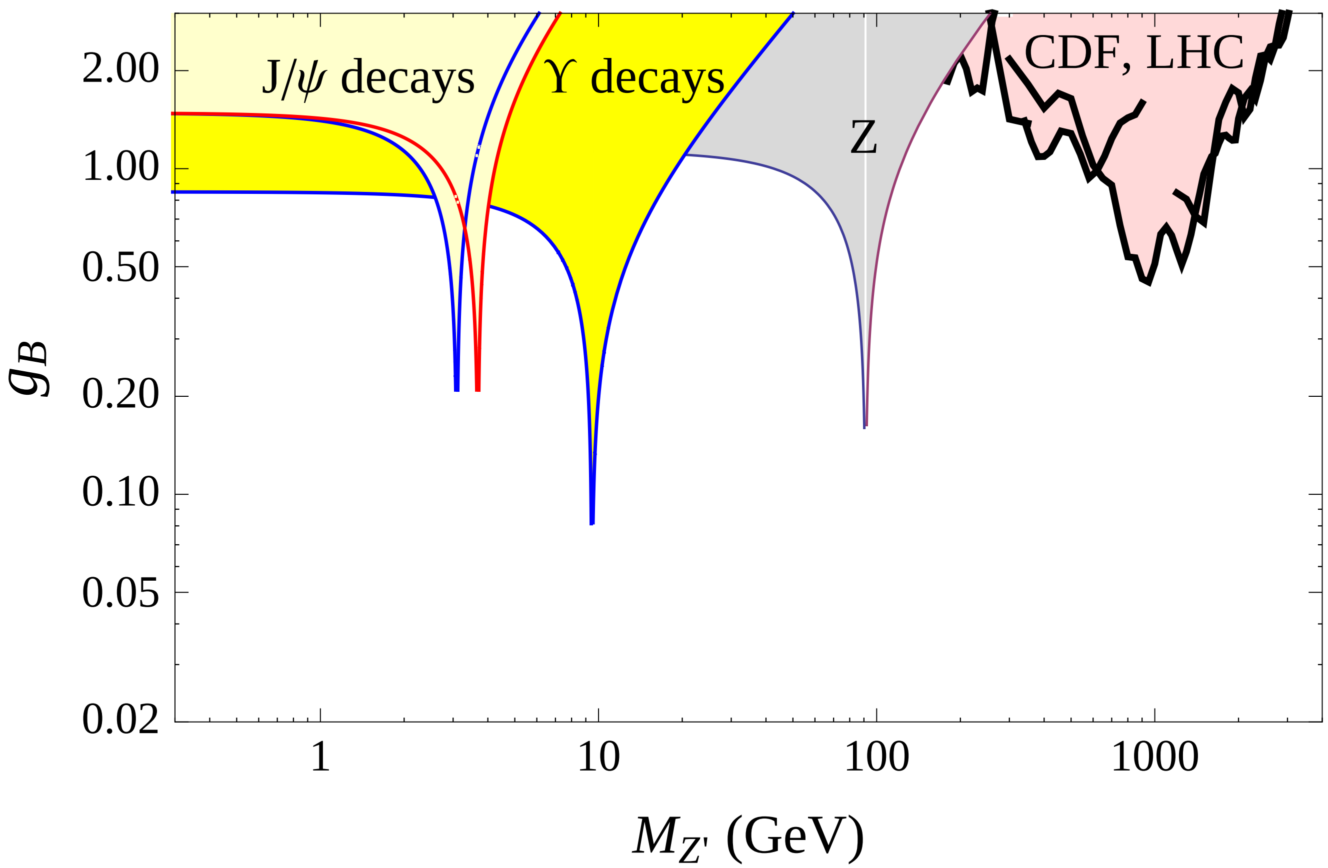
2.8σ local excess in the 1.8-2.2 TeV bin

(1407.3683)

Lepton universality violation is natural in these models.

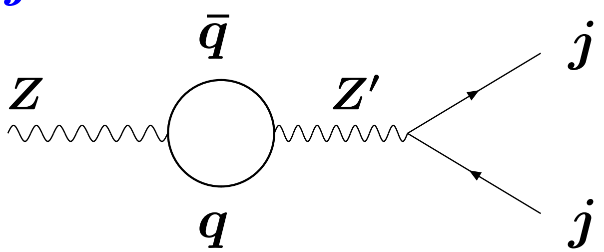


Very light leptophobic Z' bosons



ARGUS experiment, 1986: limit on $\Upsilon \to Z'^* \to jj$

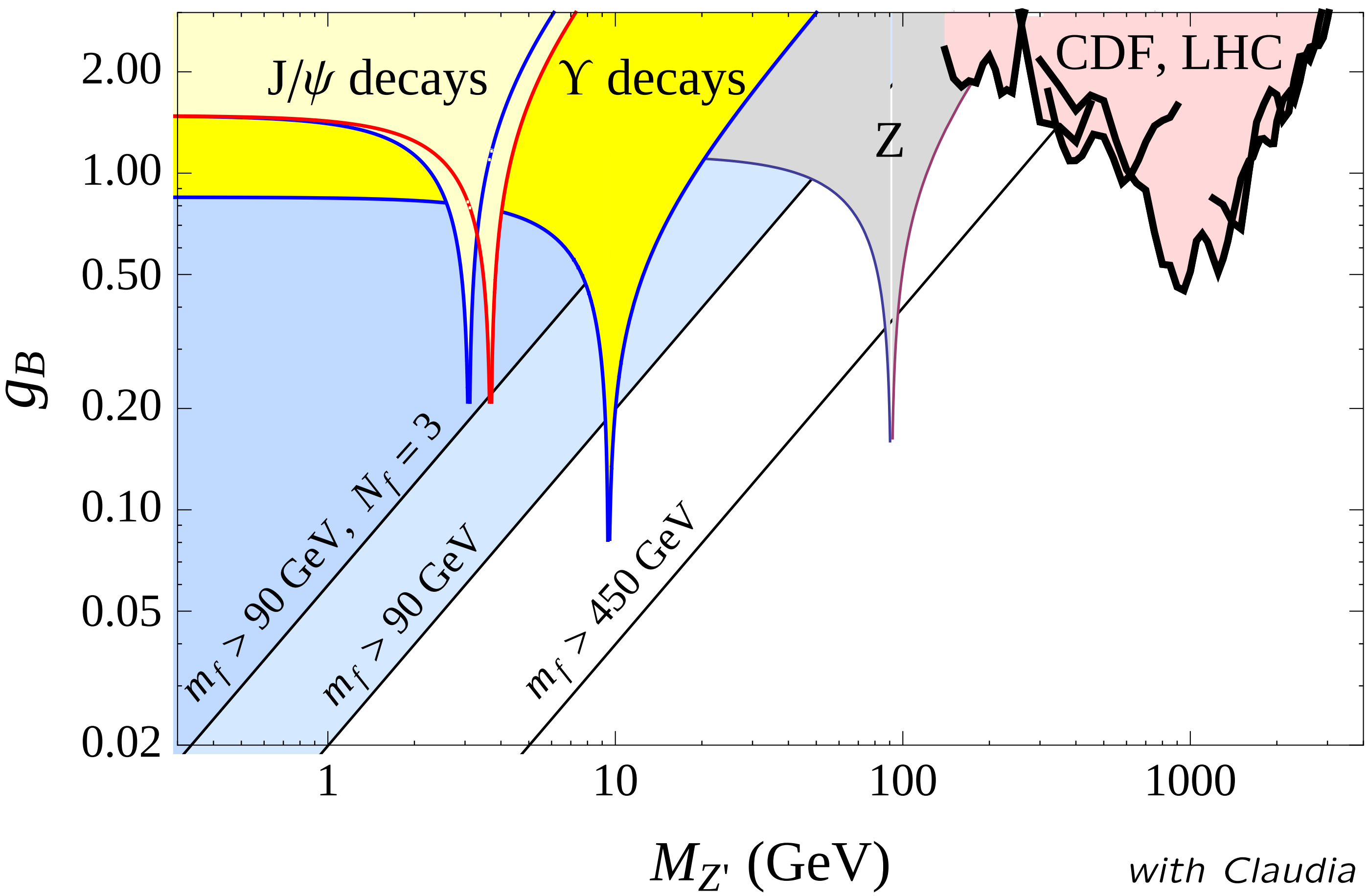
Small $Z - Z'$ mixing induced at one loop:



Z' requires a new gauge symmetry: $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_B$

$U(1)_Y[U(1)_B]^2$ anomaly cancelation $\Rightarrow$ charged vectorlike fermions

$\Rightarrow$ colliders limits on fermion masses lead to a limit on g_B:



with Claudia Frugiuele:
PRL 113, 061801 (2014)

Conclusions

- **The Run II of the LHC will push the boundaries of knowledge.**

Synergy with low-energy experiments, including neutrinos, dark matter, flavor processes, ... (many theoretical connections)

- **Heavier "versions" of the SM particles would not be copies:**

  New gauge bosons can have cascade decays.

  New fermions are vectorlike.

  New Higgs particles produce different signals.

- **Much more exotic phenomena are possible ...**