Overview of the current status and prospects of LHC for discovery

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Run I has 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 LHC Run II will find ...

Observed elementary particles:

- 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.
- Scalar (spin 0): Higgs boson

Legacy of LHC Run 1: **a 4th generation of chiral quarks and leptons is ruled out.**

Direct searches set limits $\gtrsim 700 - 800$ GeV on b_4, t_4 masses,
e.g. **$m_{t_4} > 770$ GeV from $t_4 \to Wb$ (ATLAS 1505.04306)**
$\to h\bar{t}_4 t_4$ Yukawa coupling no longer perturbative.

Vectorlike fermions

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.

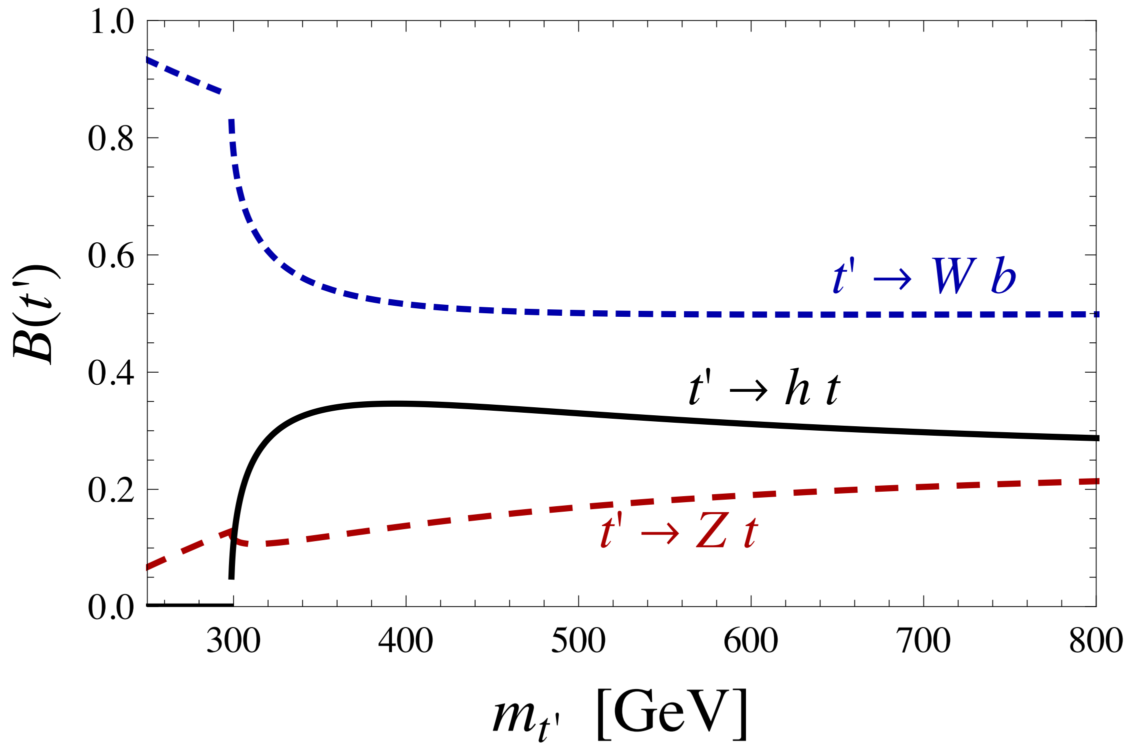
Unlike chiral fermions, vectorlike fermions have a decoupling limit:

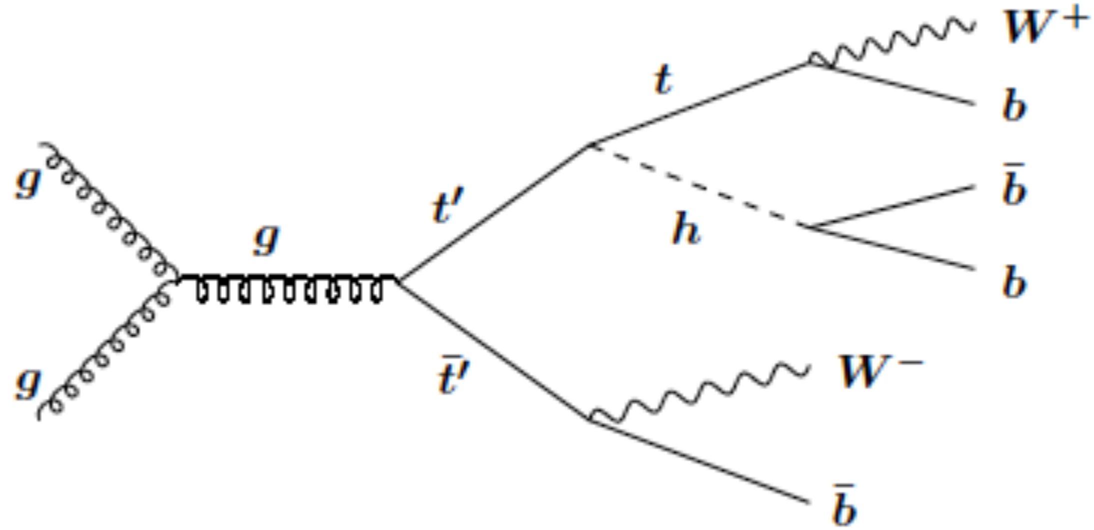
$m \gg v_H \approx 174$ GeV $\rightarrow$ Standard Model is recovered.

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 SM top quark.

Mass eigenstates: t and t'.

t' branching fractions:





Current limits: $m_{t'} \gtrsim 700$ GeV

$\longrightarrow$ boosted topologies with Wb, Zt, ht, ...

Dark matter requires particle(s) beyond the SM

DM particle can be a fermion (Majorana or Dirac) or a boson.

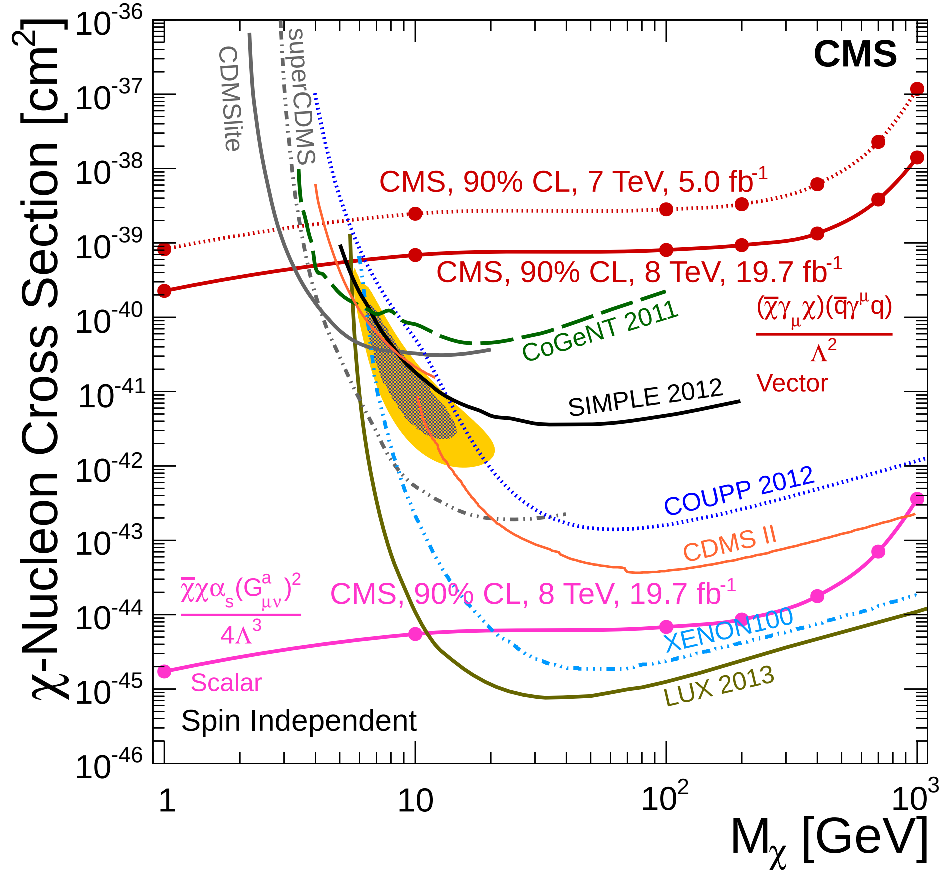
DM particle(s) may be part of a large hidden sector.

If DM particles interact with quarks, then they may be produced in pairs at the LHC *(complementary to direct detection)*

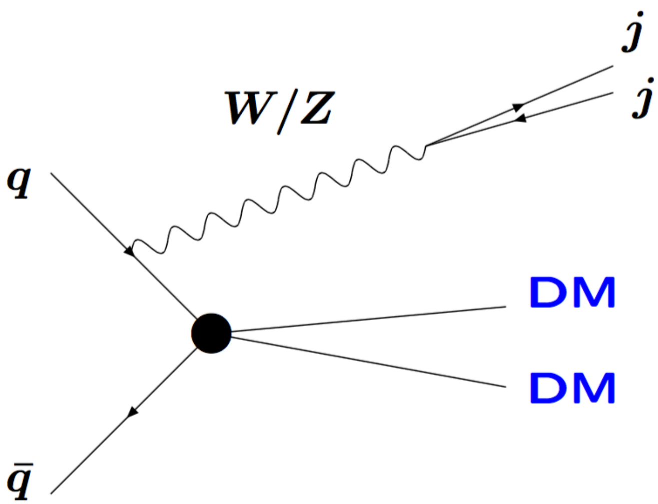
Mono-jet signature of DM

(Beltran et al 1002.4137; Bai, Fox, Harnik, 1005.3797, ...)

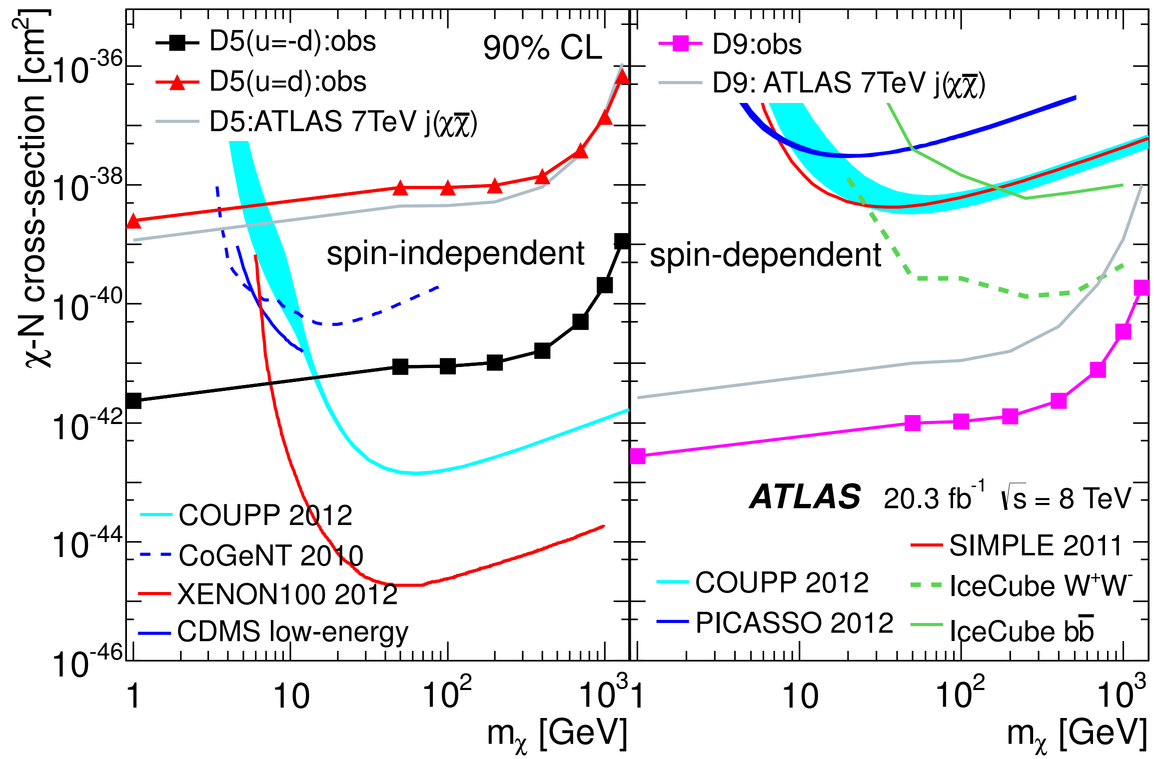
CMS 1408.3583:



Mono-W/Z search: a boosted "W/Z jet" + $\not{E}_T$



ATLAS 1309.4017



Various other DM searches at the LHC:

mono-Higgs *(Berlin, Lin, Wang 1402.7074)*, $t\bar{t} + \not{E}_T$ *(1303.6638)*, ...

W' boson near 2 TeV

$W' \to eN \to e^+e^-jj$ (no e^+e^+jj signal $\to$ Dirac mass for N)

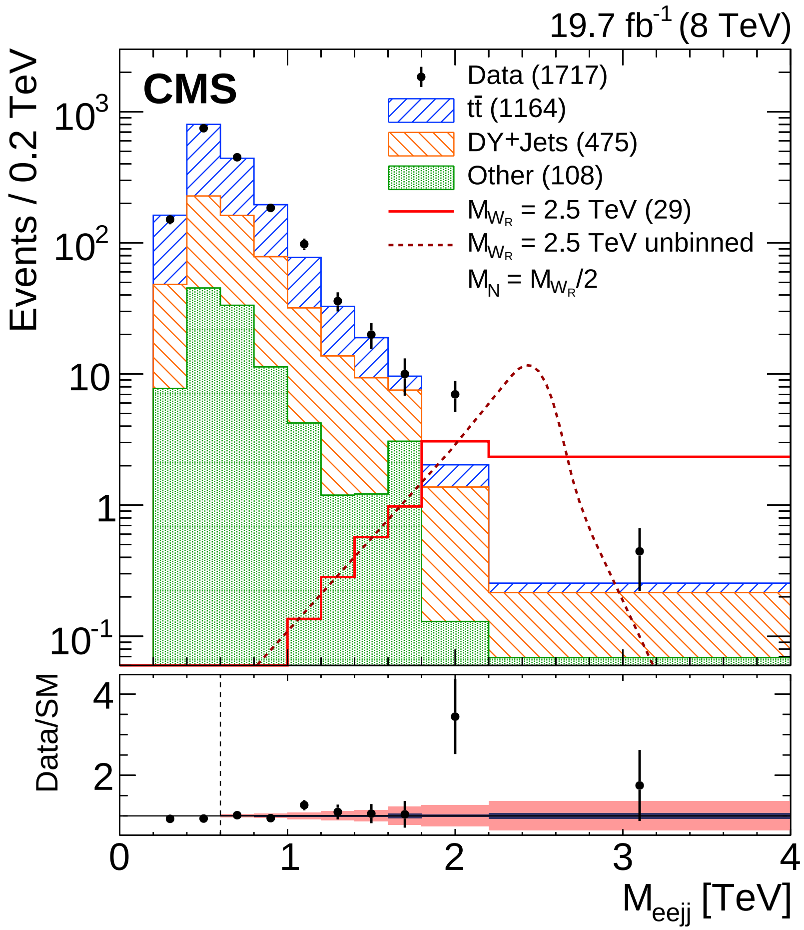
$$\frac{g_R}{\sqrt{2}} W'_\nu \overline{N}_R \gamma^\nu \left(s_{\theta_e} e_R + c_{\theta_e} \tau_R\right)$$

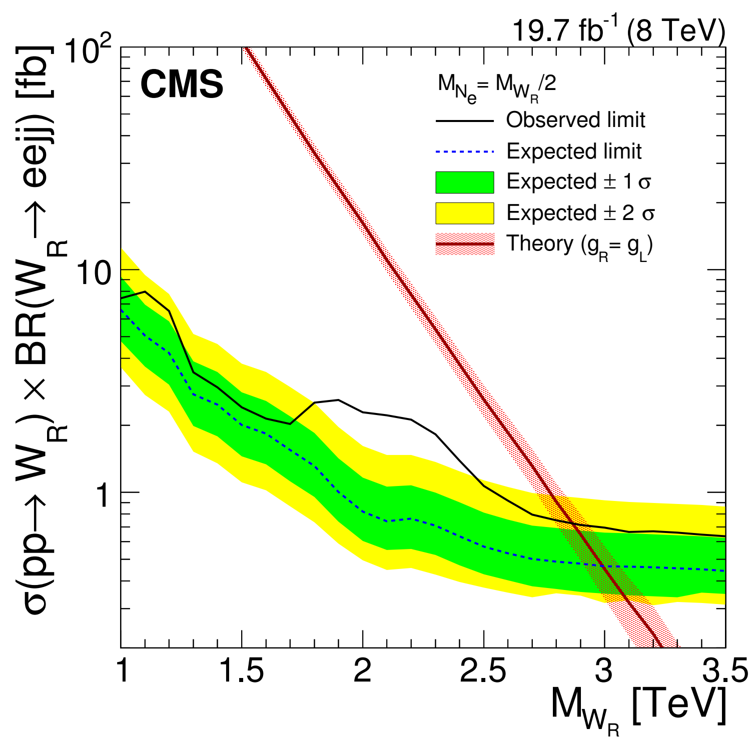
CMS (1407.3683):

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

not $L-R$ symmetric

no Majorana masses for RH neutrinos



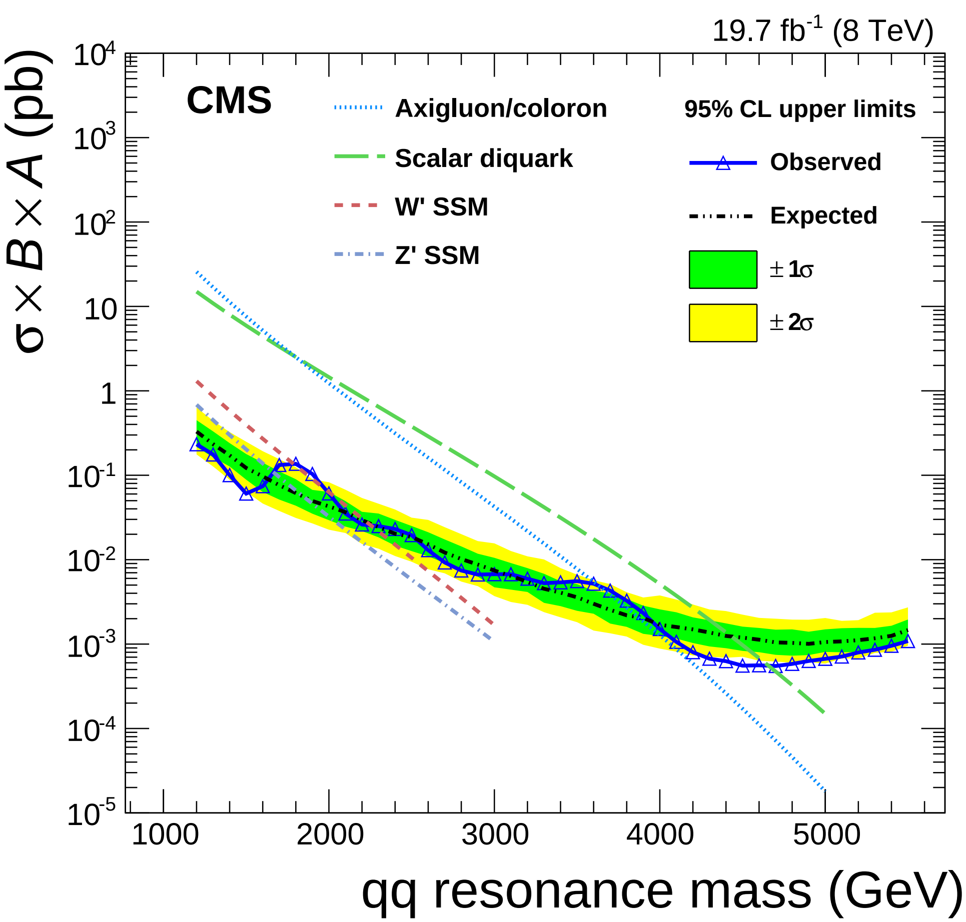


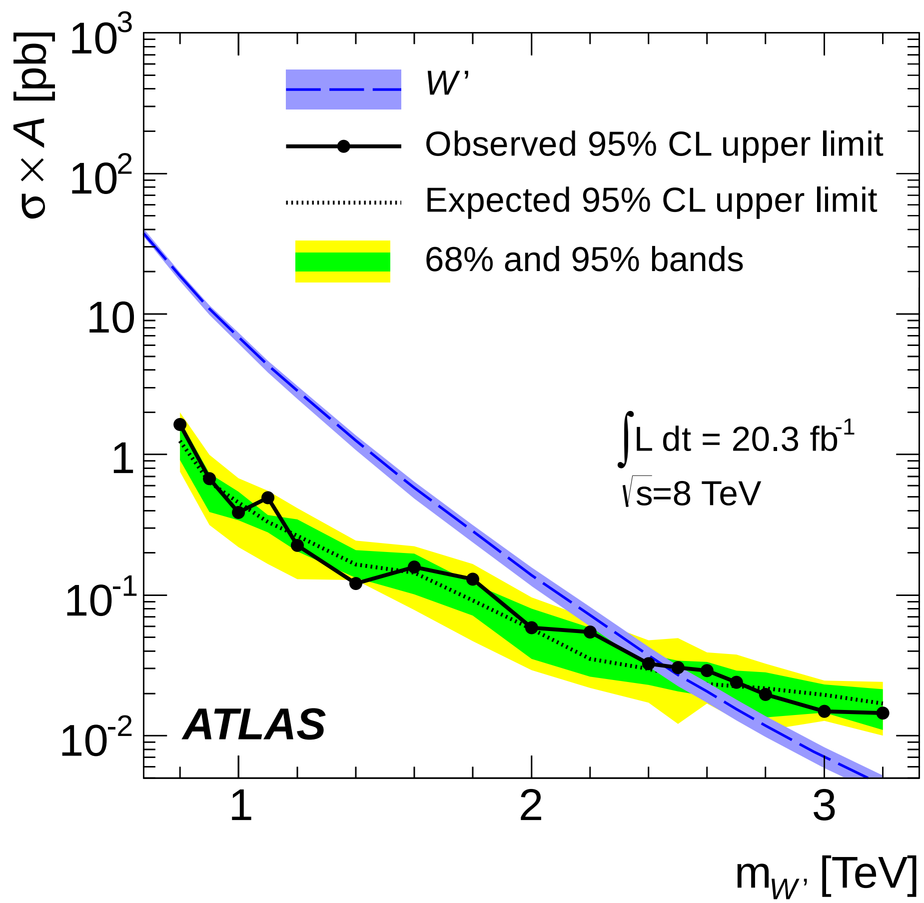
$$\underline{u\bar{d} \to W' \to jj}$$

$$\frac{g_R}{\sqrt{2}} W'_\mu \left(\bar{u}_R \gamma^\mu d_R + \bar{c}_R \gamma^\mu s_R + \bar{t}_R \gamma^\mu b_R\right)$$

CMS (1501.04198):

ATLAS (1407.1376):

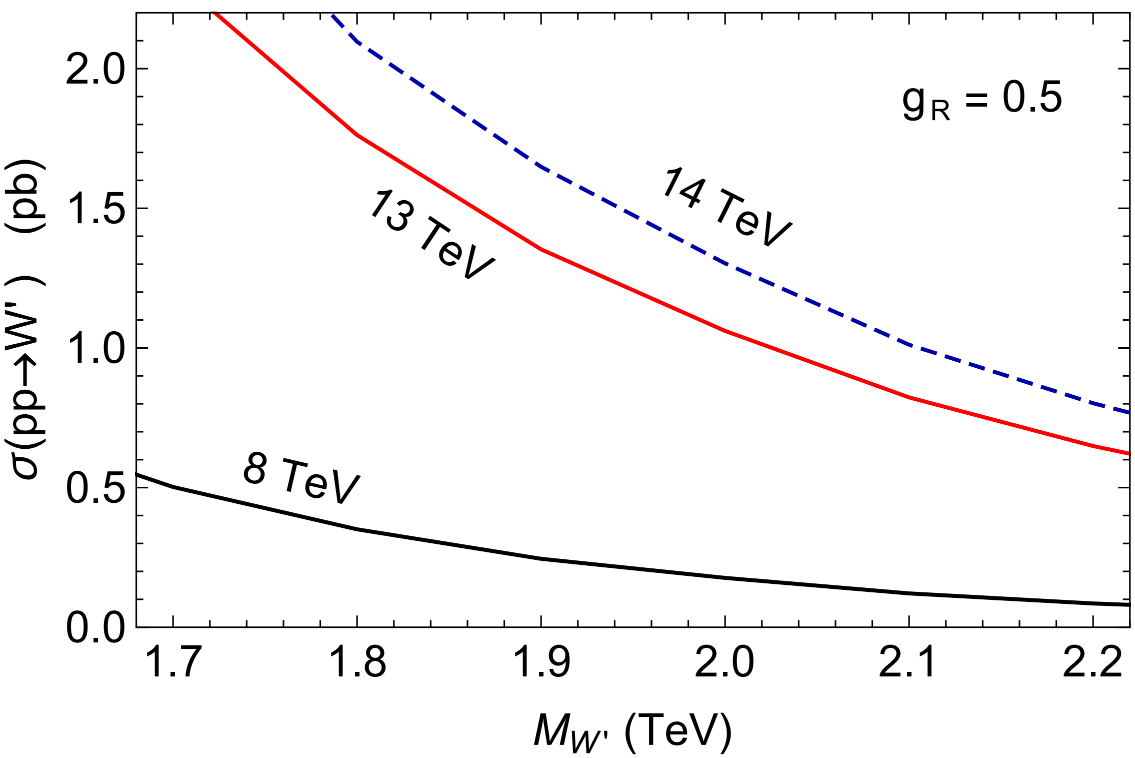




$pp \to W'$ cross section

CMS dijet excess indicate $\sigma(pp \to W' \to jj) \approx 100$–$200$ fb.

W' decays predominantly into quark pairs $\longrightarrow$ $B(W' \to jj) \approx 2/3$



Dobrescu & Liu, 1506.06736

"A W' boson near 2 TeV: predictions for Run 2 of the LHC":

Higgs sector – T:(1,3), Σ:(2,2) under $SU(2)_L \times SU(2)_R$

$$\langle T \rangle = \begin{pmatrix} 0 & 0 \\ u_T & 0 \end{pmatrix} \qquad\qquad \langle \Sigma \rangle = v_H \begin{pmatrix} \cos\beta & 0 \\ 0 & e^{i\alpha_\Sigma} \sin\beta \end{pmatrix}$$

↙ $M_{Z'} > 3.5$ TeV

↙ "maximal" $W_L - W_R$ mixing

Dobrescu & Liu, 1507.01923, (Heavy Higgs bosons and the 2 TeV W')

Mass terms for the charged gauge bosons:

$$\frac{1}{2}\left(W_L^{+\mu}, W_R^{+\mu}\right) \begin{pmatrix} g_{2_L}^2 v_H^2 & -g_{2_L} g_{2_R} v_H^2 \sin 2\beta \\ -g_{2_L} g_{2_R} v_H^2 \sin 2\beta & g_{2_R}^2 \left(2u_T^2 + v_H^2\right) \end{pmatrix} \begin{pmatrix} W_{L\mu}^- \\ W_{R\mu}^- \end{pmatrix}$$

$W_L - W_R$ **mixing:** $\quad \sin\theta_+ = \dfrac{g_{\rm R}}{g} \left(\dfrac{M_W}{M_{W'}}\right)^2 \sin 2\beta$

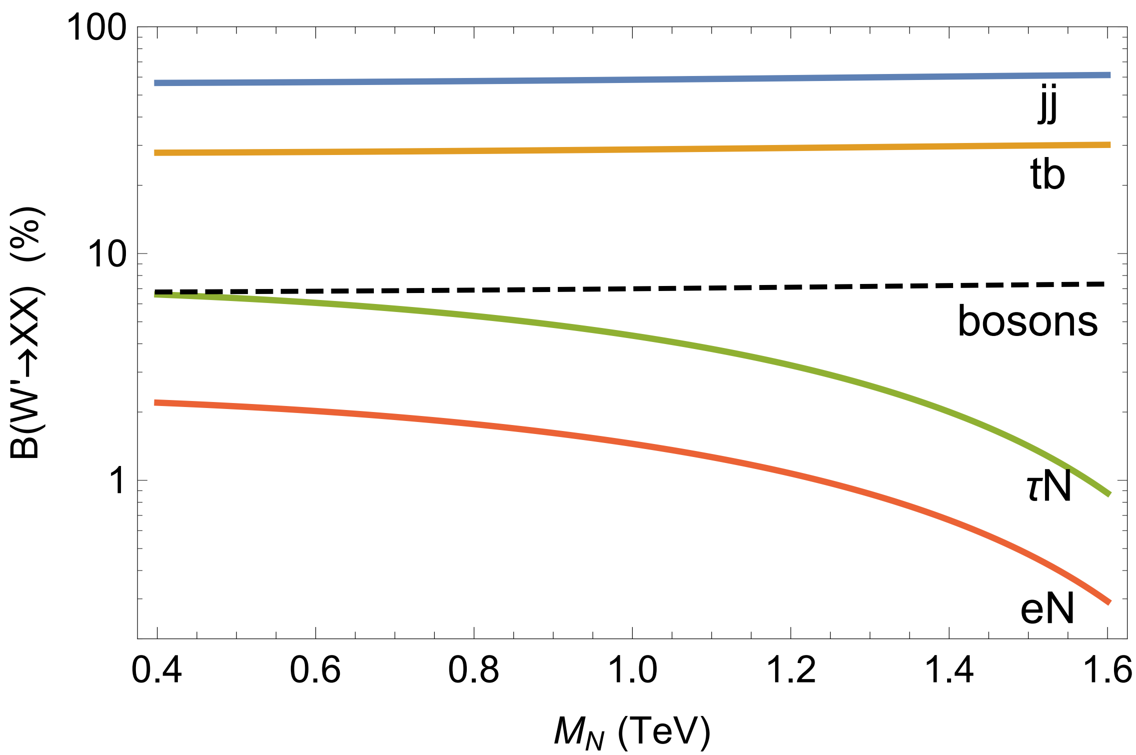
Mass eigenstates: W **and** W'.

W' branching fractions

$$\Gamma(W' \to t\bar{b}) \simeq \Gamma(W' \to c\bar{s}) = \Gamma(W' \to u\bar{d}) = \frac{g_R^2}{16\pi} M_{W'}$$

$$\Gamma(W' \to e\bar{N}) \simeq \frac{s_{\theta_e}^2 g_R^2}{48\pi} M_{W'} \quad , \quad \Gamma(W' \to \tau\bar{N}) \simeq \frac{c_\theta^2 g_R^2}{48\pi} M_{W'}$$

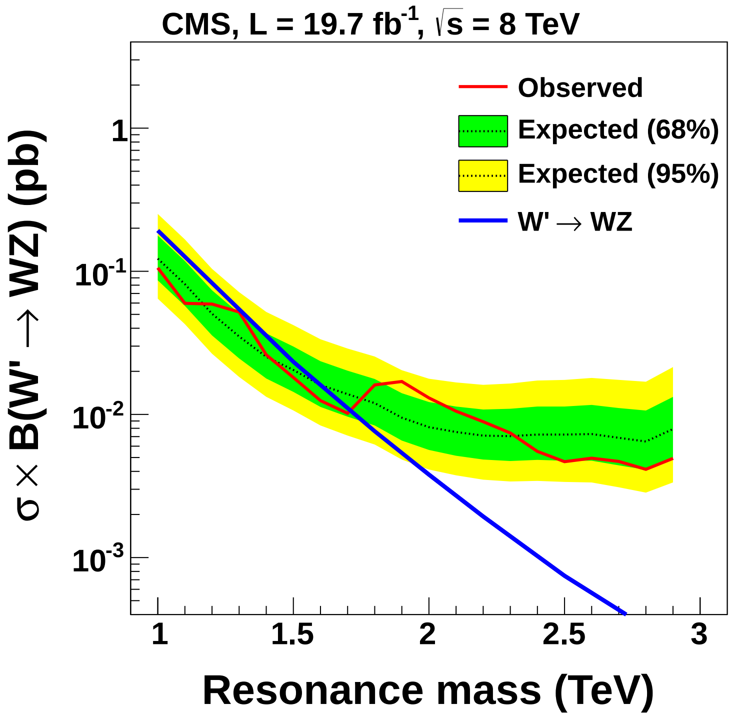
$$\frac{1}{c_W^4}\Gamma(W' \to WZ) \simeq \Gamma(W' \to Wh^0) \simeq \frac{g_R^2}{192\pi} \sin^2 2\beta\, M_{W'}$$



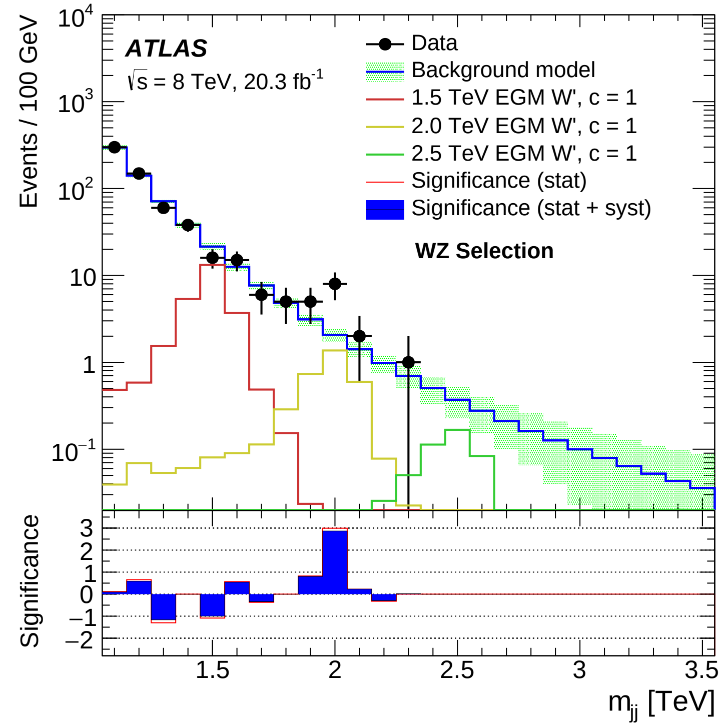
$s_{\theta_e} = 1/2$

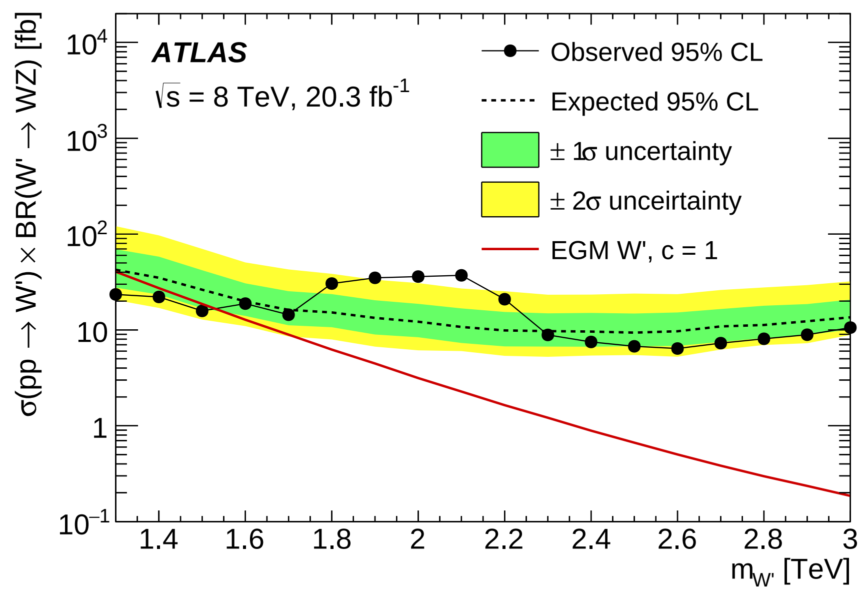
$W' \to WZ \to JJ$

CMS (1405.1994):



ATLAS (1506.00962):

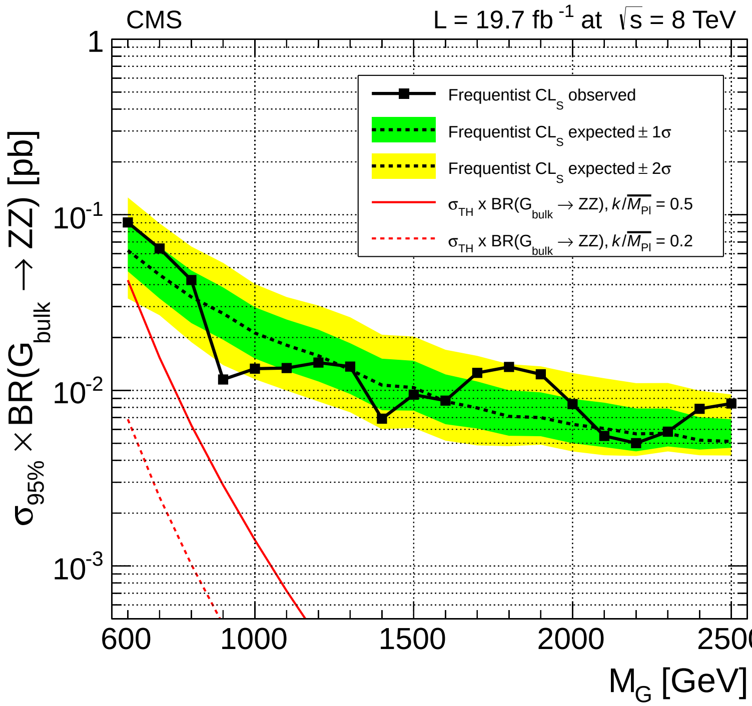


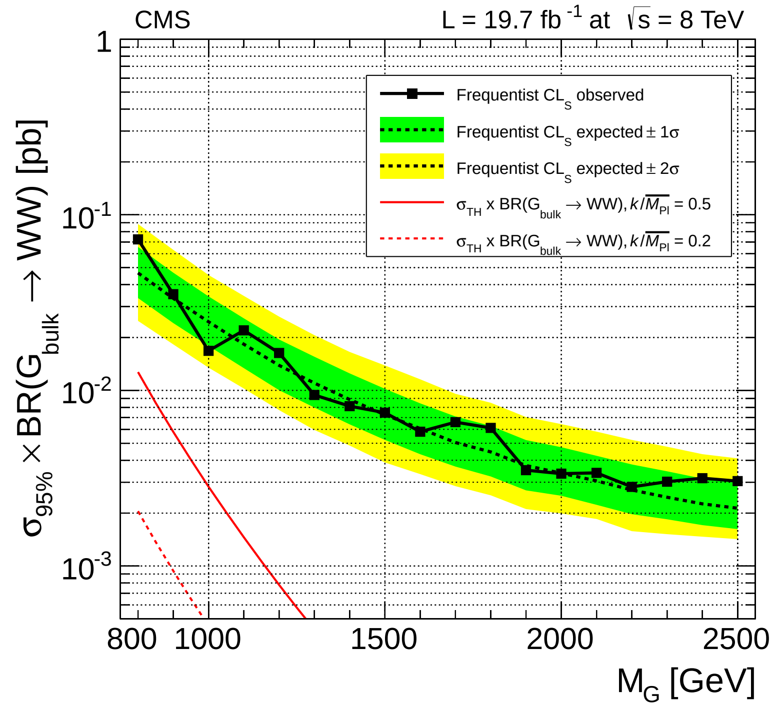


$$\sigma(pp \to W' \to WZ) = O(5)\ \textbf{fb} \longleftarrow$$

$W' \to WZ \to J(\ell^+\ell^-)$

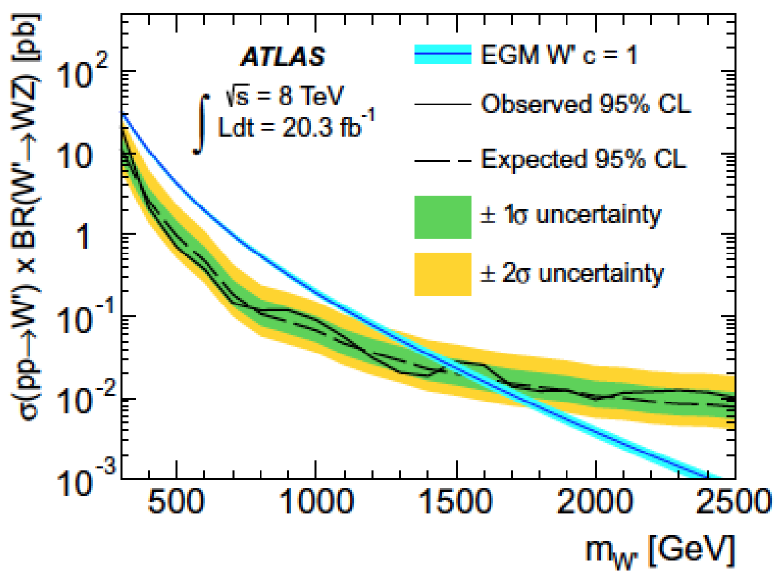
$W' \to WZ \to (\ell\nu)J$





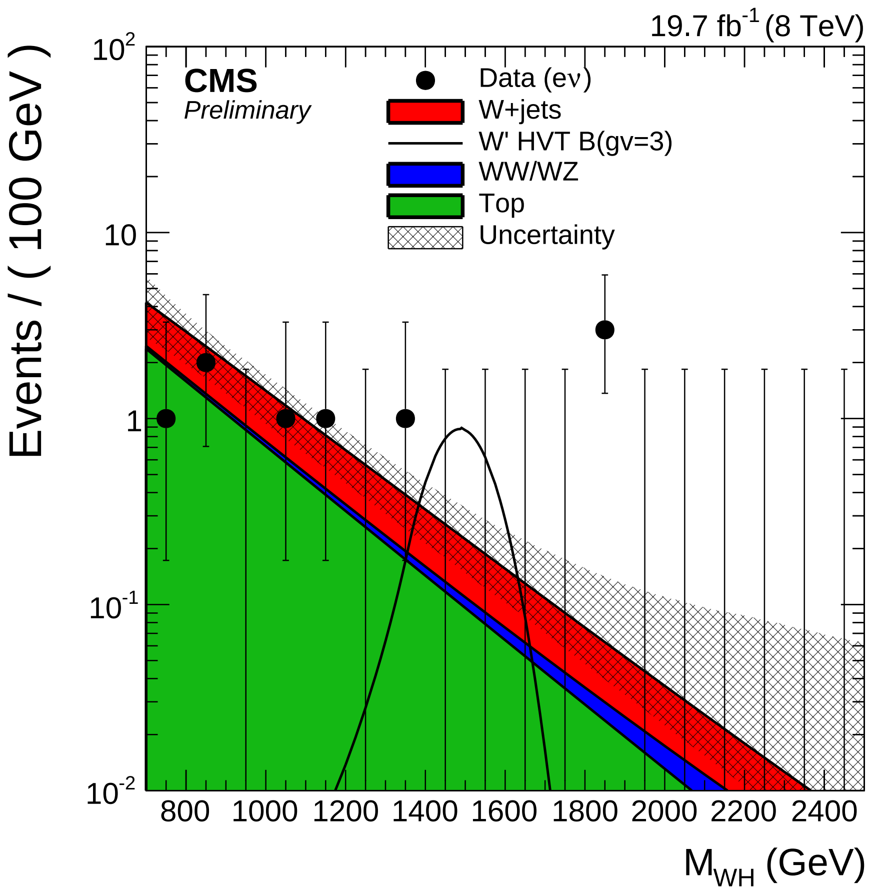
CMS (1405.3447): limit on WZ weaker by a factor of 2 (2.3) compared to ZZ (WW)

ATLAS 1503.04677:
$\sigma(pp \to W' \to WZ) > 12$ fb

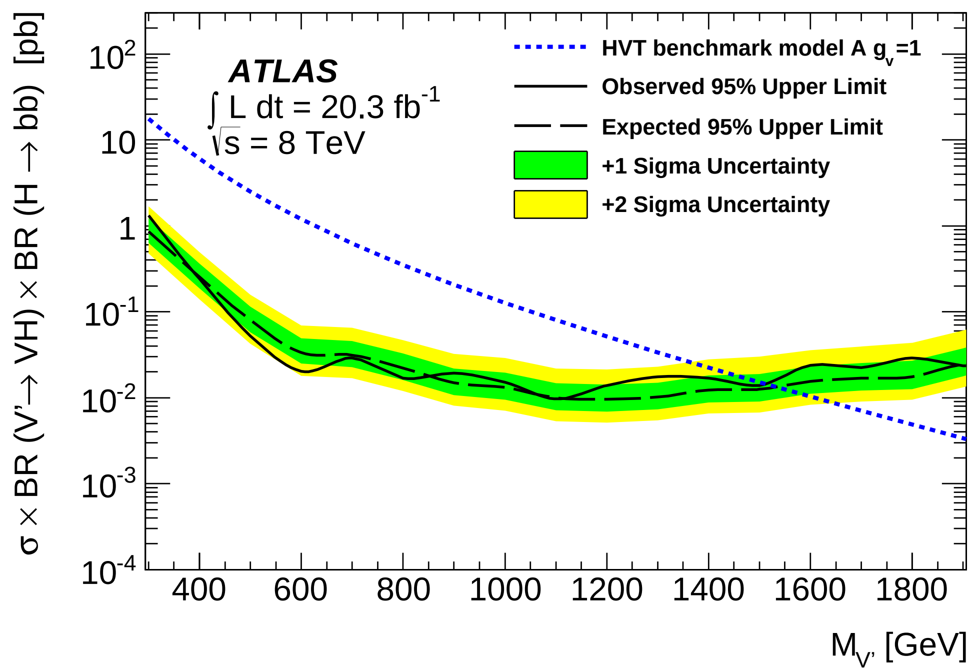


$W' \to Wh \to (\ell\nu)(b\bar{b})$

CMS (EXO-14-010):

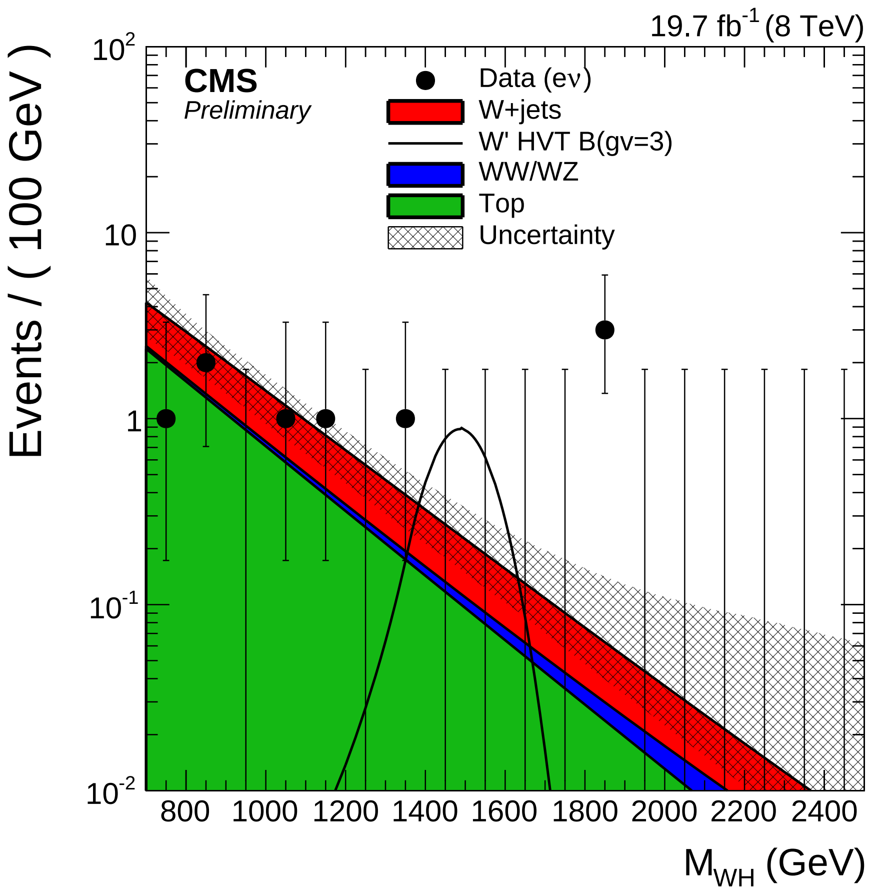


ATLAS (EXOT-2013-23, *1503.08089*):

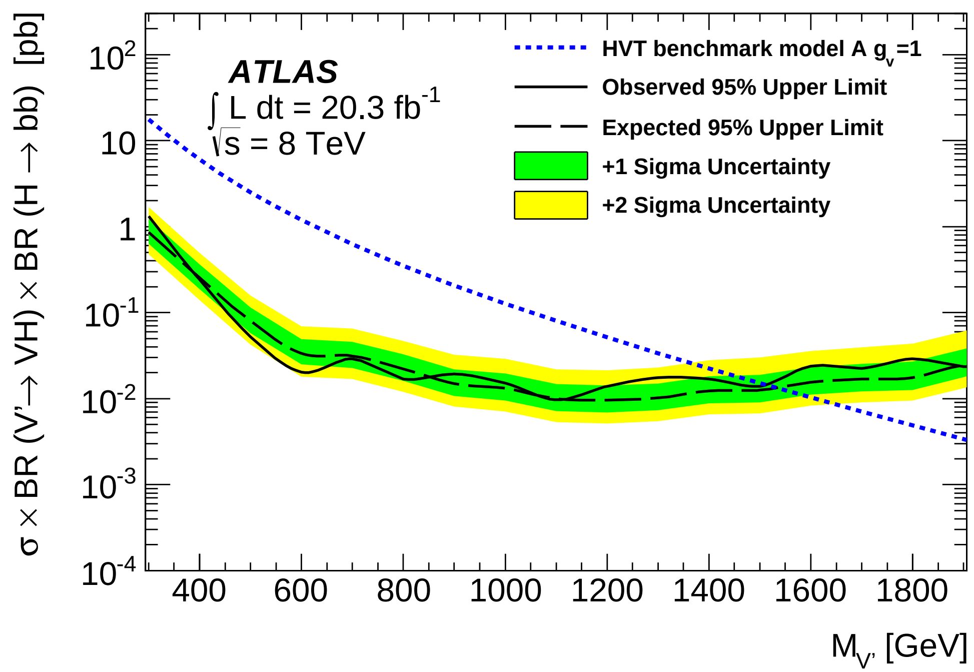


$W' \to Wh \to (\ell\nu)(b\bar{b})$

CMS (EXO-14-010):



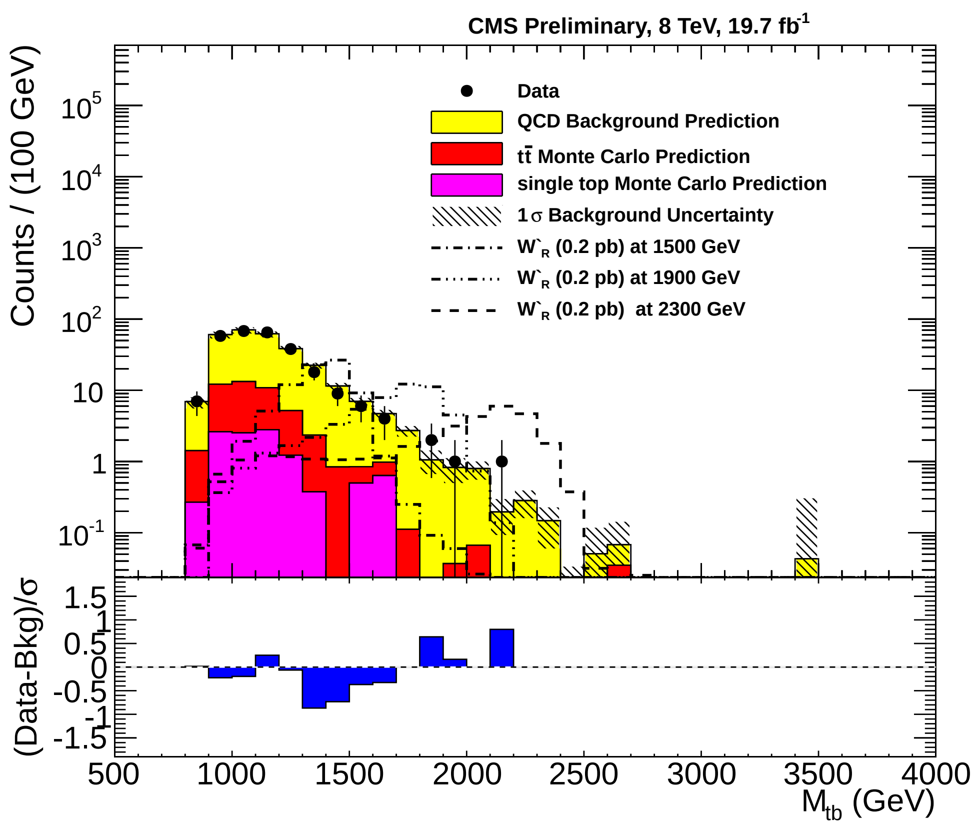
ATLAS (EXOT-2013-23, *1503.08089*):

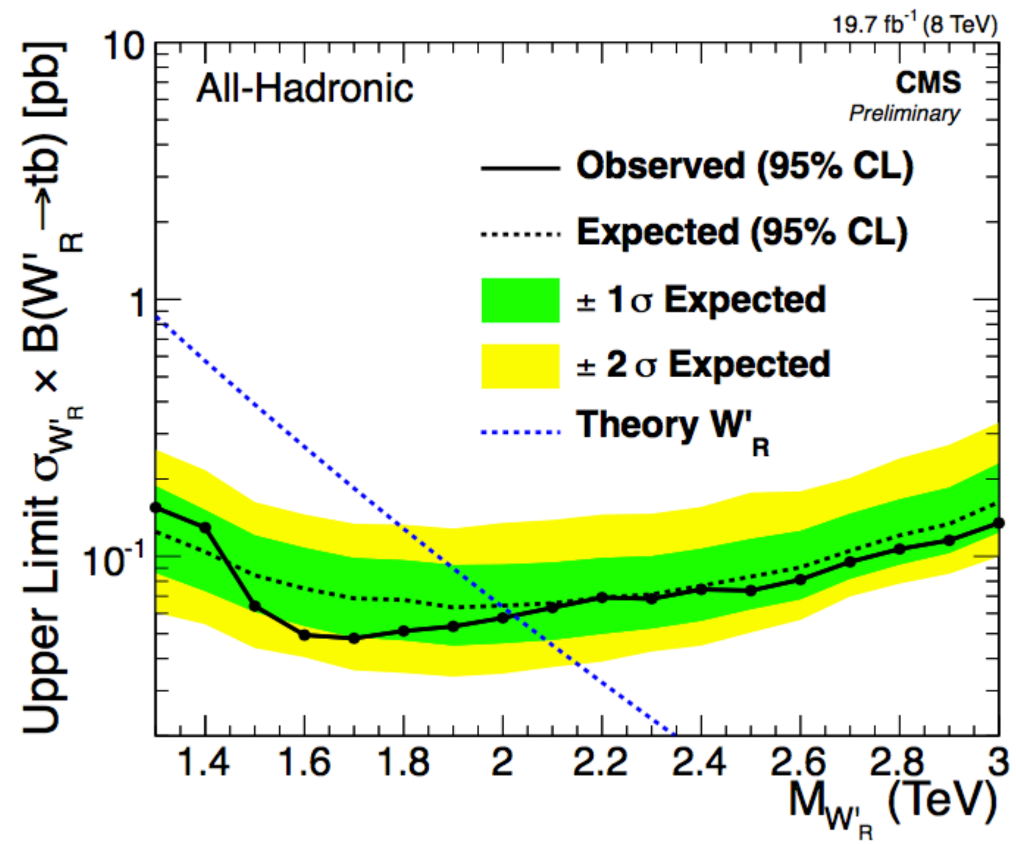


5 excesses of $\sim 2\sigma$ $\ll$ 2 excesses of 5σ $\longrightarrow$ need Run 2

$W' \to t\bar{b} \to (jjb)\bar{b}$

CMS (B2G-009):





W' decays into heavy Higgs bosons

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

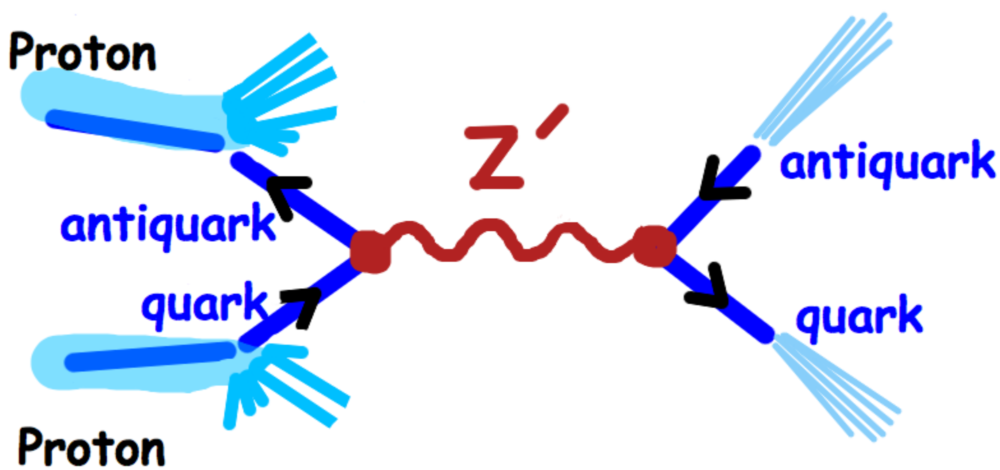
Excess explained for $M_{H^\pm} \approx M_{H^0} \approx M_{A^0} \approx 500$ GeV

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

Signal	channel	efficiency	signal events		obs. (background)
$bb\ell^{\pm}\ell^{\pm}$	$W' \to H^{\pm}(H^0/A^0) \to 3t + b$	2.5×10^{-4}	**1.0-1.8**	**4-7**	**12 (4.3**$\pm 1.1 \pm 1.1$**)**
	$W' \to (\tau/e)N \to (\tau/e)(\tau/e)tb$	5.3×10^{-4}	**2.2-3.8**		
	$pp \to t\bar{t}A^0, t\bar{t}H^0 \to 4t$	1.7×10^{-2}	**1.1**		
$\geq 3b\,\ell^{\pm}\ell^{\pm}$	$W' \to H^{\pm}(H^0/A^0) \to 3t + b$	6.3×10^{-4}	**2.5-4.4**	**5-7**	**6 (1.1**$\pm 0.9 \pm 0.4$**)**
	$pp \to t\bar{t}A^0, t\bar{t}H^0 \to 4t$	4.1×10^{-2}	**2.6**		

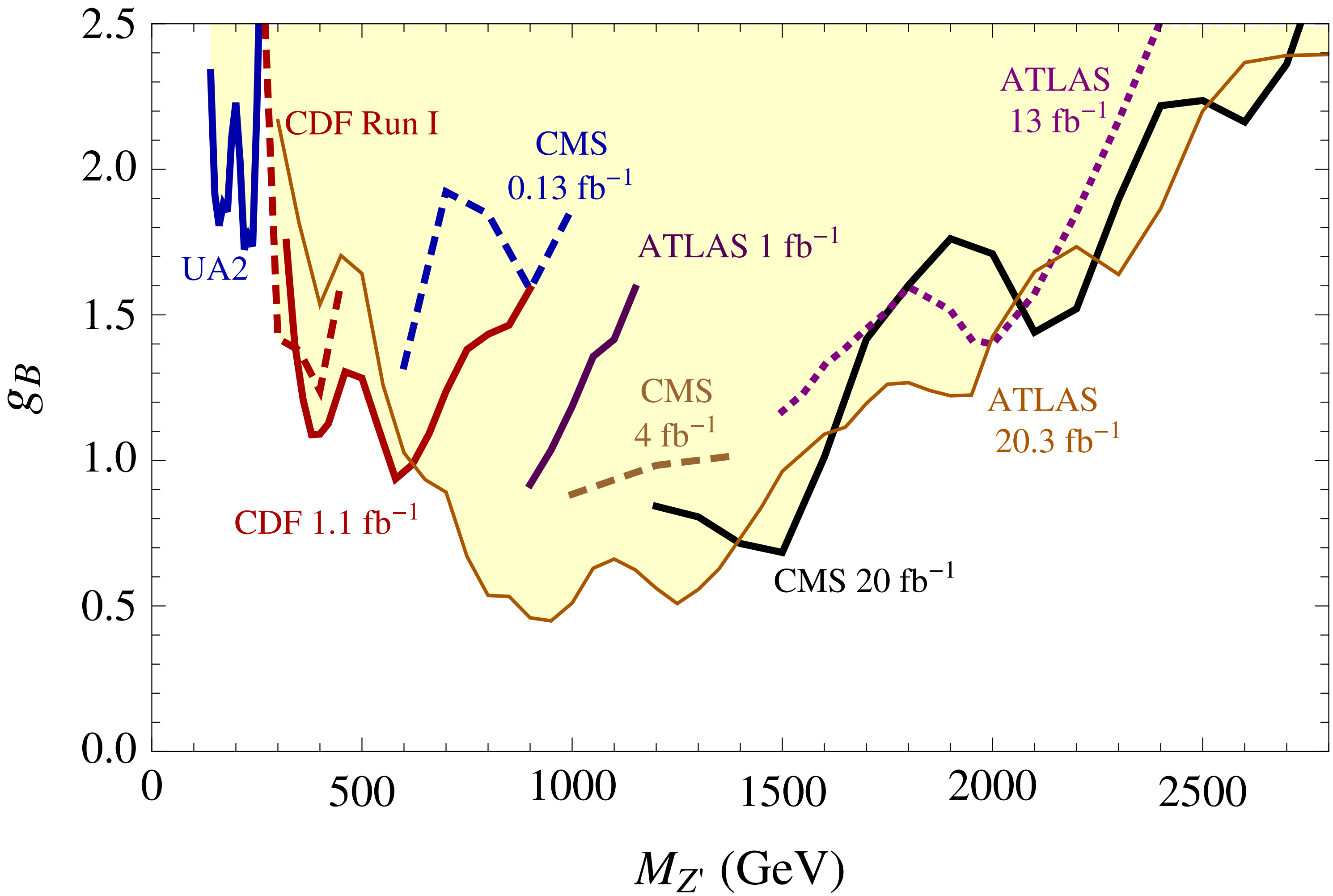
“Baryonic” Z' boson

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



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

"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

Spin-1 fields are well behaved in the UV provided that they are bound states or gauge bosons.

Leptophobic 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.**

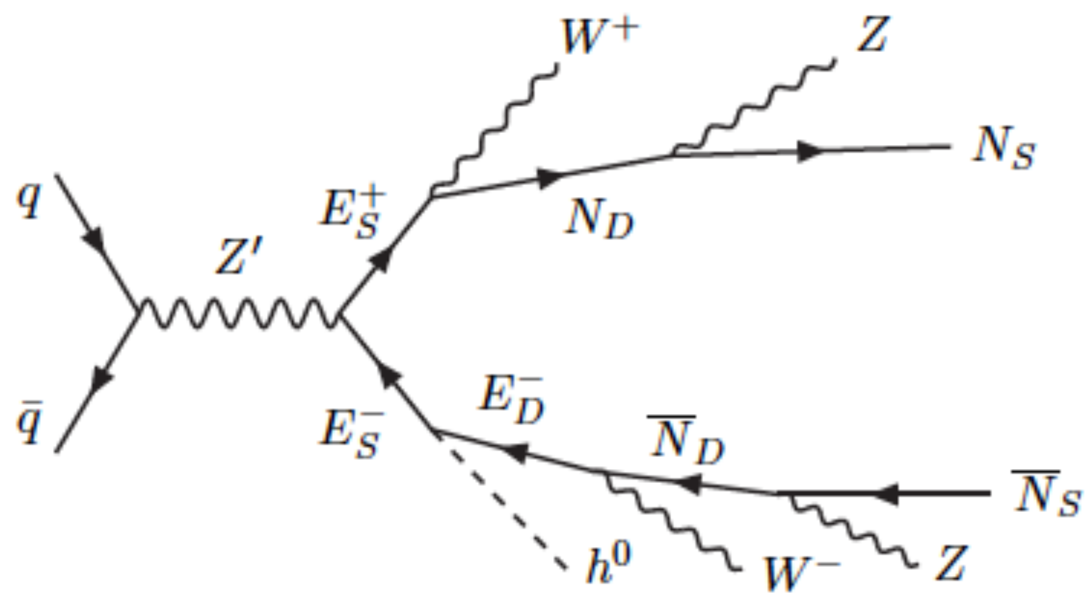
  Simple choice: a new scalar field ϕ acquires a VEV.

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

Any leptophobic Z' that couples to quarks requires 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.**

Cascade decays via anomalons:
(1506.04435)



Conclusions

- **Standard Model confirmed in Run 1 of the LHC.**
  Run 2 is exploring "Terra Incognita"
  $\rightarrow$ **huge potential for surprises, data driven environment ...**

- **Five mass peaks (each of significance between 2 and 3σ) near 1.8–2 TeV reported by CMS and ATLAS:**

$$W' \rightarrow e^+e^-jj \;\;,\; jj \;,\; Wh^0 \;,\; WZ$$

rates consistent with gauge-invariant model *(1506.06736)*

- **Jet substructure techniques are essential to searches for new physics: dark matter, vectorlike quarks, new gauge bosons, ...**