# Theories Beyond the Standard Model and final states with $W$, $Z$ and Higgs bosons

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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:**

$$M_h = 125.09 \pm 0.24 \text{ GeV}$$ *(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 ...**

**Observed elementary particles:**

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

- **Gauge bosons (spin 1):** $\gamma, W, Z, g$.

- **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.

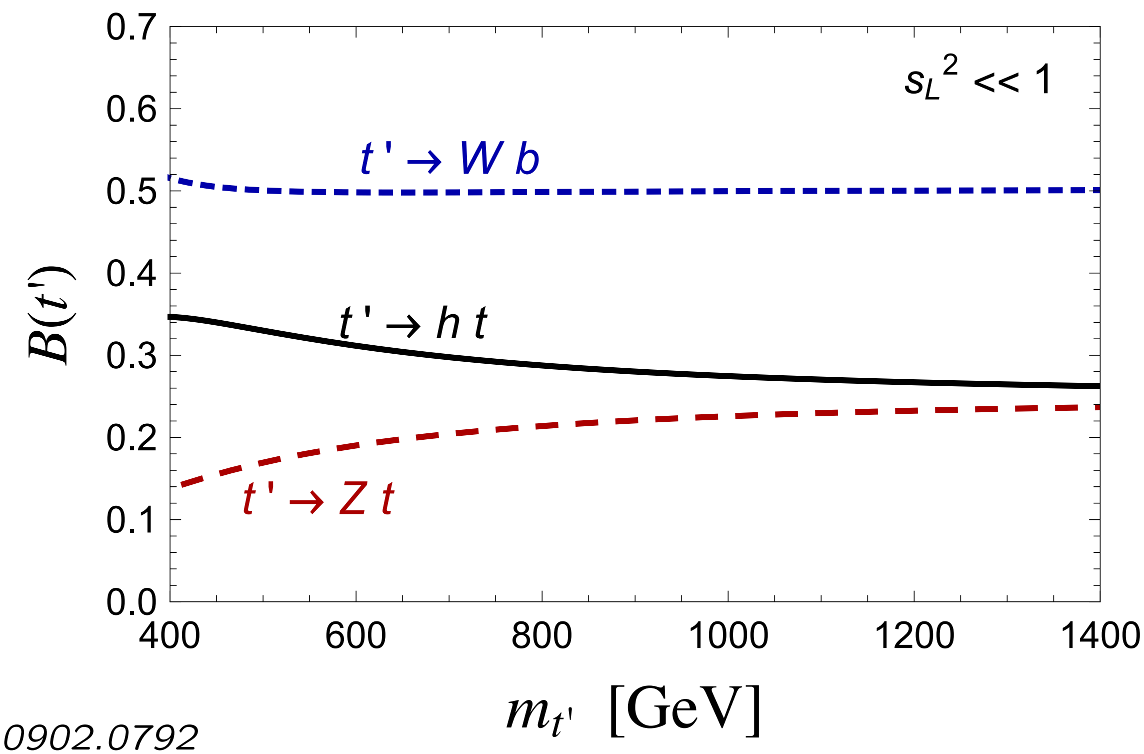
Unlike chiral fermions, vectorlike fermions have a decoupling limit:
$m \gg v_H \approx 174$ GeV $\rightarrow$ Standard Model is recovered.

**A vectorlike quark $\chi$ 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.**

*$\chi$ is predicted in composite Higgs models (Chivukula et al, hep-ph/9809470),*
*little Higgs models (Arkani-Hamed et al, hep-ph/0206020),*
*...*

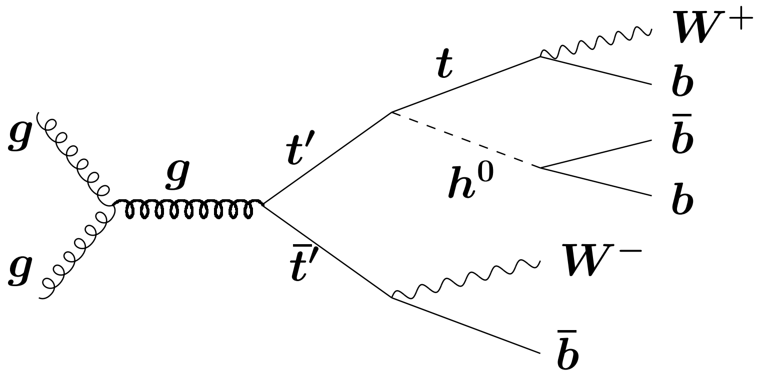
**Mass eigenstates: $t$ and $t'$. Mixing $\sin\theta_L \equiv s_L$.**

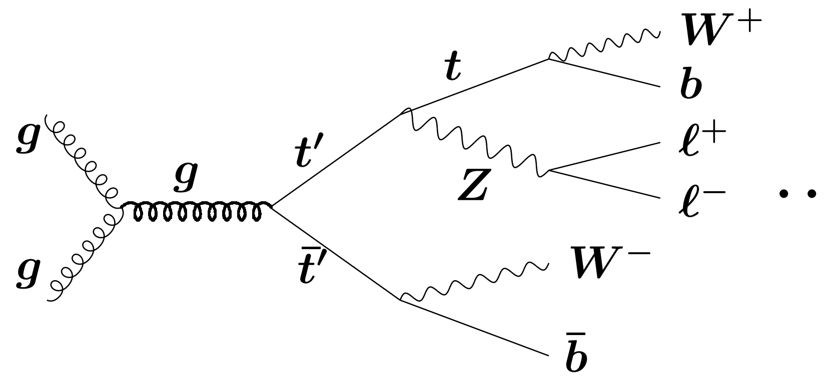
**$t'$ branching fractions:**




*with K. Kong and R. Mahbubani, 0902.0792*

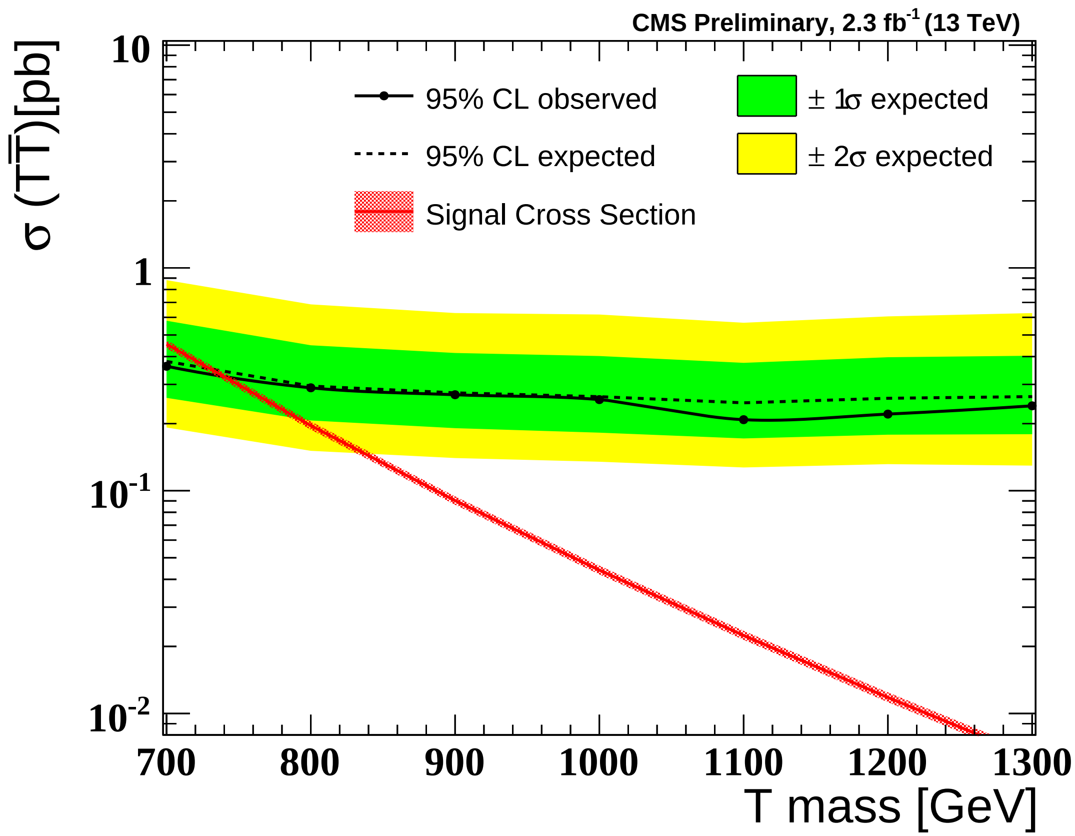
*T. Han, H. Logan, L. Wang, hep-ph/0506313*




Current limit: $m_{t'} \gtrsim 750$ GeV

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



'Standard' decay widths of $t'$:

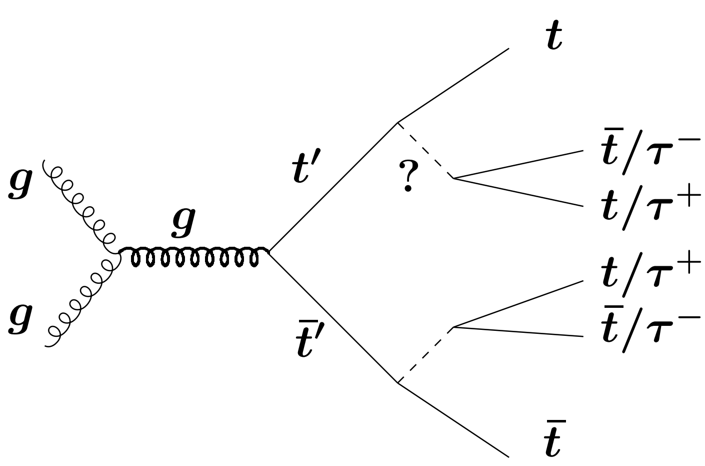
$$\Gamma(t' \to W^+ b) = \frac{s_L^2 \; m_{t'}^3}{32\pi v_H^2}\left[1 + O\left(\frac{M_W^4}{m_{t'}^4}\right)\right]$$

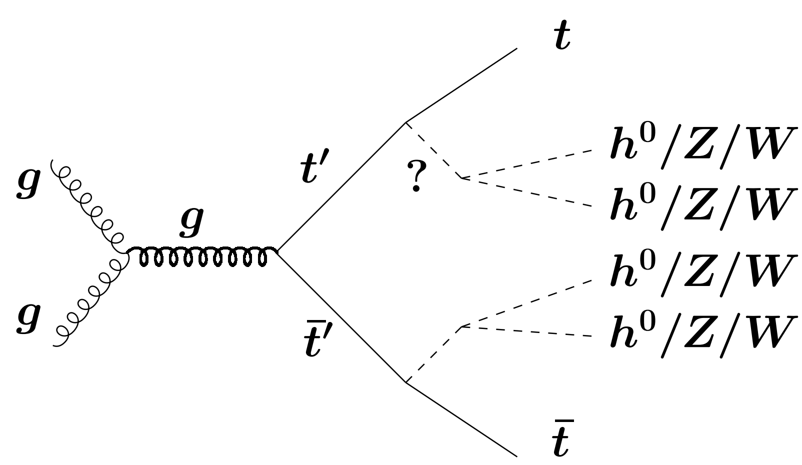
$$\Gamma(t' \to Zt) = \frac{s_L^2 c_L^2 \; m_{t'}^3}{64\pi v_H^2}\left[1 - \frac{m_t^2}{m_{t'}^2} + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

$$\Gamma(t' \to ht) = \frac{s_L^2 c_L^2 m_{t'}^3}{64\pi v_H^2}\left[1 + 5\frac{m_t^2}{m_{t'}^2} + O\left(\frac{m_t^4}{m_{t'}^4}\right)\right]$$

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

*(work with Felix Yu)*



# New gauge bosons

**Is $SU(3)_c \times SU(2)_W \times U(1)_Y$ embedded into a larger gauge group?**

## New gauge bosons

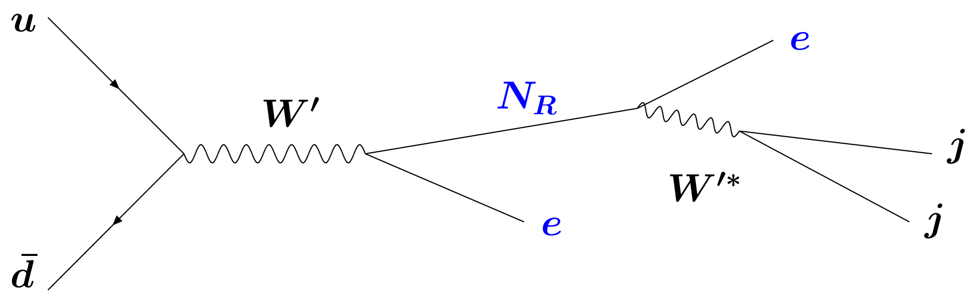
**Is $SU(3)_c \times SU(2)_W \times U(1)_Y$ embedded into a larger gauge group?**

| Fields | $SU(3)_c$ | $SU(2)_L$ | $SU(2)_R$ | $U(1)_{B-L}$ |
|---|---|---|---|---|
| $q_L = (u_L,\ d_L)^\top$ | 3 | 2 | 1 | $+1/3$ |
| $q_R = (u_R,\ d_R)^\top$ | 3 | 1 | 2 | $+1/3$ |
| $L_L = (\nu_L,\ \ell_L)^\top$ | 1 | 2 | 1 | $-1$ |
| $L_R = (N_R,\ \ell_R)^\top$ | 1 | 1 | 2 | $-1$ |

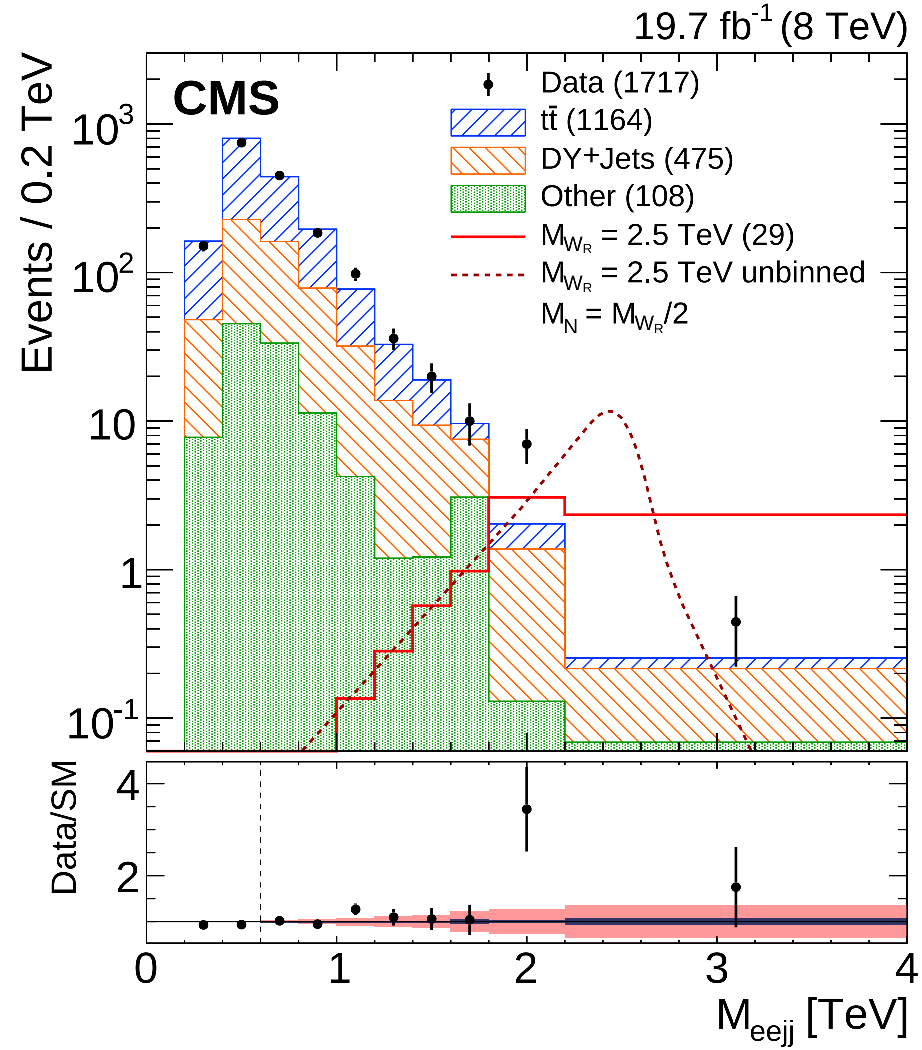
*Marshak, Mohapatra, 1980*

*Electroweak and flavor constraints push the masses of the $SU(2)_R$ gauge bosons above O(1) TeV, a region recently opened for exploration at the LHC.*

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




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




**CMS (1407.3683) – $eejj$ mass distribution:**

**$M_{eejj}$ = 1.8–2.2 TeV bin:**

**14 events observed**

**background = 4.3 events**

**$2.8\sigma$ excess**

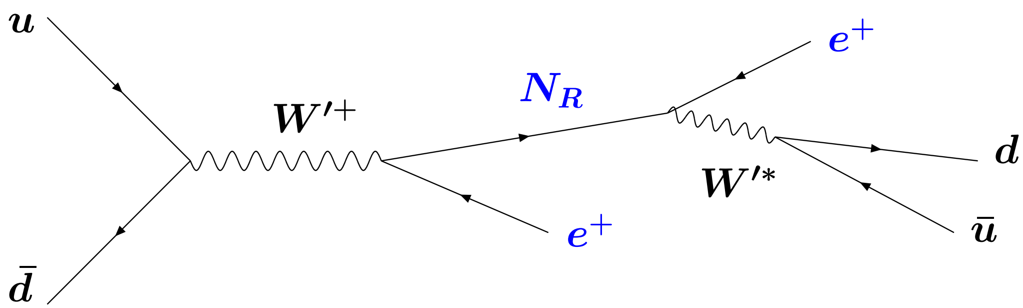
Classic prediction of Left-Right symmetric model:

*(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 $W' \to eN \to e^+e^-jj$ interpretation would require $N$ to have Dirac mass at the TeV scale.

**Could $N_R$ have a "left-handed" Dirac partner?**

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

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

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

*with Zhen Liu, 1507.01923 ;*

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

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

# Right-handed neutrino sector with a Dirac fermion

*with Pilar Coloma and Jacobo Lopez-Pavon 1508.04129*

**Assume a flavor structure for the Majorana masses:**

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

**right-handed neutrinos acquire masses:**

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

**Two right-handed neutrinos make a Dirac fermion $N_D$:**

$$N_R^\tau \equiv N_{D_L}^c \quad , \quad N_R^e \equiv N_{D_R}$$

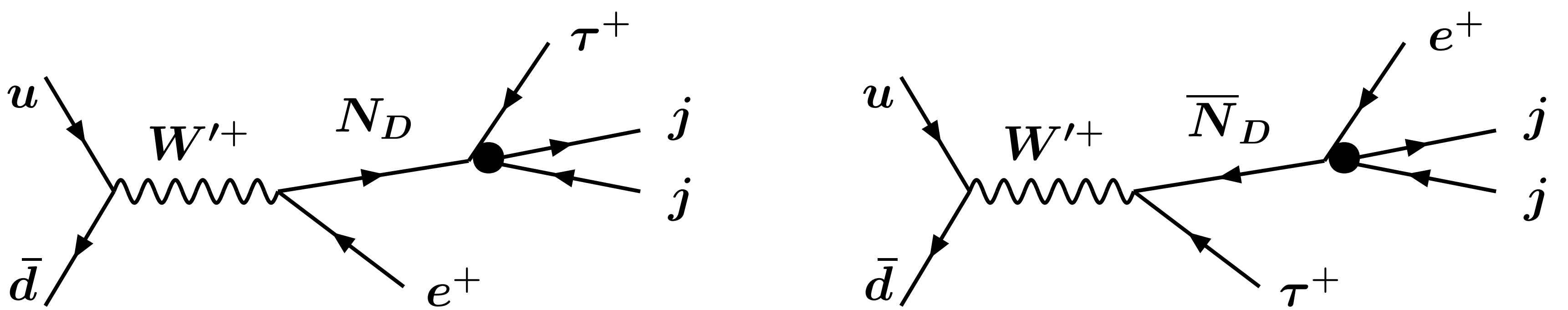
**Interactions of $N_D$ with $W'$:**

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

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

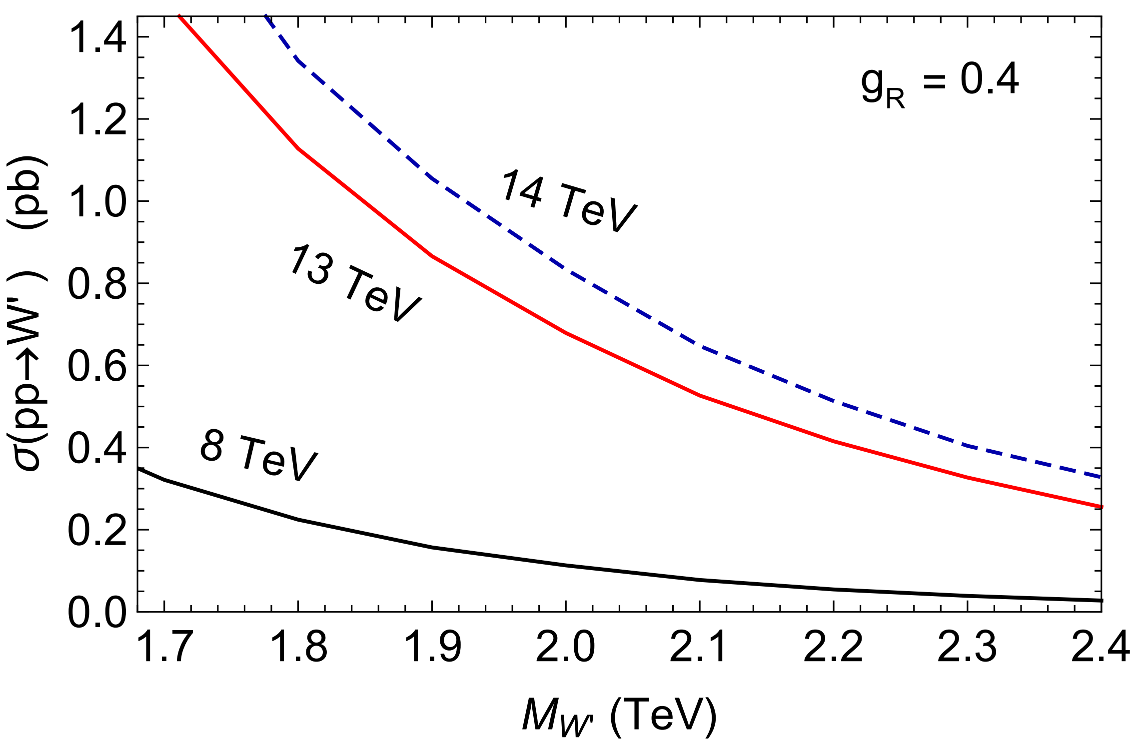
Implications for the LHC:

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



## $pp \to W'$ 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 more weakly coupled than $W$:*

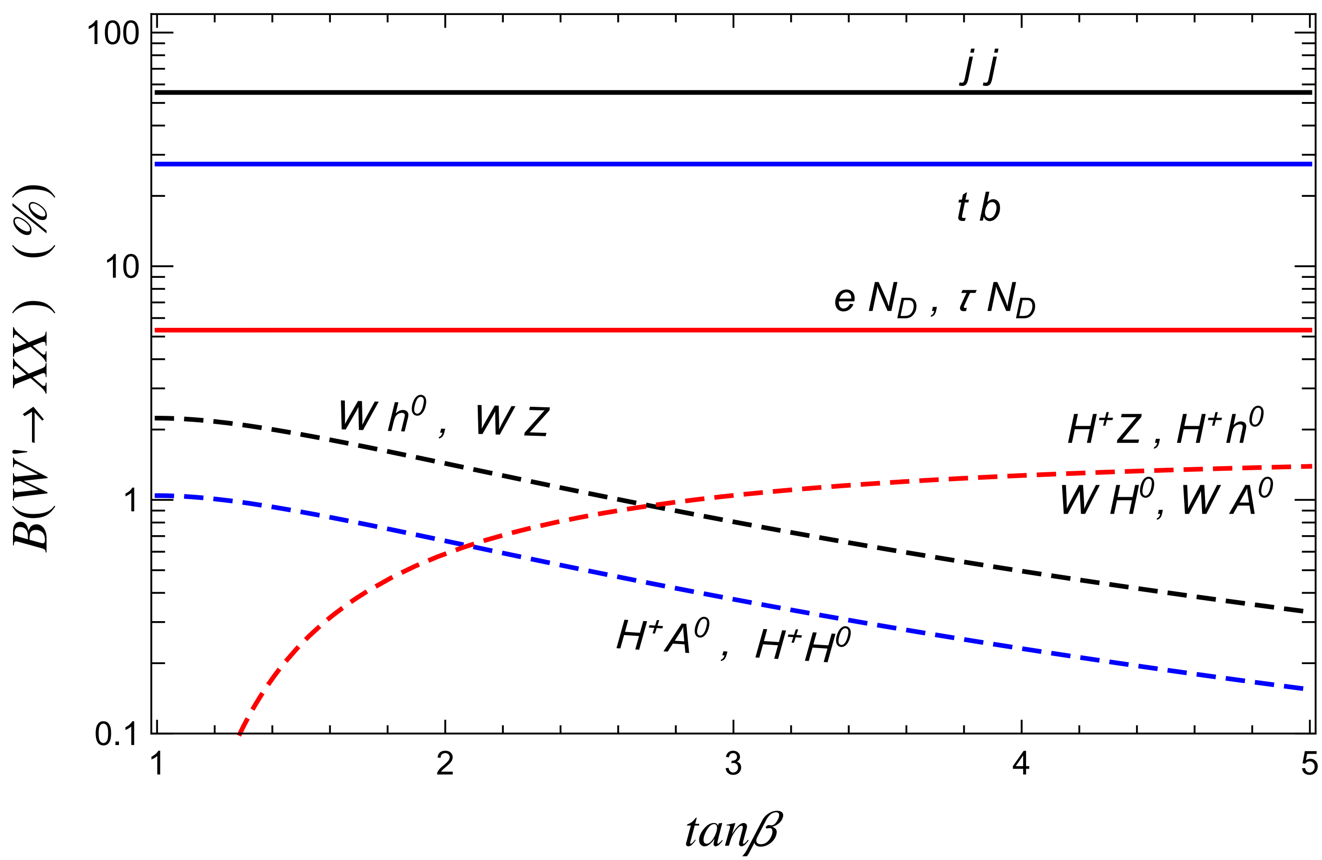
$$g_R < g \approx 0.63$$

# $W'$ widths and branching fractions

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

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

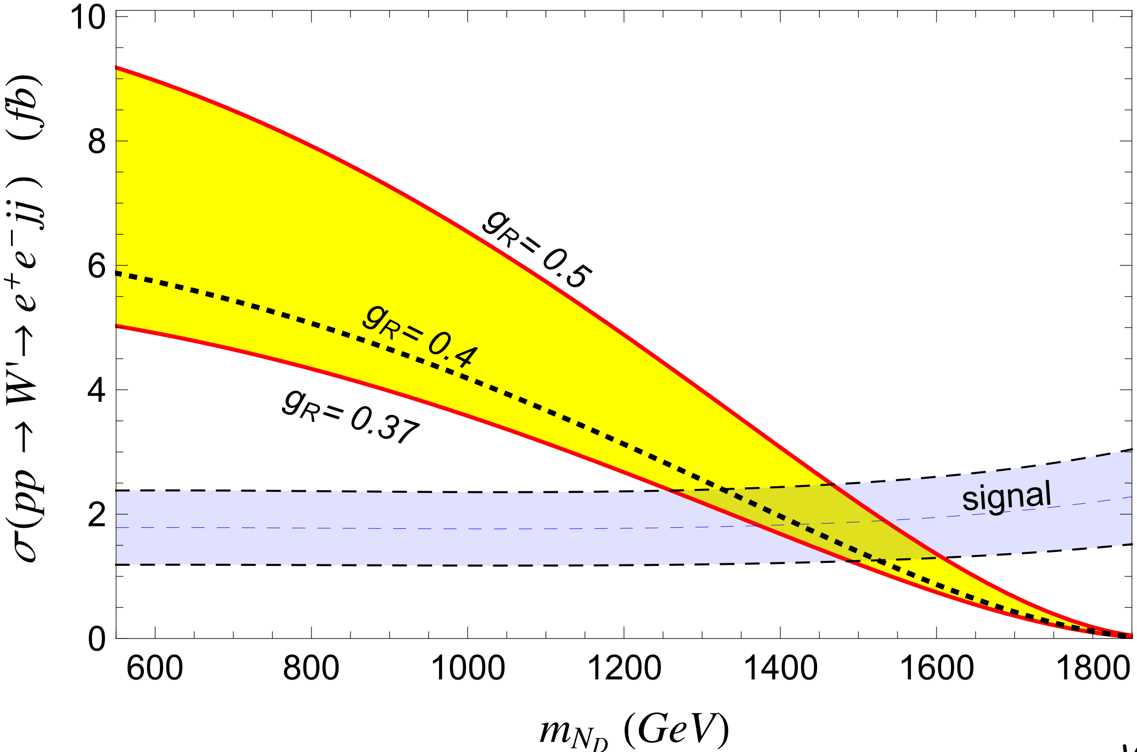
$$\Gamma(W' \to WZ) \simeq \Gamma(W' \to Wh^0) \simeq \frac{g_R^2}{192\pi} \sin^2 2\beta \, M_{W'}$$




$m_N = 1$ **TeV**

*Heavy Higgs bosons (part of the bidoublet),* $H^\pm, H^0, A^0$*, have approximately the same mass (assumed here at 600 GeV).*

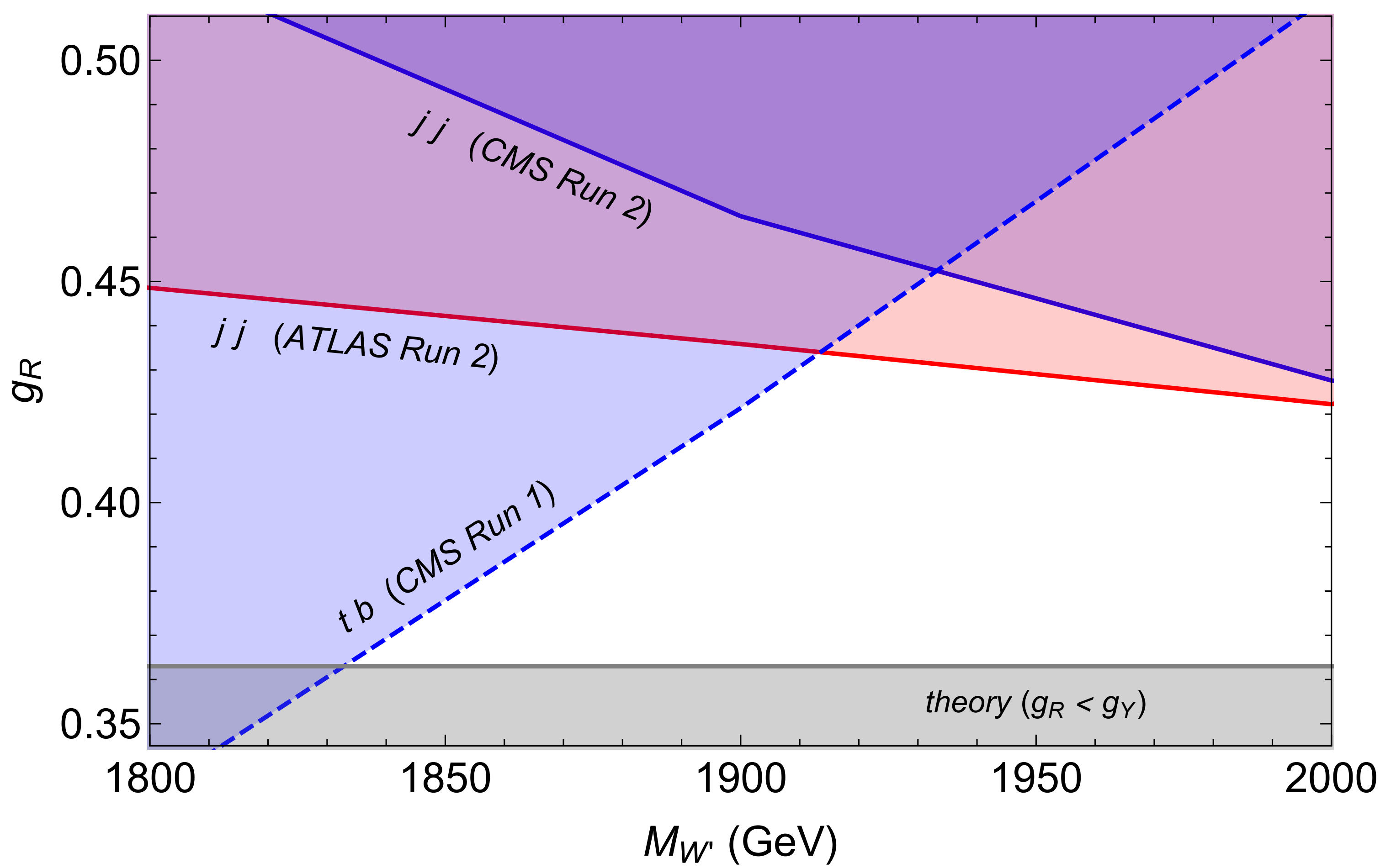
Comparison of the CMS $e^+e^-jj$ excess with the $W' \to eN_D \to e^+e^-jj$ rate allows a determination of $m_{N_D}$:




*with Patrick Fox, 1511.02148*

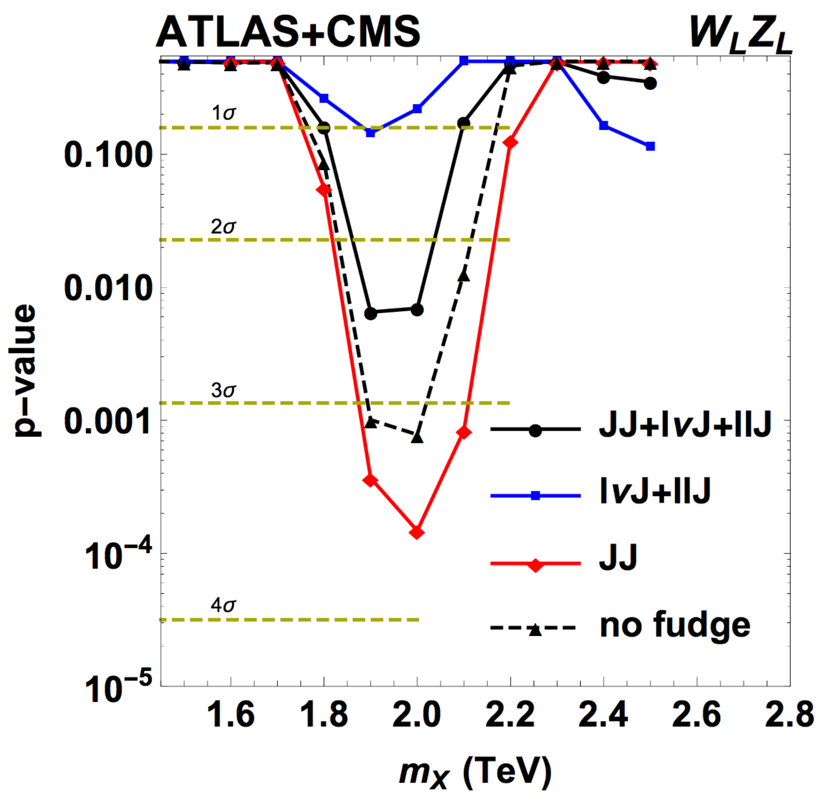
$\Rightarrow$ $m_{N_D} \approx 1.2$–$1.5$ TeV

**Constraints from $u\bar{d} \to W' \to jj$ and $t\bar{b}$ searches:**

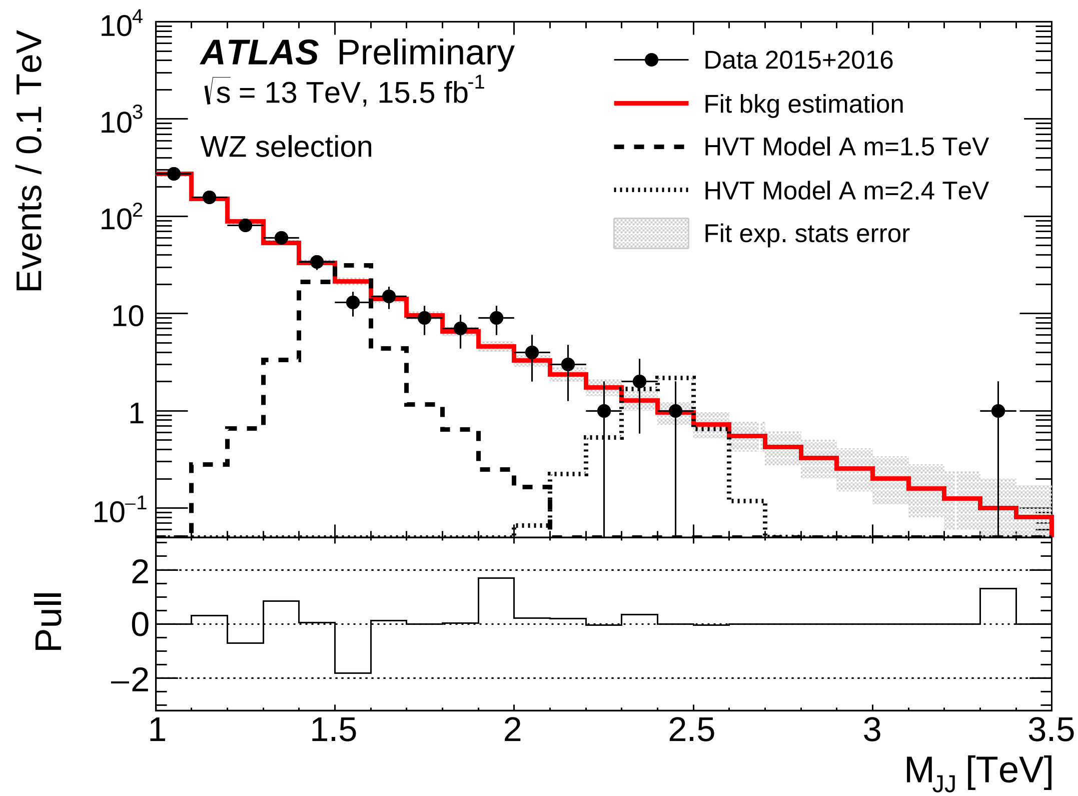


# $W' \to WZ$

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




Run 2: ATLAS-CONF-2016-055




$\sigma_8 \approx 5 \pm 2$ fb

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

# $W'$ decays into heavy Higgs bosons

*with Zhen Liu, 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 |
| $\mu^+e^+$ | 3 | 3 | 1439 | 239 |
| $\mu^-\mu^+\mu^-$ | 4 | 4 | 1072 | 176 |

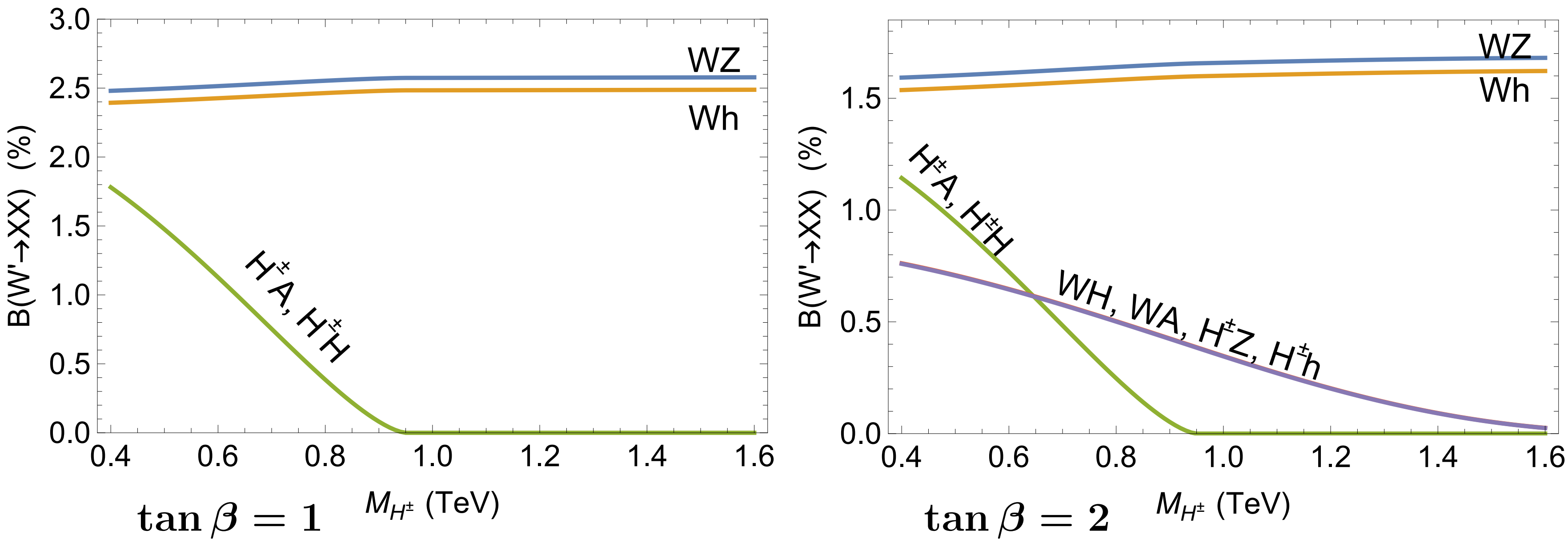
| Type | $N_j$ | $H_T$ [GeV] | $E_T^{miss}$ [GeV] |
|---|---|---|---|
| $e^-e^-$ | 3 | 807 | 171 |
| $e^+e^+$ | 5 | 862 | 268 |
| $e^+e^+$ | 5 | 868 | 113 |
| $\mu^-e^-$ | 6 | 1346 | 353 |
| $e^+\mu^+$ | 5 | 810 | 106 |
| $e^-\mu^-$ | 3 | 707 | 184 |
| $e^-\mu^-$ | 2 | 706 | 174 |
| $\mu^+e^+$ | 8 |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

**Excess explained for $M_{H^\pm} \approx M_{H^0} \approx M_{A^0} \approx 500$–$600$ GeV**

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

| Signal | channel | efficiency | signal events | | obs. (background) |
|---|---|---|---|---|---|
| $bb\ell^\pm\ell^\pm$ | $W' \to H^\pm(H^0/A^0) \to 3t+b$ | $2.5\times10^{-4}$ | 1.0-1.8 | 4-7 | 12 (4.3$\pm$1.1 $\pm$ 1.1) |
| | $W' \to (\tau/e)N \to (\tau/e)(\tau/e)tb$ | $5.3\times10^{-4}$ | 2.2-3.8 | | |
| | $pp \to t\bar{t}A^0, t\bar{t}H^0 \to 4t$ | $1.7\times10^{-2}$ | 1.1 | | |
| | | | | | |
| $\geq 3b\,\ell^\pm\ell^\pm$ | $W' \to H^\pm(H^0/A^0) \to 3t+b$ | $6.3\times10^{-4}$ | 2.5-4.4 | 5-7 | 6 (1.1$\pm$0.9 $\pm$ 0.4) |
| | $pp \to t\bar{t}A^0, t\bar{t}H^0 \to 4t$ | $4.1\times10^{-2}$ | 2.6 | | |

**Branching fractions for bosonic decays of $W'$:**



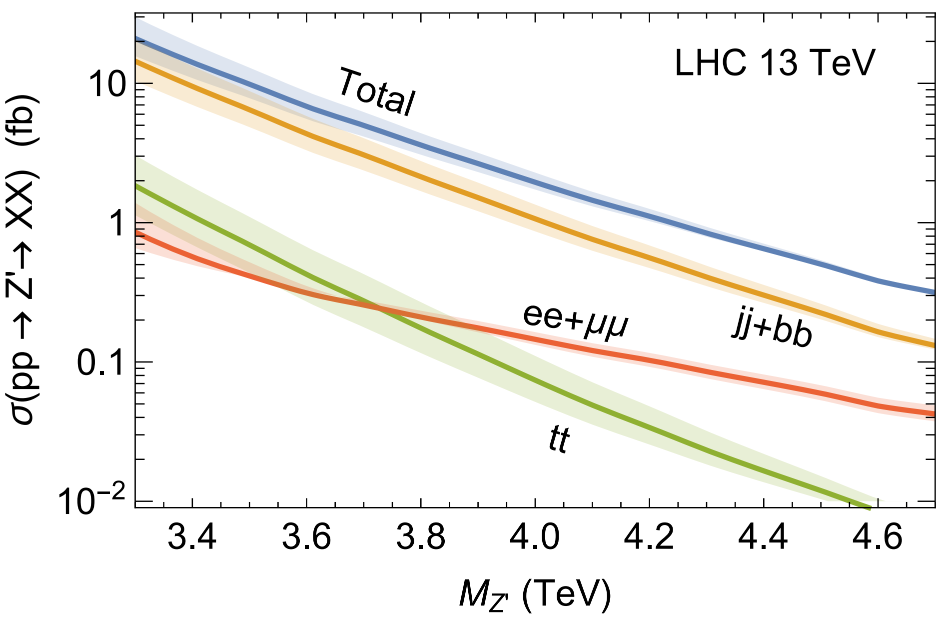
$Z'$ **couplings to quarks and leptons:**

$$\frac{1}{\sqrt{g_{\rm R}^2 + g_{B-L}^2}} \left( g_{\rm R}^2 T_R^3 - g_{B-L}^2 \frac{B-L}{2} \right)$$

**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*




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

# Cascade decays of a leptophobic $Z'$

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

**$Z'$ is associated with a new gauge symmetry.**

**Simple choice:** $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_B$

**$Z'_B$ is leptophobic, couples to quarks:**

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

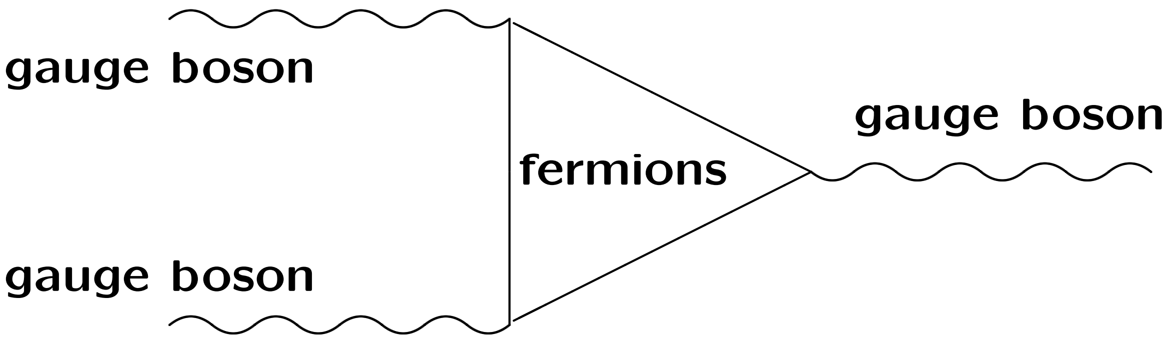
*Limits from $jj$ resonance searches on $g_B$, see 1306.2629 (with Felix Yu)*

# Gauge anomaly cancellation

*W. Bardeen, 1969, ...*

**Gauge symmetries may be broken by quantum effects.**

**Cure: sums over fermion triangle diagrams must vanish.**




*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.**

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

| field | spin | $SU(3)_c$ | $SU(2)_W$ | $U(1)_Y$ | $U(1)_B$ |
|---|---|---|---|---|---|
| $L_L$ <br> $L_R$ | 1/2 | 1 | 2 | $-1/2$ | $-1$ <br> $+2$ |
| $E_L$ <br> $E_R$ | 1/2 | 1 | 1 | $-1$ | $+2$ <br> $-1$ |
| $N_L$ <br> $N_R$ | 1/2 | 1 | 1 | 0 | $+2$ <br> $-1$ |
| $\phi$ | 0 | 1 | 1 | 0 | $+3$ |

There are two charged "anomalons", $E$ and $L^e$, which can mix, and two neutral anomalons, $N$ and $L^\nu$, which can also mix.

**Yukawa couplings of anomalons to $\phi$:**

$$-y_E\phi\overline{E}_L E_R - y_N\phi\overline{N}_L N_R - y_L\phi\overline{L}_R L_L$$

**Yukawa couplings of anomalons to the SM Higgs doublet:**

$$-y_{EL}\overline{E}_L\widetilde{H}L_R - y_{LE}e^{i\theta_E}\overline{L}_L H E_R - y_{NL}\overline{N}_L H L_R - y_{LN}e^{i\theta_N}\overline{L}_L\widetilde{H}N_R$$

$\widetilde{H} \equiv i\sigma_2 H^*$

The $y_{EL}$, $y_{LE}$, $y_{NL}$, $y_{LN}$ parameters can be chosen real.

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

Left-handed neutral anomalons in the mass eigenstate basis:

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

Right-handed ones:

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

Mass difference between the charged and neutral physical states that are mostly part of the weak-doublet anomalon:

$$m_{E_D} - m_{N_D} \simeq \left(y_{EL}^2 - y_{NL}^2\right)\frac{v_H^2}{2y_L\langle\phi\rangle} + \left[s_N^2\left(y_N^2 - y_L^2\right) - s_E^2\left(y_E^2 - y_L^2\right)\right]\frac{\langle\phi\rangle}{2y_L}$$

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 $N_S\, Z$.

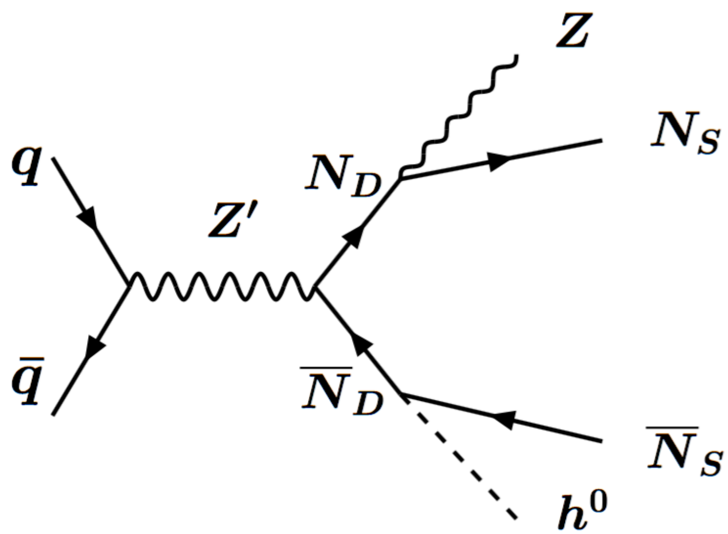
For $m_{N_D} - m_{N_S} \gg M_h$:

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

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

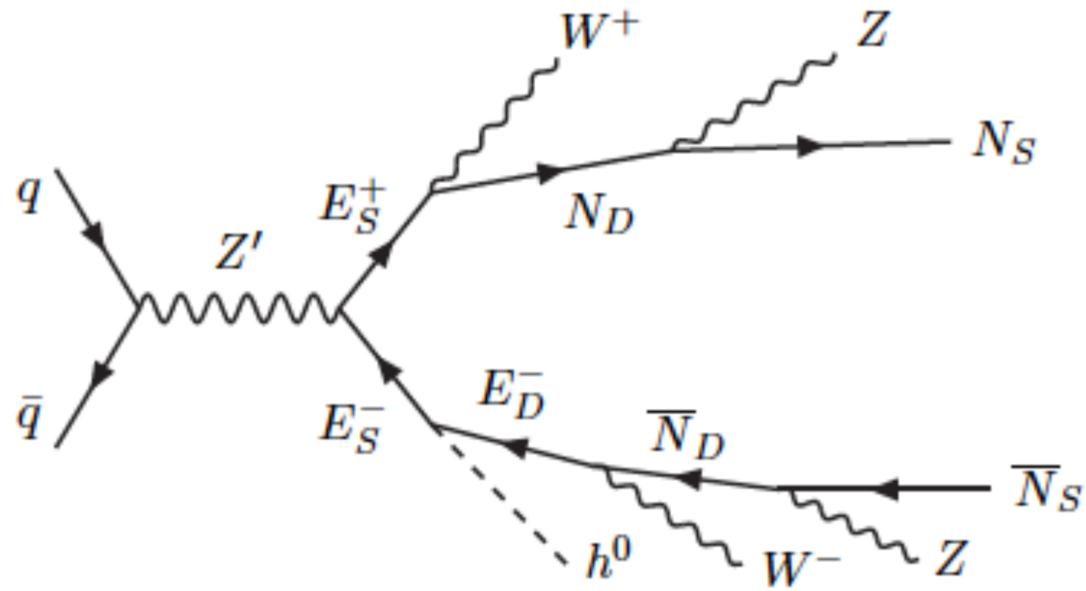
Cascade decays via anomalons:

(1506.04435)



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

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




Longer cascade decays:

$$Z' \to E_S^+ E_S^- \to E_D^+ E_D^- + 2(Z/h) \to N_D \bar{N}_D W W + 2(Z/h)$$

$$\to N_S \bar{N}_S W^+ W^- + 4(Z/h)$$

## Dark matter requires particle(s) beyond the SM

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

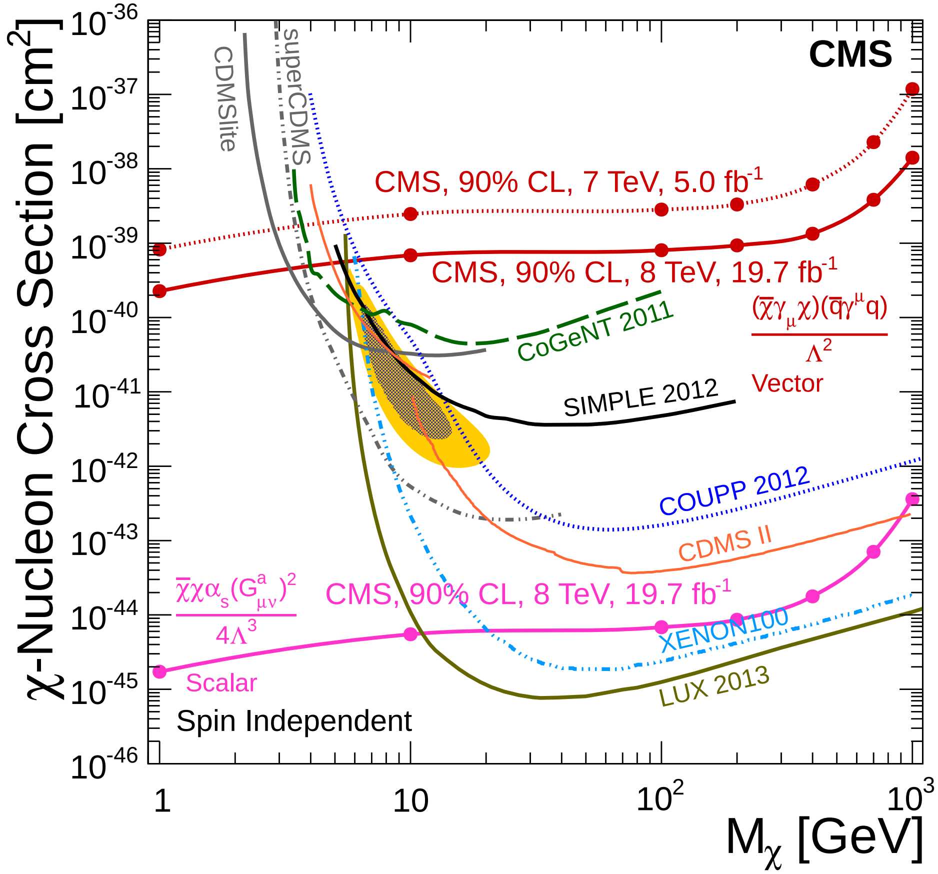
**DM particle(s) may be part of a large hidden sector.**

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

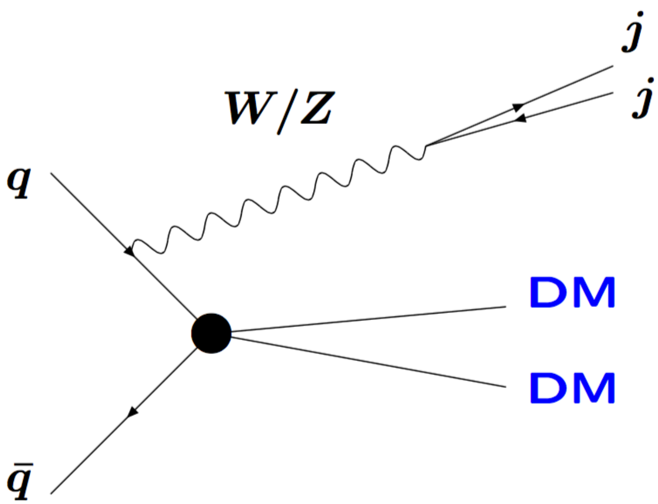
**Mono-jet signature of DM**

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

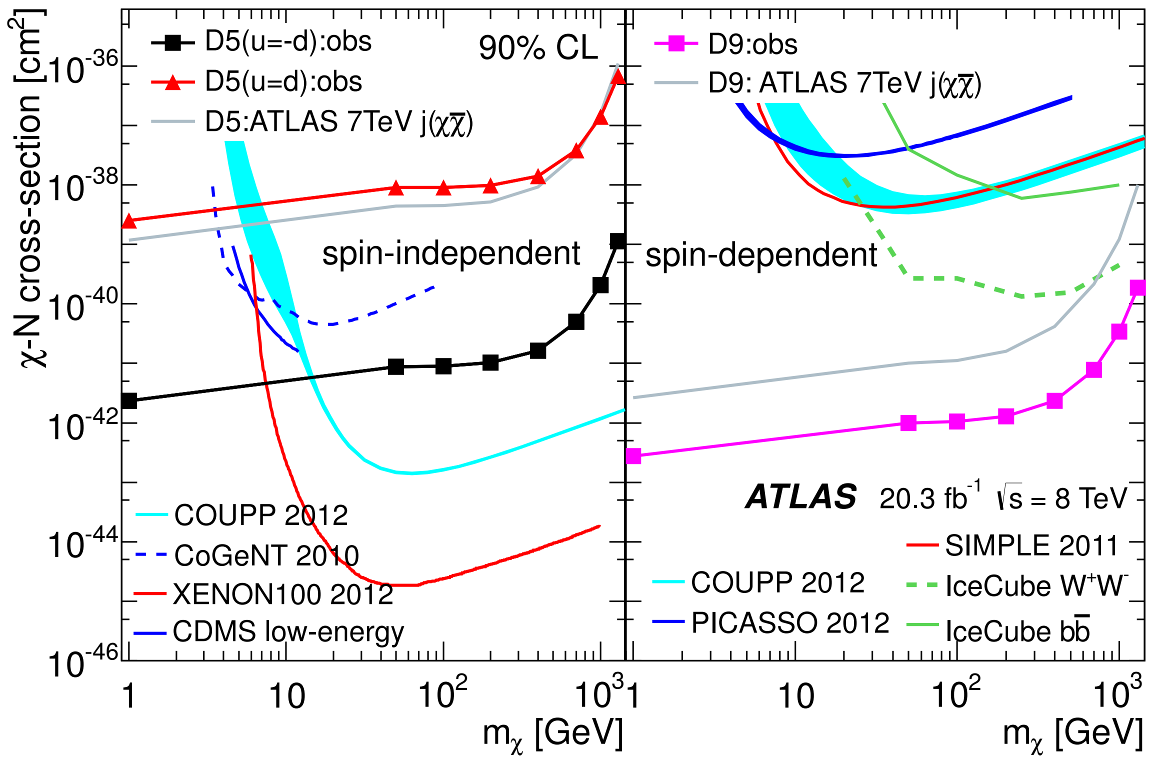
**CMS 1408.3583:**



# 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)*, ...

# 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, dark matter, ...

- An $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ gauge model with $U(1)$ lepton flavor symmetry allows $W' \rightarrow e^+e^-jj$ (consistent with CMS result at 2 TeV).

- $W' \rightarrow H^+A^0 \rightarrow 3t + W$ consistent with $\sim 3\sigma$ ATLAS excess in $\ell^\pm\ell^\pm + \geq 2b$.

- $Z'$ bosons may undergo cascade decays through anomalons, leading to final states with $W$, $Z$ and Higgs bosons.