Signals of a W' boson near 2 TeV

Bogdan Dobrescu

Fermilab, Theoretical Physics Department

Based on work with:

- **Zhen Liu**

  1506.06736 *("A W' boson near 2 TeV: predictions for Run 2 of the LHC")*

  1507.01923 *("Heavy Higgs Bosons and the 2 TeV W' Boson")*

- **Pilar Coloma and Jacobo Lopez-Pavon**

  1508.04129 *("Right-Handed Neutrinos and the 2 TeV W' Boson")*

- **Patrick Fox, 1511.02148** *("Signals of a 2 TeV W' boson and a heavier Z'")*

January 10, 2015 – seminar at the Invisibles Network

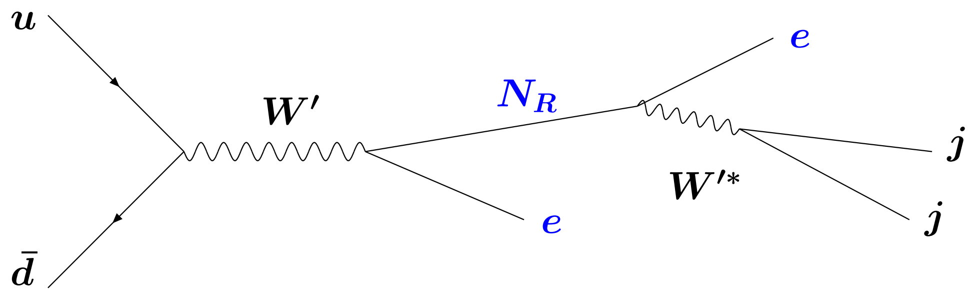
The LHC experiments have confirmed many aspects of the Standard Model, and measured $M_h = 125.09 \pm 0.24$ GeV

(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 LHC will find next ...

$W' \to eN \to e^+e^-jj$

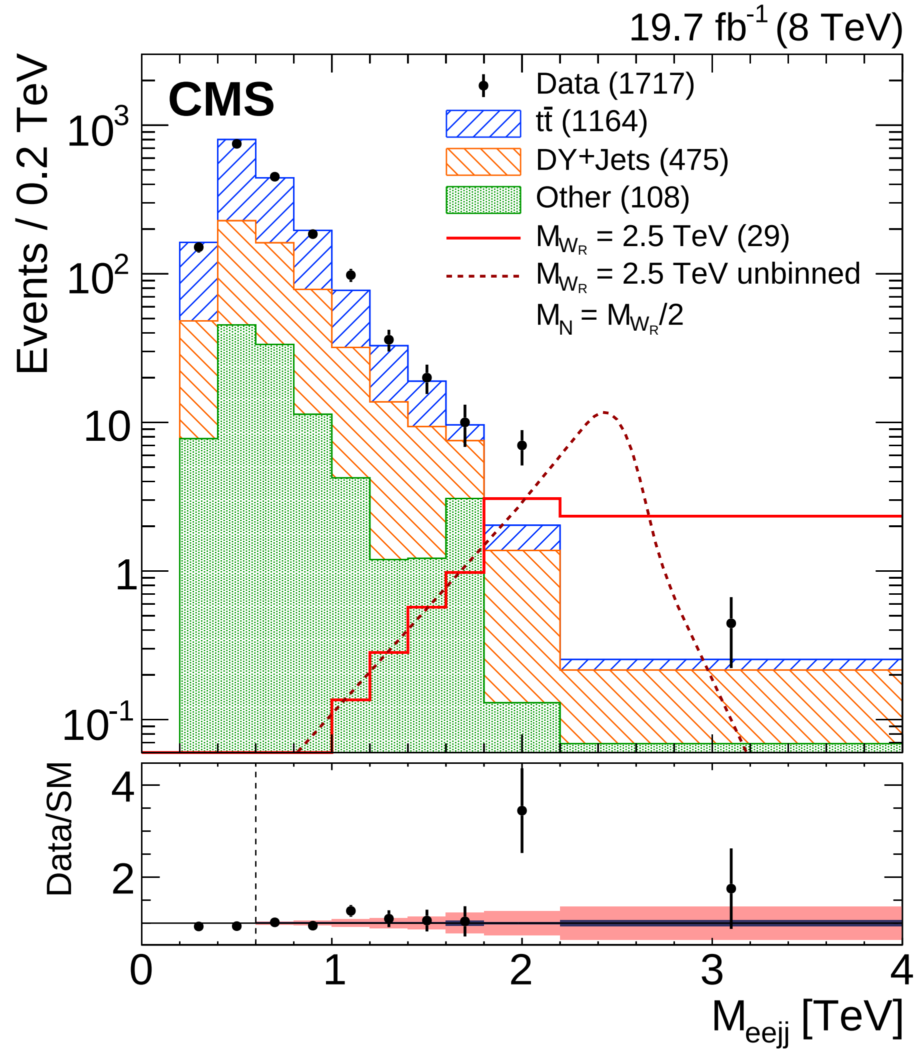


N_R - right-handed neutrino

W' boson associated with $SU(2)_R$

(Mohapatra, Pati, 1974)

CMS (1407.3683) – $eejj$ mass distribution:



M_{eejj} = 1.8–2.2 TeV bin:

14 events observed

background = 4.3 events

2.8σ excess

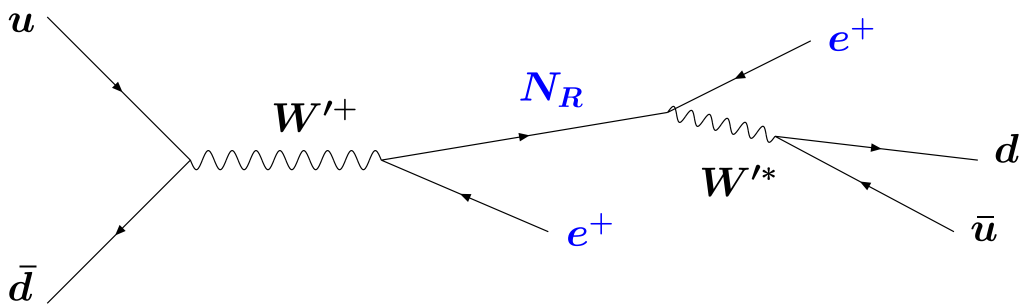
Classic prediction of Left-Right symmetric model:

(Keung, Senjanovic, 1983)

N_R has Majorana mass $\Rightarrow \Gamma(N \to e^- u\bar{d}) = \Gamma(N \to e^+ \bar{u} d)$

$\Rightarrow$ equal number of e^+e^-jj (opposite sign) and

$e^\pm e^\pm jj$ (same sign) events



CMS observed 13 opposite-sign events out of the 14 $eejj$ events, so a $W' \to eN \to e^+e^-jj$ explanation requires N to have Dirac mass at the TeV scale.

Who is the "left-handed" Dirac partner of N_R ?

Models

To specify an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model we need:

- a right-handed neutrino sector ...

- an extended Higgs sector

  At least one scalar must break $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ down to $SU(2)_W \times U(1)_Y$, so that $M_{W'} \approx 2$ TeV.

  Simple choices: $SU(2)_R$ doublet or triplet

  Other scalar(s) must break the electroweak symmetry, and include the SM-like Higgs boson.

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

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

$$M_{Z'} > 3.4 \text{ TeV} \qquad v_H \approx 174 \text{ GeV}$$

Mass terms for the charged gauge bosons:

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

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

Mass eigenstates: W and W'.

Right-handed neutrino sector

Include a vectorlike lepton $\psi = (\psi^N, \psi^e)$, give a Majorana mass to ψ_R^N $(\bar{\psi}_R^c T^\dagger \psi_R)$, and a Dirac mass to $\bar{N}_R \psi_L^N$ $\longrightarrow$ opposite-sign $eejj$ events!

Fields	spin	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$q_L = (u_L,\ d_L)^\top$	1/2	3	2	1	$+1/3$
$q_R = (u_R,\ d_R)^\top$	1/2	3	1	2	$+1/3$
$L_L = (\nu_L,\ \ell_L)^\top$	1/2	1	2	1	-1
$L_R = (N_R,\ \ell_R)^\top$	1/2	1	1	2	-1
$\psi_{L,R} = (\psi^N, \psi^e)^\top_{L,R}$	1/2	1	1	2	$+1$
Σ	0	1	2	2	0
T	0	1	1	3	$+2$

Assume N_R^μ is heavier than W' $\Longrightarrow$ no $\mu\mu jj$ events

N_R^e and N_R^τ may mix:
$$\frac{g_{\rm R}}{\sqrt{2}} W'_\nu \, \overline{N}_R \gamma^\nu \left(s_{\theta_e} e_R + c_{\theta_e} \tau_R \right)$$

A simpler right-handed neutrino sector

with Pilar Coloma and Jacobo Lopez-Pavon 1508.04129

Assume a flavor structure for the Majorana masses:

$$-\frac{y_{\mu\mu}}{2}(\overline{L}^{\mu}_{R})^{c}\, i\sigma_2\, T\, L^{\mu}_{R} - y_{e\tau}(\overline{L}^{e}_{R})^{c}\, i\sigma_2\, T\, L^{\tau}_{R}$$

right-handed neutrinos acquire masses:

$$-u_T \left(\overline{N}^{e}_{R}, \overline{N}^{\mu}_{R}, \overline{N}^{\tau}_{R}\right)^{c} \begin{pmatrix} 0 & 0 & y_{e\tau} \\ 0 & y_{\mu\mu} & 0 \\ y_{e\tau} & 0 & 0 \end{pmatrix} \begin{pmatrix} N^{e}_{R} \\ N^{\mu}_{R} \\ N^{\tau}_{R} \end{pmatrix}$$

Two right-handed neutrinos make a Dirac fermion N_D:

$$N^{\tau}_{R} \equiv N^{c}_{D_L} \quad , \quad N^{e}_{R} \equiv N_{D_R}$$

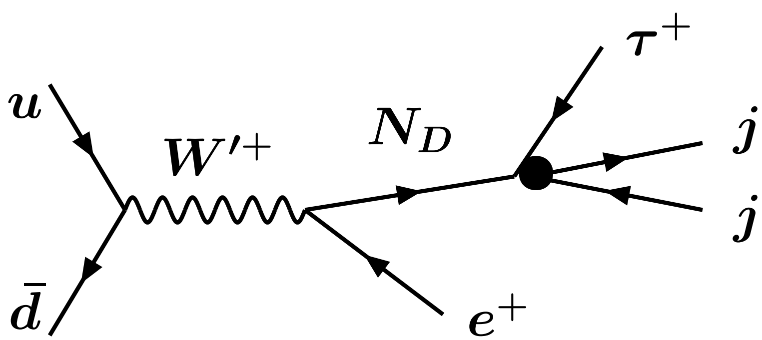
Interactions of N_D with W':

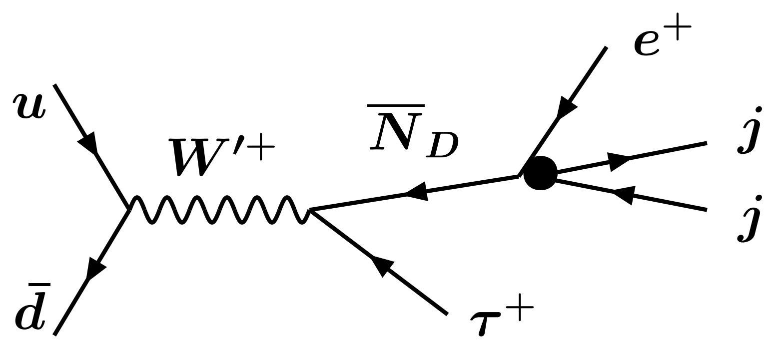
$$\frac{g_{\rm R}}{\sqrt{2}} W'_{\nu} \left(\overline{N}_{D_R}\gamma^{\nu} e_R + \overline{N}^{c}_{D_L}\gamma^{\nu}\tau_R\right)$$

Flavor structure can be enforced by a global $U(1)$ symmetry with the L_R^e, L_R^μ, L_R^τ doublets carrying charges $-1, 0, +1$.

Implications for the LHC:

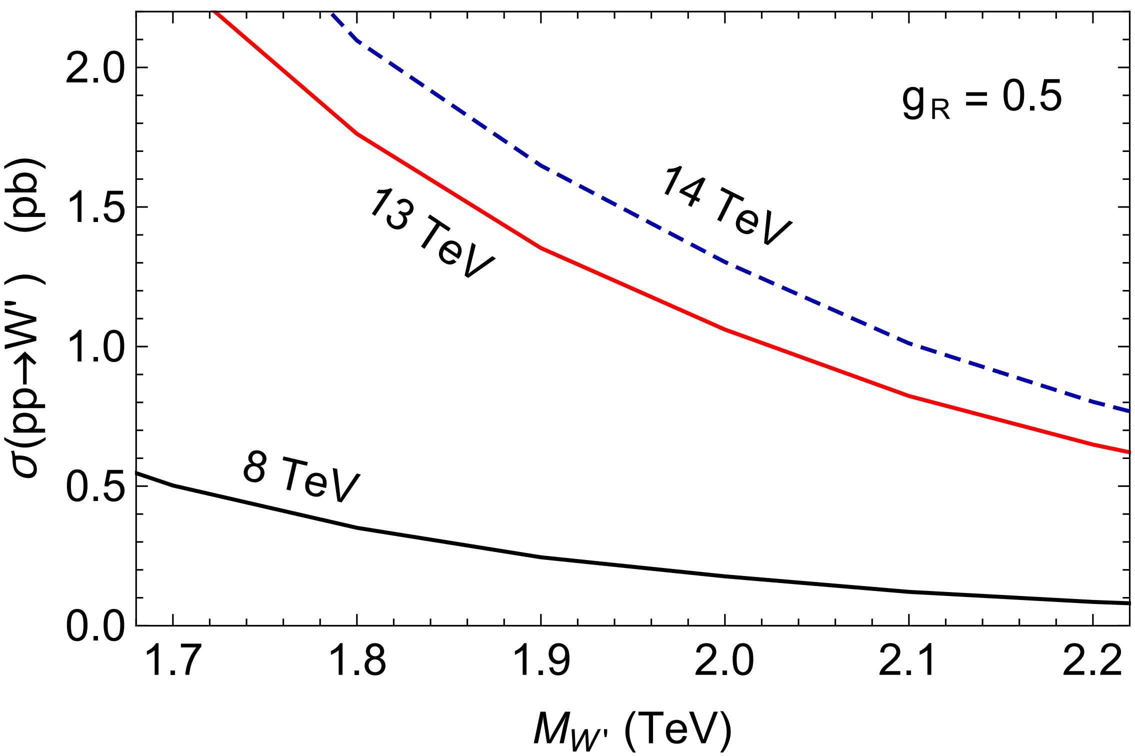
$$
\begin{aligned}
B(W'^+ \to e^+ N_D \to e^+ e^- jj) &= B(W'^+ \to \tau^+ \overline{N}_D \to \tau^+ \tau^- jj) \\
&= B(W'^+ \to e^+ N_D \to e^+ \tau^+ jj) \\
&= B(W'^+ \to \tau^+ \overline{N}_D \to \tau^+ e^+ jj)
\end{aligned}
$$





$pp \to W'$ cross section

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



W' is slightly more weakly coupled than W:

$$g_R < g \approx 0.63$$

$$\sigma_{13}(W') \approx 700\,\mathrm{fb} \left(\frac{g_R}{0.4}\right)^2$$

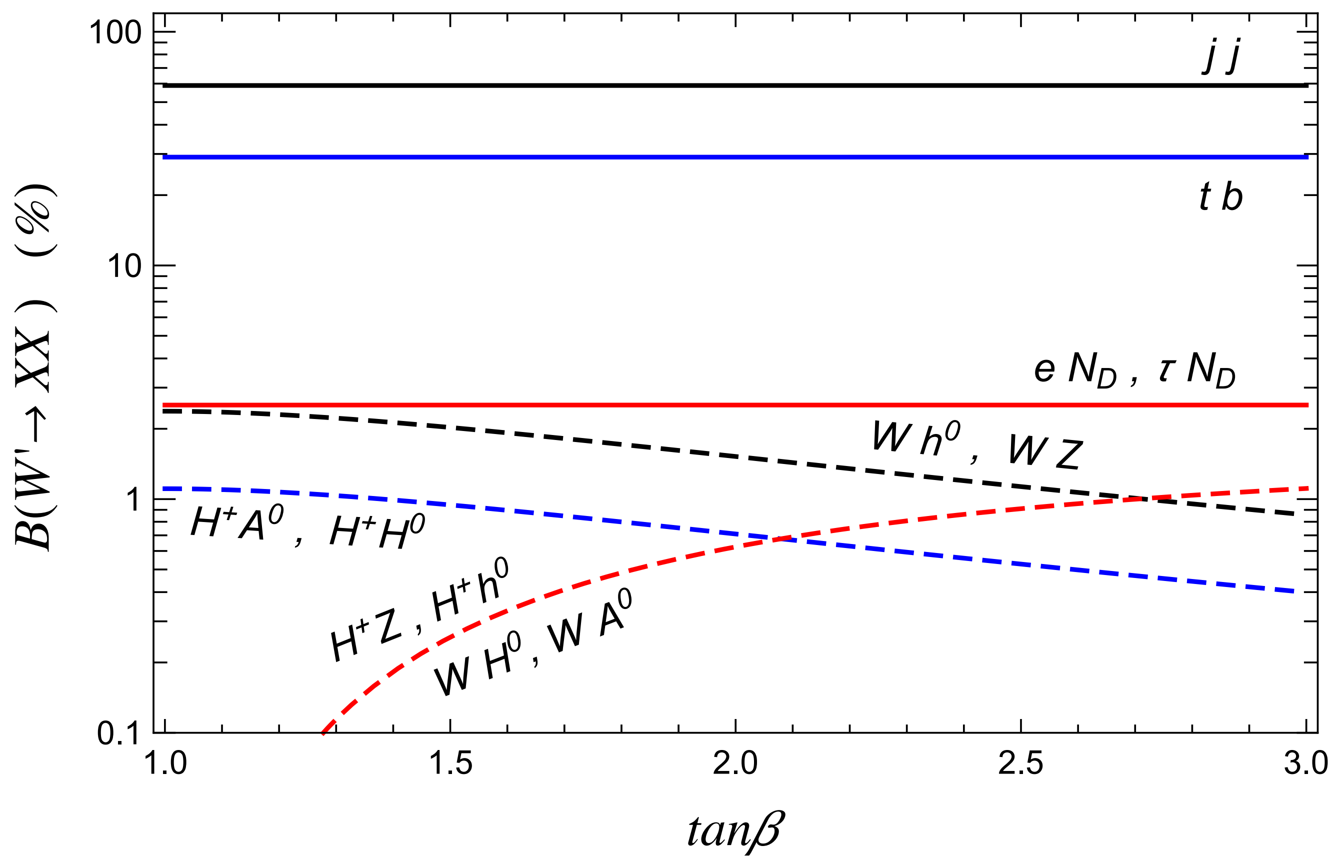
at $M_{W'} = 1.9$ TeV.

W' widths and branching fractions

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

$$\Gamma(W' \to e\bar{N}) \simeq \Gamma(W' \to \tau\bar{N}) \simeq \frac{g_R^2}{48\pi} M_{W'} \left(1 + \frac{m_{N_D}^2}{2M_{W'}^2}\right)\left(1 - \frac{m_{N_D}^2}{M_{W'}^2}\right)^2$$

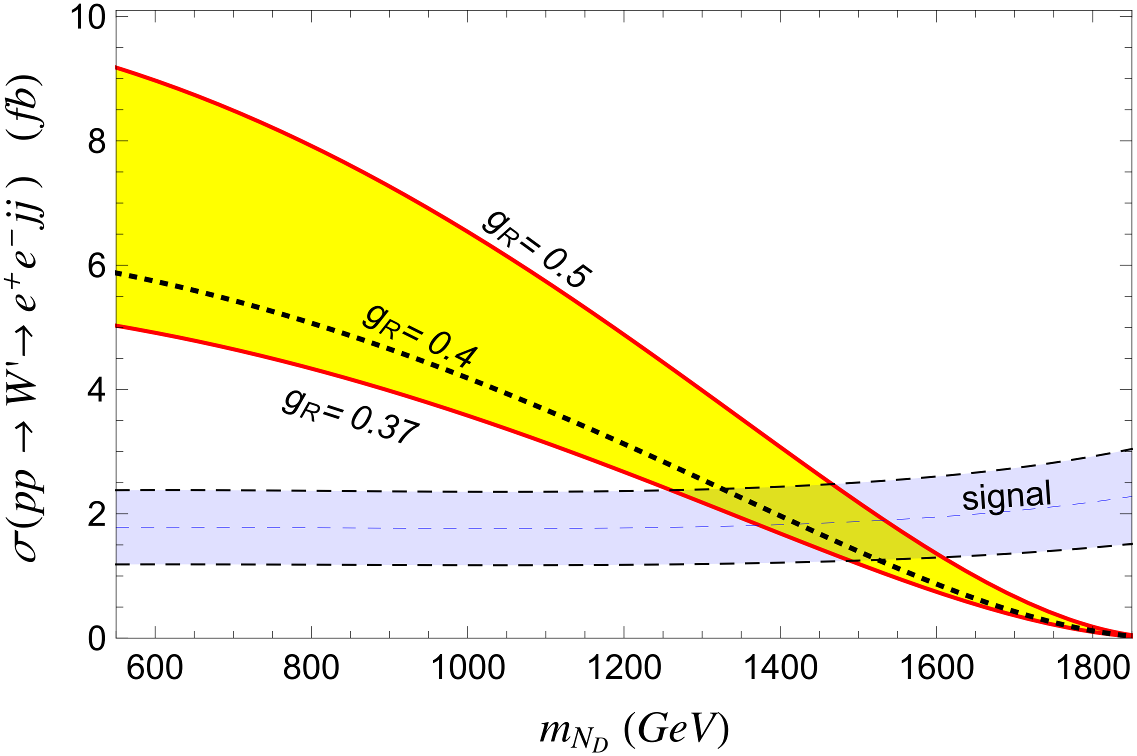
$$\Gamma(W' \to WZ) \simeq \Gamma(W' \to Wh^0) \simeq \frac{g_R^2}{192\pi} \sin^2 2\beta \, M_{W'}$$



$m_N = 1.4$ **TeV**

Heavy Higgs bosons (part of the bidoublet), $H^{\pm}, H^0, A^0$*, have approximately the same mass (assumed here in the 500–600 GeV range).*

Comparison of the CMS e^+e^-jj excess with the $W' \to eN_D \to e^+e^-jj$ rate allows a determination of m_{N_D}:



with P. Fox, 1511.02148

$\Rightarrow$ $m_{N_D} \approx 1.4$ **TeV**

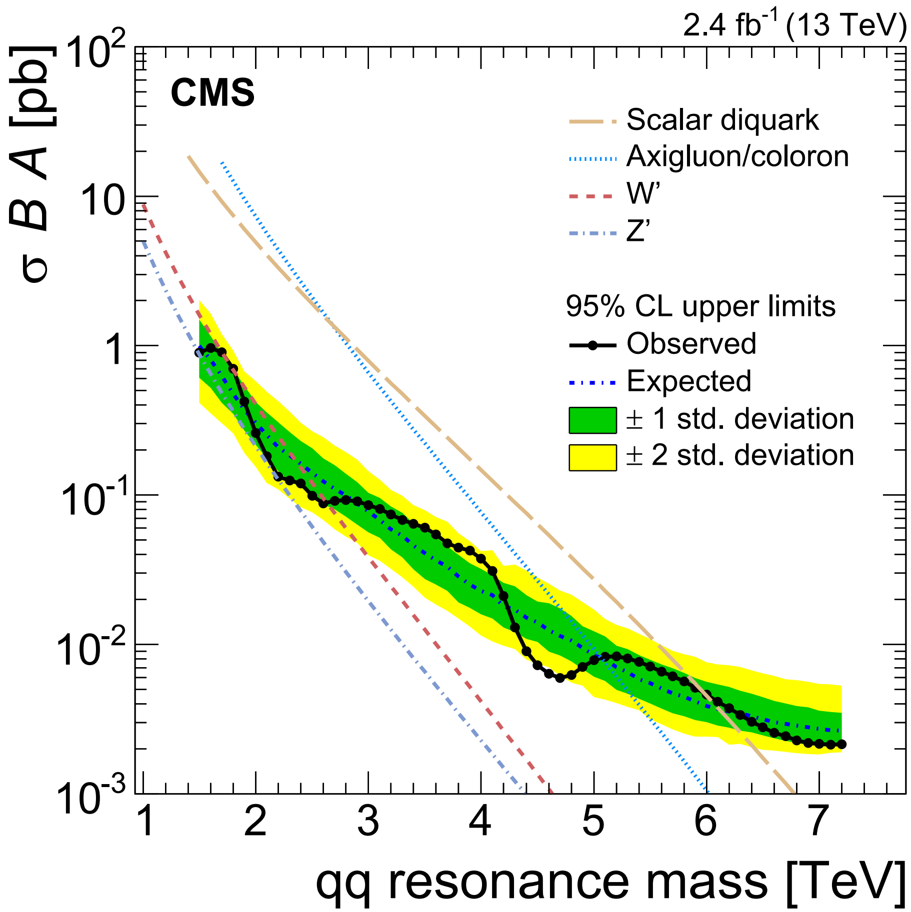
$u\bar{d} \to W' \to jj$

W' decays predominantly into quark pairs $\longrightarrow$ $B(W' \to jj) \approx 60\%$

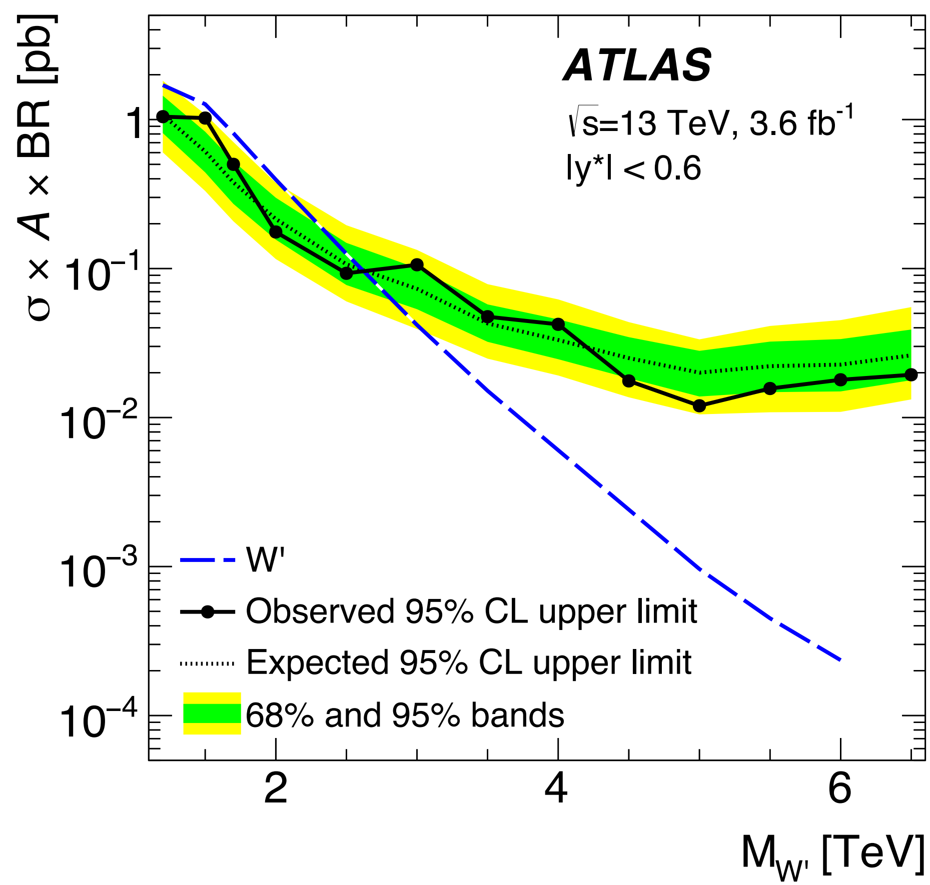
Highly boosted t, W, Z, h^0 often look like jets $\longrightarrow$ $B(W' \to \text{“}jj\text{”}) \approx 85\%$

with P. Fox, 1511.02148

CMS (1512.01224):

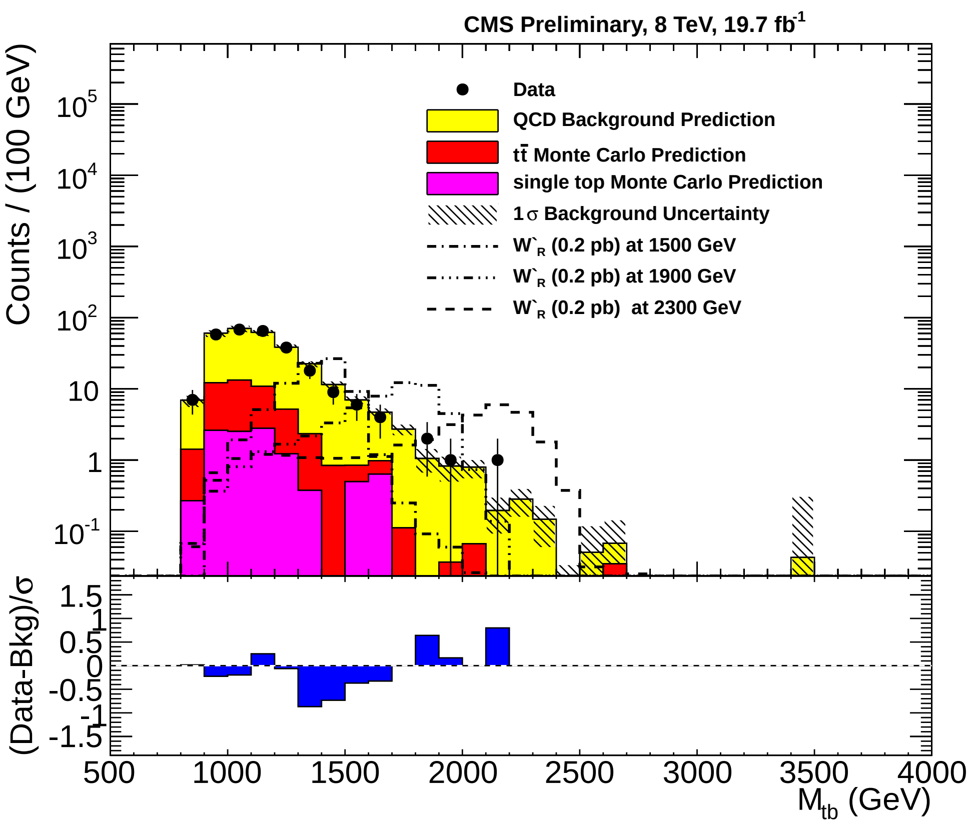


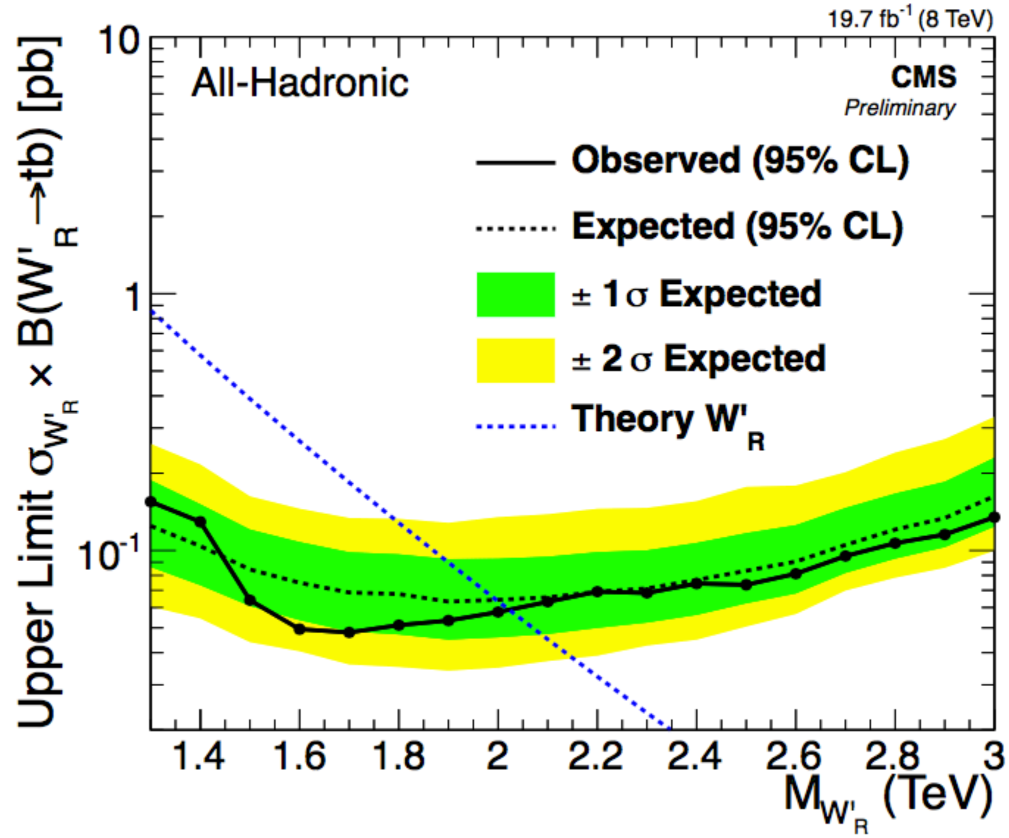
ATLAS (1512.01530):



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

CMS (B2G-009):

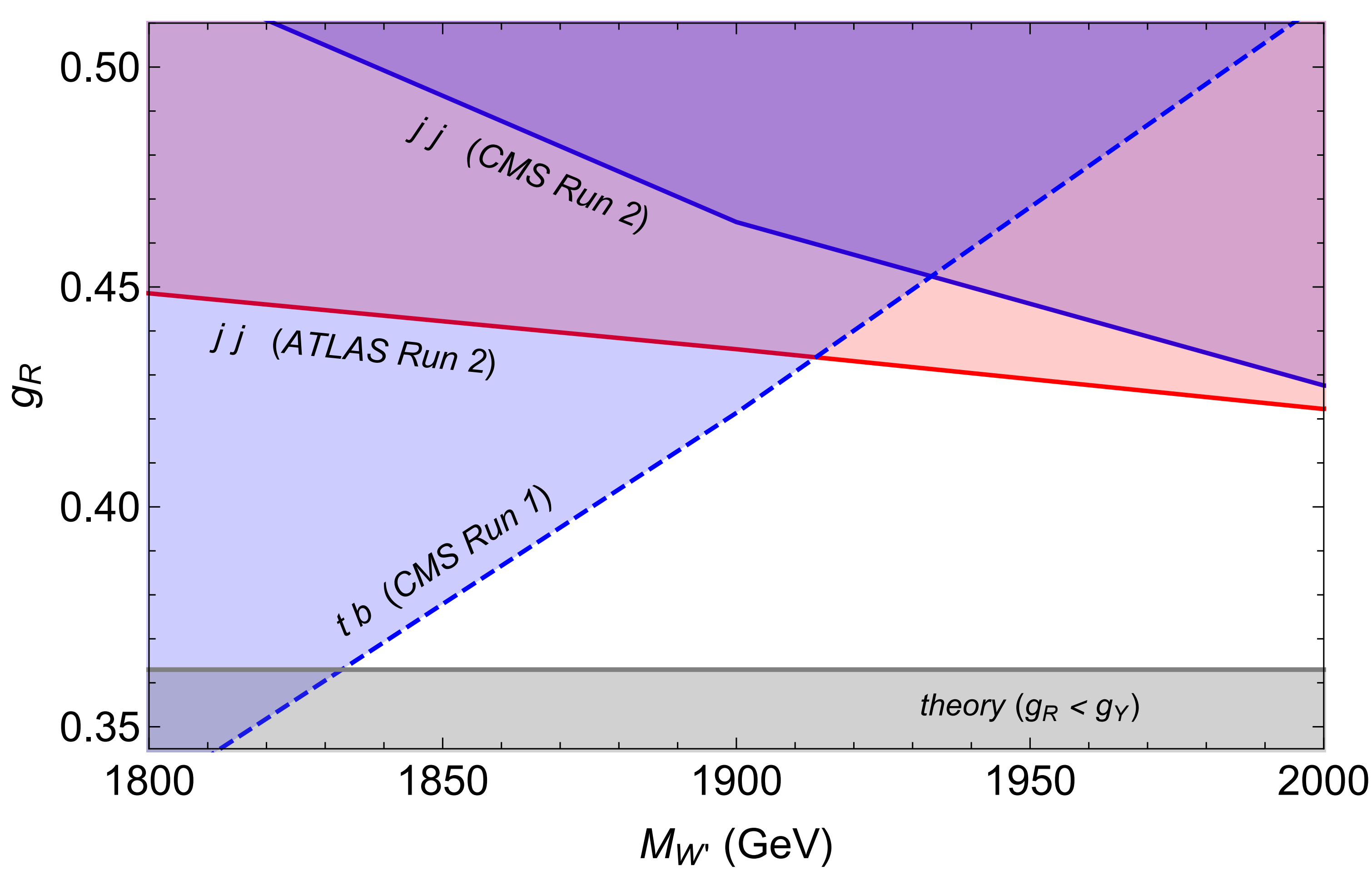




$g_{\rm R} \lesssim 0.45$ – some tension with the jj and WZ preferred values.

W' width used by CMS (based on $g_L = g_R$): ~ 65 GeV.

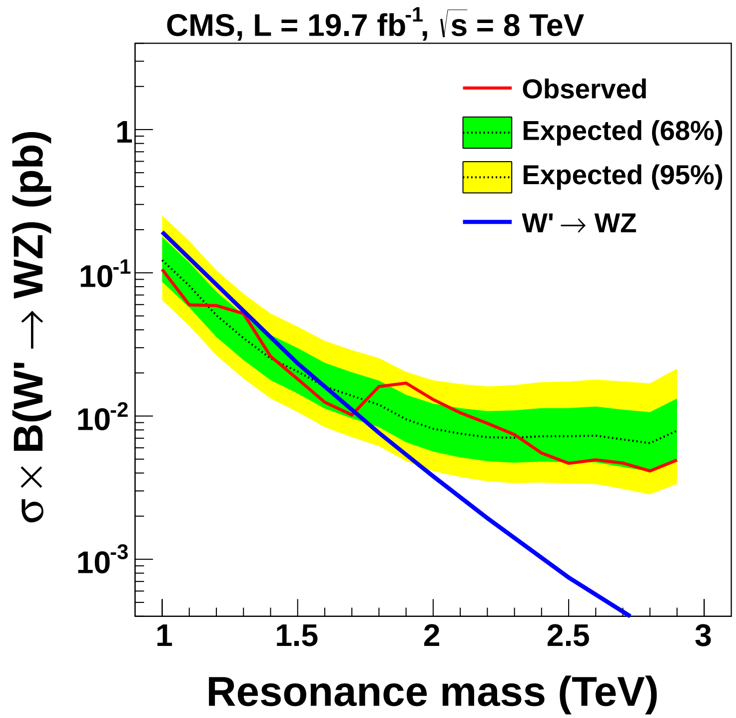
W' width in this model: $\Gamma_{W'} \approx 30$ GeV: does the limit on $g_{\rm R}$ relax?



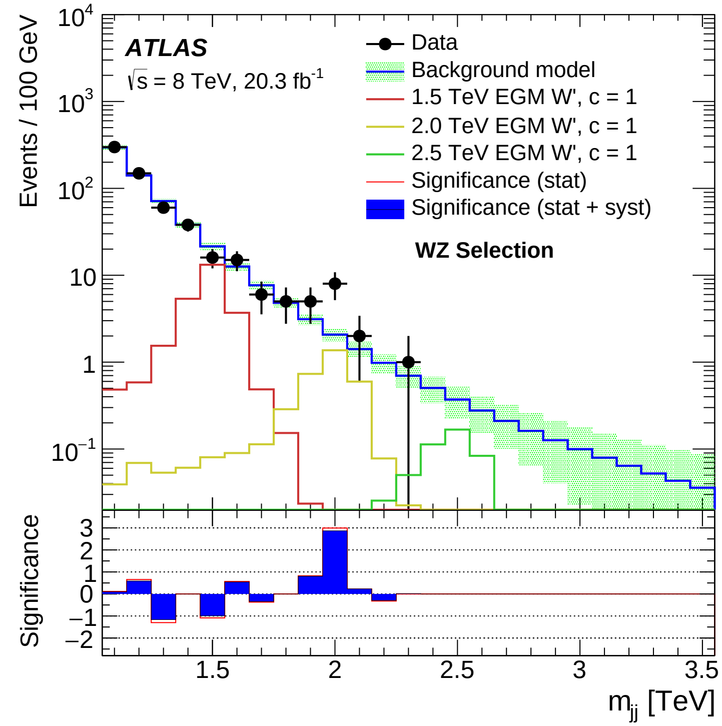
0.50
0.45
0.40
0.35
1800
1850
1900
1950
2000
g_R
$M_{W'}$ (GeV)
j j (CMS Run 2)
j j (ATLAS Run 2)
t b (CMS Run 1)
theory ($g_R < g_Y$)

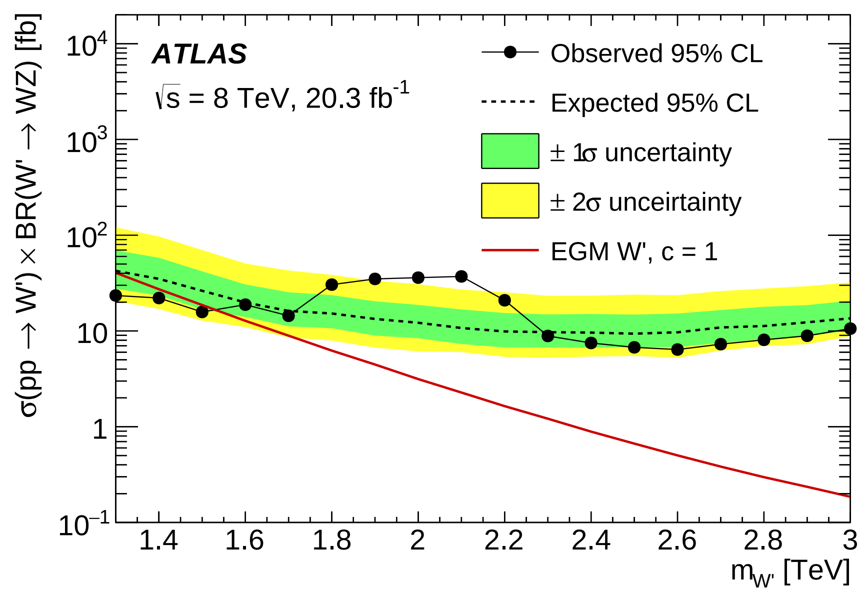
$W' \to WZ \to JJ$

CMS (1405.1994):



ATLAS (1506.00962):

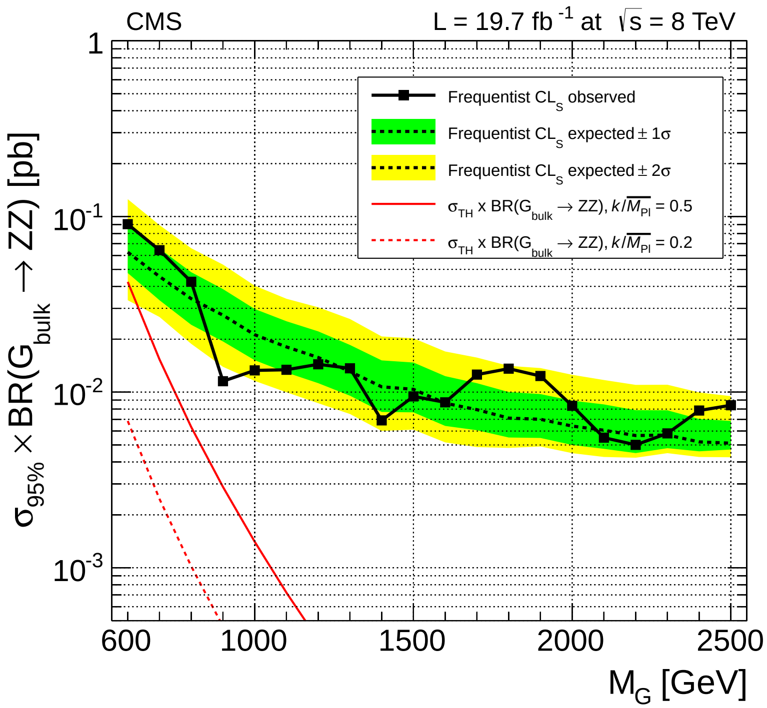




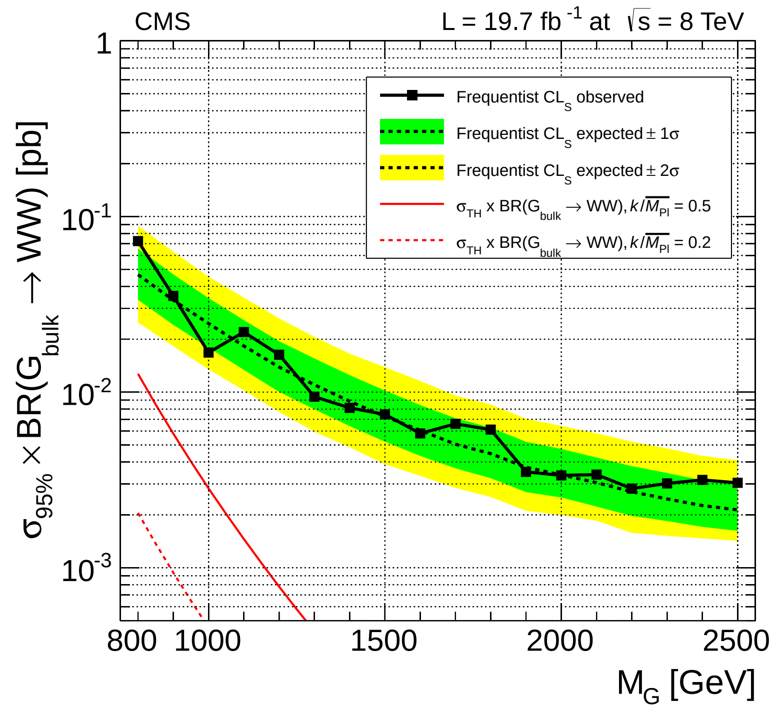
$$\sigma(pp \to W' \to WZ) = O(5)\ \text{fb} \longleftarrow$$

Consistent with $\Gamma(W' \to WZ) = \Gamma(W' \to Wh^0)$

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

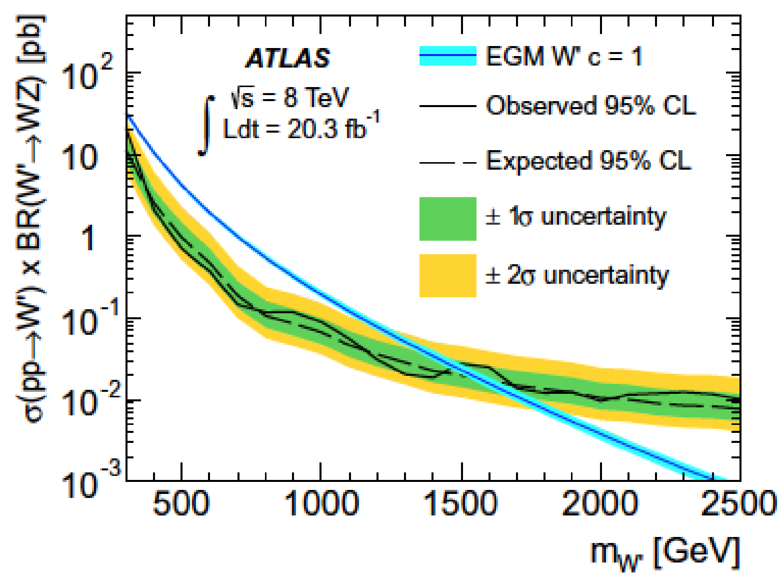


$W' \to WZ \to (\ell\nu)J$



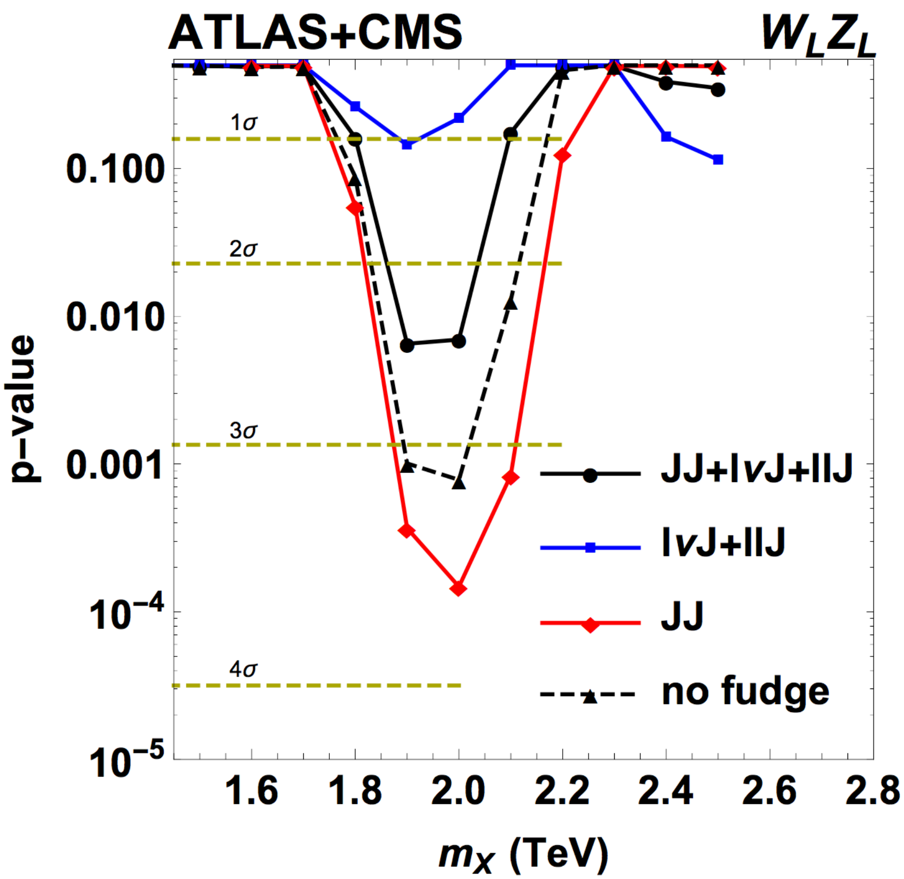
CMS (1405.3447): limit on WZ weaker by a factor of 2 (2.3) compared to ZZ (WW)

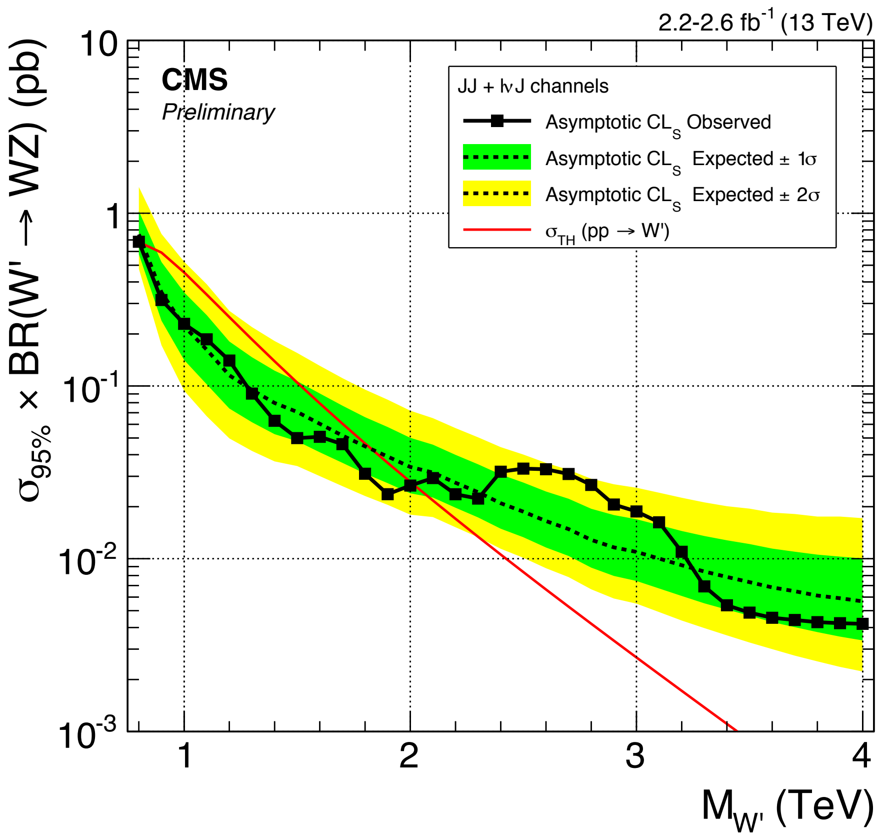
ATLAS 1503.04677:
$\sigma(pp \to W' \to WZ) < 12$ fb



Run 1 combination
(F. Dias et al, 1512.03371):

Run 2: CMS-EXO-15-002



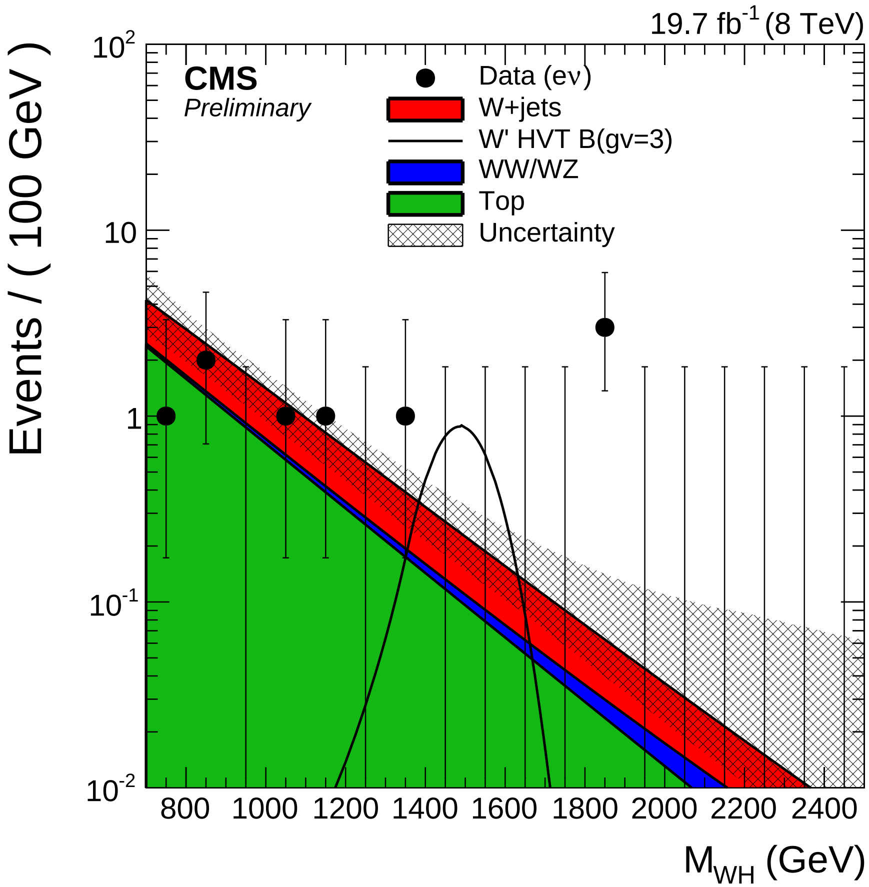


$\sigma_8 \approx 5 \pm 2$ fb

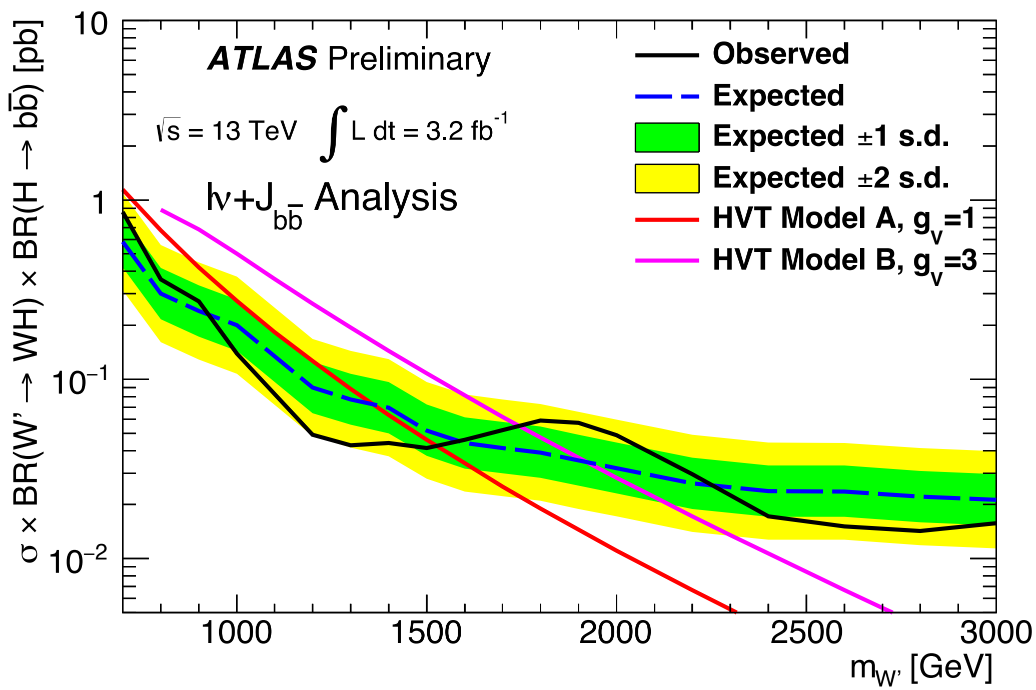
$\sigma_{13}/\sigma_8 \approx 6.5$ for $M_{W'} = 1.9$ TeV

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

CMS (EXO-14-010):



ATLAS (CONF-2015-074):



The $W' \to Wh^0$ rate is consistent with the $eejj$ excess.

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

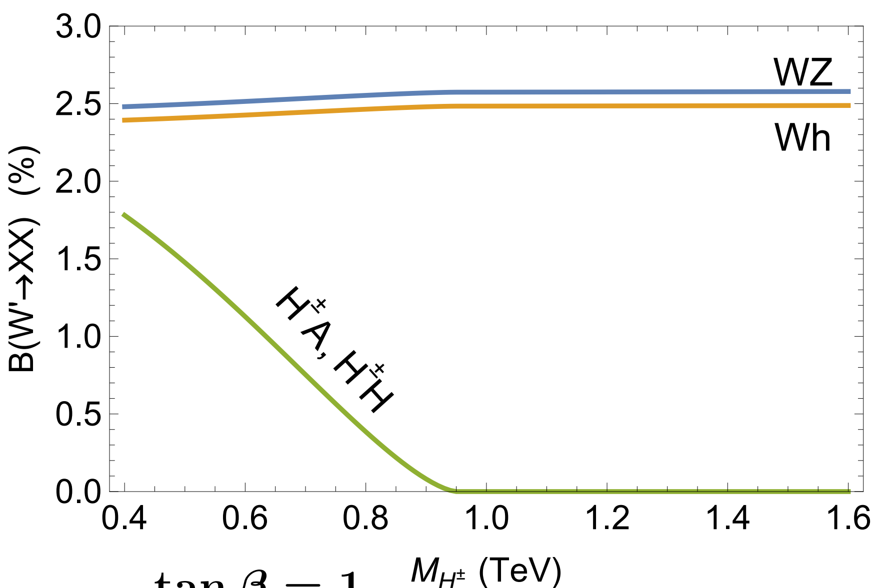
Type	N_j	H_T [GeV]	E_T^{miss} [GeV]
e^-e^-	3	807	171
e^+e^+	5	862	268
e^+e^+	5	868	113
μ^-e^-	6	1346	353
$e^+\mu^+$	5	810	106
$e^-\mu^-$	3	707	184
$e^-\mu^-$	2	706	174
μ^+e^+	8	882	150
μ^+e^+	4	860	112
$\mu^+\mu^+$	5	888	111
$\mu^-e^+e^+$	5	773	197
$\mu^-e^+e^+$	9	968	355

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

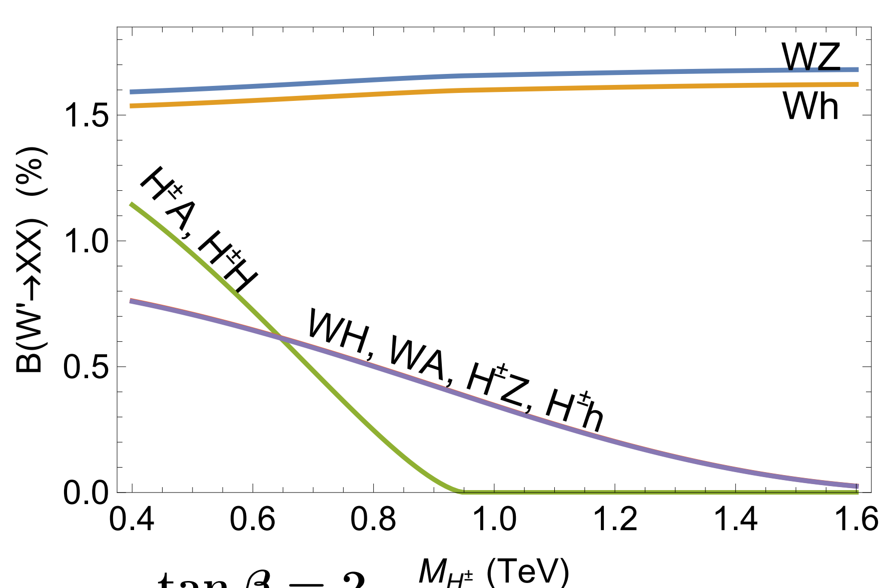
($M_{W'} \approx 1.9 - 2$ TeV)

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		

Branching fractions for bosonic decays of W':



$\tan\beta = 1$

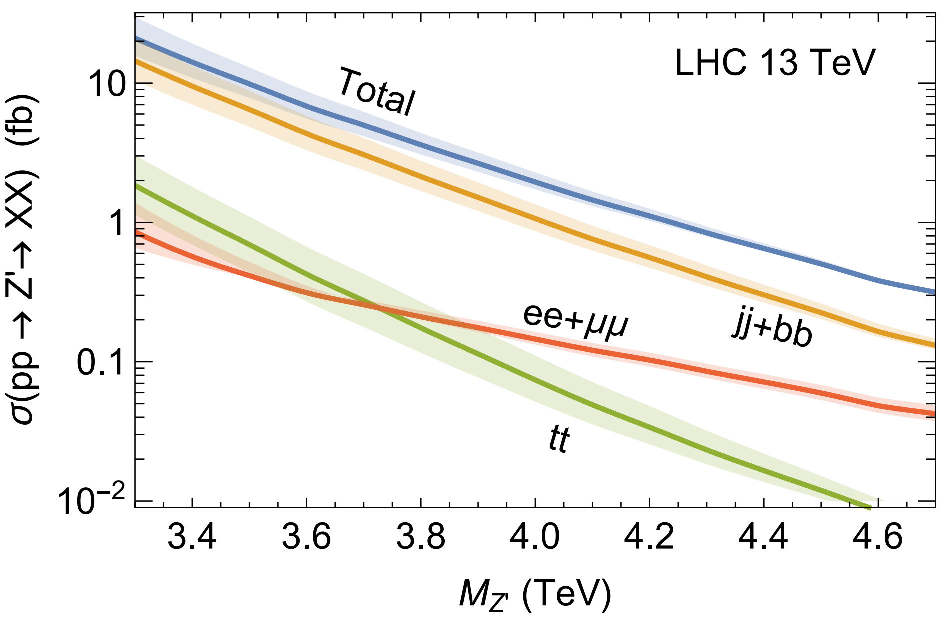


$\tan\beta = 2$

Z' **couplings to quarks and leptons:** $$\frac{1}{\sqrt{g_{\rm R}^2 + g_{B-L}^2}}\left(g_{\rm R}^2 T_R^3 - g_{B-L}^2 \frac{B-L}{2}\right)$$

If $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ **breaking is due to an** $SU(2)_R$ **triplet:**

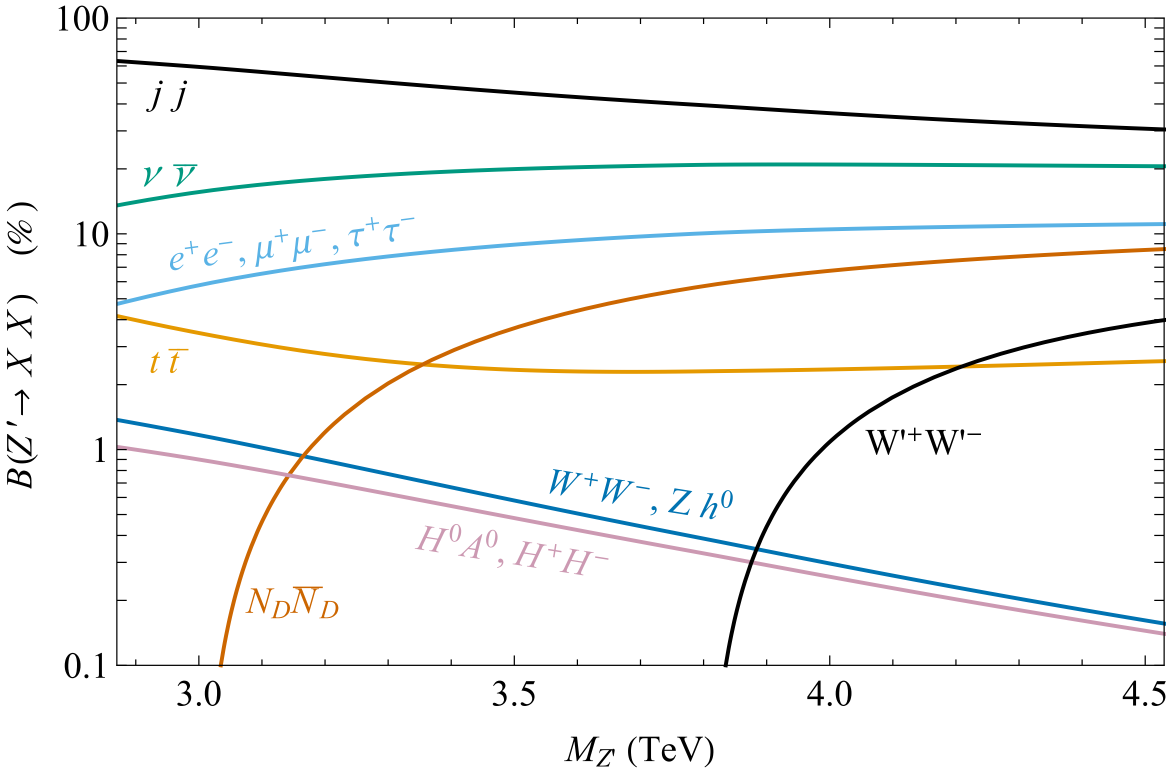
$$M_{Z'} = \sqrt{2}\,\frac{g_{\rm R}}{\left(g_{\rm R}^2 - g_Y^2\right)^{1/2}}\,M_{W'}$$, $g_Y \approx 0.36$ *is the SM hypercharge coupling*



$$\frac{1}{g_{B-L}^2} = \frac{1}{g'^2} - \frac{1}{g_{\rm R}^2}$$

Z' can be lighter than 3.4 TeV if the $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ breaking is due to an $SU(2)_R$ doublet

with P. Fox, 1511.02148



$$M_{Z'} = \frac{M_{W'}}{\sqrt{1 - g_Y^2/g_R^2}}$$

Conclusions

- **Excess events near**
  1.8–2 TeV reported by CMS and ATLAS:

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

  Rates consistent with $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ gauge model

(1511.02148)

- **If a W' will be confirmed, a new era of discoveries will follow: measurements of the Z' boson, right-handed neutrinos, heavy Higgs bosons, ... , will lead us to deeper organizing principles.**