The W’ solution

W’ to the rescue!

Avelino Vicente
IFIC – CSIC / U. Valencia

2nd LHCb open semitauonic workshop
Orsay
Outline

The facts

Anomalous $R(D)$ and $R(D^*)$

The $W'$ solution

Motivations for extended gauge sectors

An example model

Boucenna, Celis, Fuentes-Martin, AV, Virto

[ 1604.03088, 1608.01349 ]
The facts
The $b \to c$ anomalies
The $b \rightarrow c$ anomalies

**New LHCb results**
Talk by Marianna Fontana: September 13th

LHCb-PAPER-2017-035

\[
R(J/\psi) = \frac{BR(B_c^+ \rightarrow J/\psi \tau^+\nu)}{BR(B_c^+ \rightarrow J/\psi \mu^+\nu)}
\]

Signal reconstructed with tau leptonic decays and Run 1 data \((3\text{fb}^{-1})\)

\[R(J/\psi)_{\text{exp}} = 0.71 \pm 0.17 \pm 0.18\]

Compatible with $R(D)$ & $R(D^*)$

[1709.08644, 1710.04127]

Important:
again exp > SM
Some interesting facts

Current data are compatible with universal scaling in $R(D)$ and $R(D^*)$

$$\frac{R(D)_{\text{exp}}}{R(D)_{\text{SM}}} = \frac{R(D^*)_{\text{exp}}}{R(D^*)_{\text{SM}}}$$

The $q^2$ differential distributions are SM-like [BaBar & Belle]

The $\tau$ polarization in $B \rightarrow D^* \tau \nu$ is compatible with the SM [Belle]

Important messages for model builders
The W’ solution

W’ to the rescue!
Why the W’ solution?

Theoretical reasons

Extended gauge sectors can help understanding the nature of EW symmetry breaking: Left-Right, 331, ...

Experimental reasons

A W' with couplings to fermions similar to those of the SM W would scale up the decay rates but leave other observables unaffected: exactly as observed!

A W' always comes with a Z’. Perhaps this boson can address other anomalies in B-meson decays?
The $b \rightarrow s$ anomalies

![Graphs showing $B^+ \rightarrow K^+\mu^+\mu^-$ and $R_K$ versus $q^2$]
Killing two birds with one stone

\( R_{K,K^*} \) \( \leftrightarrow \) A common NP framework \( \leftrightarrow \) \( R(D^{(*)}) \)

Chuck Norris fact of the day

*Chuck Norris can kill two stones with one bird*
Warning

Of course, the $W'$ candidate has to respect a long list of experimental constraints...

Other flavor observables: $B \to K^{(*)}\bar{\nu}\nu$, $b \to s\gamma$, ...

Direct LHC searches: tension with $R(D^{(*)})$

Lepton universality tests: $Z \to \ell\ell$, ...

Precision EW data

... and it may well be that it does not work after all!
An example model

Boucenna, Celis, Fuentes-Martin, AV, Virto

Simplest $Z'$-$W'$ explanation of the anomalies

**Ingredients:**

- Add an extra $SU(2)$ factor to the SM gauge group
- Null or negligible couplings to electrons, as suggested by data
- Couplings to left-handed fermions, as suggested by $b \rightarrow s$ and $R(D^{(*)})$ apparent universal scaling

It looks easy, right?
The model

Particle content

- Two scalar doublets: $\phi = (1, 2)_{1/2}$, $\phi' = (2, 1)_{1/2}$
- A bidoublet: $\Phi = (2, 2)_0$
- SM fermions (f): charged universally under SU(2)$_2$
- VL fermions (F): charged universally under SU(2)$_1$

$SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y$

$\langle \Phi \rangle \sim u \gg v \quad M_{Z'}, M_{W'} \sim O(u)$

$SU(2)_L \otimes U(1)_Y$

$\langle \phi \rangle, \langle \phi' \rangle \sim v \quad M_Z, M_W \sim O(v)$

$U(1)_{em}$

$\mathcal{L}_{mix} = \lambda^\dagger \overline{F}_R \Phi f_L$
The issue of gauge mixing

For unsuppressed $\xi$, gauge mixing effects are potentially of the same size as $Z'$, $W'$ tree-level exchange (for certain observables)

$$Z', W' \text{ tree-level: } \sim \frac{1}{M^2_{W'}} \quad Z, W \text{ tree-level + GM: } \sim \frac{1}{M^2_W} \frac{v^2}{u^2} \sim \frac{1}{M^2_{W'}}$$

$\Rightarrow$ Potential to spoil the desired couplings
(Anomalous couplings to electrons, corrections to $C_9^{NP} = - C_{10}^{NP}$, ...)

$\Rightarrow$ Constrained by LEP at the per-mil level (Z- and W-pole observables)

Solution: A second Higgs doublet $\phi' = (2, 1)_{1/2}$
Our global fit


- Bounds from Z and W pole observables  [Efrati et al, 2015]

- Tests of lepton universality violation in tree-level charged current processes: \(\ell \rightarrow \ell' \nu \bar{\nu}, \pi/K \rightarrow \ell \nu, \tau \rightarrow \pi/K \nu, K^+ \rightarrow \pi \ell \nu, D \rightarrow K \ell \nu, D_s \rightarrow \ell \nu, B \rightarrow D^{(*)} \ell \nu\) and \(B \rightarrow X_c \ell \nu\)

- \(|\Delta F| = 1,2\) transitions in the \(b \rightarrow s\) sector receiving NP contributions at tree-level

- Bounds from the leptonic flavor-violating decays \(\tau \rightarrow 3 \mu\) and \(Z \rightarrow \tau \mu\)

- CKM inputs from a fit by the CKMfitter group with only tree-level processes
Gauging the anomalies away

The model gives a good fit to data

Global fit
- EW precision data
- Flavor data

Gauge-mixing must be suppressed.
Otherwise $R(D^*)$ cannot be explained
More on gauge mixing

Explaining the $R(D^*)$ best-fit requires a tiny GM parameter (otherwise too large NP contribution in other charged current processes)

$R_K$ not very sensitive to GM effects (the required $Z$ coupling is loop suppressed in the SM)
Predictions

(1) Additional $b \to c$ observables

NP contributions have the same Dirac structure as the SM ones

$$\frac{R(D)}{R(D)_{\text{SM}}} = \frac{R(D^*)}{R(D^*)_{\text{SM}}} = \ldots$$

$\implies$ Enhancement in the $R(X_c)$ inclusive ratio

$\implies$ Global rescaling in the $B \to D^{(*)} \tau \nu$ decay rate. Differential distributions are SM-like.

(2) Other $R_M$ observables

$R_K$, $R_{K^*}$ and $R_\Phi$ are strongly correlated

$$\implies R_{K^*} \sim R_K < 1$$ (for example)
(3) Lepton flavor violation

Z’ tree-level exchange can lead to observables LFV effects

\[ \text{BR}(\tau \rightarrow 3\mu) \text{ can be close to the experimental bound} \]

(4) LHC direct searches

The Z’ boson will be produced at the LHC via Drell-Yan processes due to its couplings to the 2\textsuperscript{nd} and 3\textsuperscript{rd} generation quarks

\[ \text{The usual limits (1\textsuperscript{st} generation couplings) do not apply} \]

\[ \text{Nevertheless: the LHC is sensitive} \]

\[ \text{ATLAS search for a narrow } \tau^+ \tau^- \text{ resonance excludes the light Z’ region } (M_{Z’} < 1 \text{ TeV}). \text{ Some tension for } M_{Z’} \sim 1 \text{ TeV unless the Z’ is broad} \text{ [Greljo et al, 1609.07138, 1704.09015]} \]

[tension in almost all models for } b \rightarrow c \text{ anomalies]
Summary
The $R(D)$ and $R(D^*)$ anomalies constitute an intriguing set of hints for New Physics

A heavy $W'$ boson is a theoretically well-motivated candidate to address these anomalies... and it automatically explains some of the experimental features!

Building specific UV models is crucial: one may find unexpected difficulties, features and predictions
Summary

Merci de votre attention!
Backup slides
The $b \rightarrow c$ anomalies

- **BaBar had. tag**
  - $0.440 \pm 0.058 \pm 0.042$

- **Belle had. tag**
  - $0.375 \pm 0.064 \pm 0.026$

- **Average**
  - $0.407 \pm 0.039 \pm 0.024$

- **FNAL/MILC (2015)**
  - $0.299 \pm 0.011$

- **HPQCD (2015)**
  - $0.300 \pm 0.008$

- **Belle (hadronic tau)**
  - $0.270 \pm 0.035 \pm 0.027$

- **LHCb**
  - $0.336 \pm 0.027 \pm 0.030$

- **LHCb (hadronic tau)**
  - $0.285 \pm 0.019 \pm 0.029$

- **Average**
  - $0.304 \pm 0.013 \pm 0.007$

- **S. Fajfer et al. (2012)**
  - $0.252 \pm 0.003$

---

Orsay, 14/11/17  
Avelino Vicente - The W' solution
Model classification

Breaking pattern

L-BP:

\[
SU(2)_L \otimes SU(2)_H \otimes U(1)_H
\]
\[
\downarrow
\]
\[
SU(2)_L \otimes U(1)_Y
\]

Y-BP:

\[
SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y
\]
\[
\downarrow
\]
\[
SU(2)_L \otimes U(1)_Y
\]

Source of non-universality

\textbf{g-NU}: Non-universal gauge couplings

\textbf{y-NU}: Through non-universal mixings with other fermions

<table>
<thead>
<tr>
<th></th>
<th>L-BP</th>
<th>Y-BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>g-NU</td>
<td>\xmark No left-handed currents</td>
<td>\xmark Perturbativity</td>
</tr>
<tr>
<td>y-NU</td>
<td>\xmark No GIM</td>
<td>\checkmark</td>
</tr>
</tbody>
</table>
### The model

<table>
<thead>
<tr>
<th>generations</th>
<th>$\text{SU}(3)_C$</th>
<th>$\text{SU}(2)_1$</th>
<th>$\text{SU}(2)_2$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\phi'$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$q_L$</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$u_R$</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$d_R$</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\ell_L$</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$e_R$</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$Q_{L,R}$</td>
<td>$n_{VL}$</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$L_{L,R}$</td>
<td>$n_{VL}$</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
The model

Fermion representations

\[ q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L = (3, 1, 2)_{\frac{1}{6}} \quad \ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L = (1, 1, 2)_{-\frac{1}{2}} \]

\[ Q_{L,R} = \begin{pmatrix} U \\ D \end{pmatrix}_{L,R} = (3, 2, 1)_{\frac{1}{6}} \quad L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} = (1, 2, 1)_{-\frac{1}{2}} \]

Scalar representations

\[ \phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi^0 & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \quad \phi' = \begin{pmatrix} \varphi'^+ \\ \varphi'^0 \end{pmatrix} \]

self-dual bidoublet: \( \Phi = \tilde{\Phi} = \sigma_2 \Phi^* \sigma_2 \)

\( \bar{\Phi}^0 = (\Phi^0)^* \quad \Phi^- = (\Phi^+)^* \)
The model

Standard Yukawa terms

\[-\mathcal{L}_\phi = \overline{q_L} y^d \phi d_R + \overline{q_L} y^u \tilde{\phi} u_R + \overline{\ell_L} y^e \phi e_R + \text{h.c.}\]

VL mass terms

\[-\mathcal{L}_M = \overline{Q_L} M_Q Q_R + \overline{L_L} M_L L_R + \text{h.c.}\]

\(M_Q, M_L : n_{\text{VL}} \times n_{\text{VL}} \text{ matrices}\)

VL-SM Yukawa terms

\[-\mathcal{L}_\Phi = \overline{Q_R} \lambda^q \Phi q_L + \overline{L_R} \lambda^\ell \Phi \ell_L + \text{h.c.}\]

\(\lambda_q, \lambda_\ell : 3 \times n_{\text{VL}} \text{ matrices}\)

\[-\mathcal{L}_{\phi'} = \overline{Q_L} \tilde{y}^d \phi' d_R + \overline{Q_L} \tilde{y}^u \tilde{\phi}' u_R + \overline{L_L} \tilde{y}^e \phi' e_R + \text{h.c.}\]
The model

Scalar potential and symmetry breaking

\[ V = m_\phi^2 |\phi|^2 + \frac{\lambda_1}{2} |\phi|^4 + m_{\phi'}^2 |\phi'|^2 + \frac{\lambda_2}{2} |\phi'|^4 + m_\Phi \text{Tr}(\Phi^\dagger \Phi) + \frac{\lambda_3}{2} [\text{Tr}(\Phi^\dagger \Phi)]^2 \\
+ \lambda_4 (\phi^\dagger \phi)(\phi'^\dagger \phi') + \lambda_5 (\phi^\dagger \phi)\text{Tr}(\Phi^\dagger \Phi) + \lambda_6 (\phi'^\dagger \phi')\text{Tr}(\Phi^\dagger \Phi) + (\mu \phi'^\dagger \Phi \phi + \text{h.c.}) \]

\[ \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\phi \end{pmatrix} \quad \langle \phi' \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{\phi'} \end{pmatrix} \quad \langle \Phi \rangle = \frac{1}{2} \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} \]

\[ \text{SU}(2)_1 \times \text{SU}(2)_2 \times \text{U}(1)_Y \xrightarrow{u} \text{SU}(2)_L \times \text{U}(1)_Y \xrightarrow{v} \text{U}(1)_{\text{em}} \]

\[ v_\phi = v \sin \beta \quad u \sim \text{TeV} \gg v \simeq 246 \text{ GeV} \]

Doublets

\[ v_{\phi'} = v \cos \beta \]

VEVs

\[ v^2 = v_\phi^2 + v_{\phi'}^2 \]

\[ Q = (T_3^1 + T_3^2) + Y = T_3^L + Y \]
The model

Particle spectrum I: Scalars

\[ \{\phi, \Phi, \phi'\} \quad \rightarrow \quad \text{W, Z, W', Z'} \]
\[ \quad \text{long. components} \]
\[ \quad \text{6 d.o.f.} \]
\[ + \quad 3 \quad \text{CP-even} \]
\[ + \quad 1 \quad \text{CP-odd} \]
\[ + \quad 1 \quad \text{Charged} \]
\[ \text{2 d.o.f.} \]

[ constrained 2HDM + CP-even singlet scenario ]

Particle spectrum II: Fermions

\[ F_{L,R}^I \equiv (f_{L,R}^i, F_{L,R}^k) \]
\[ i = 1, 2, 3 \]
\[ k = 1, \ldots, n_{\text{VL}} \]
\[ I = 1, \ldots, 3 + n_{\text{VL}} \]

\[ \mathcal{M}_F = \begin{pmatrix} \frac{1}{\sqrt{2}} y_f v_\phi & \frac{1}{2} \lambda_f u \\ \frac{1}{\sqrt{2}} \tilde{y}_f v_{\phi'} & M_F \end{pmatrix} \]

SM-VL mixing induced by \( \lambda_f \)
The model

Particle spectrum III: Gauge bosons

Neutral gauge bosons

\[ \mathcal{V}^0 = (W^1_3, W^2_3, B) \]

\[
\mathcal{M}^2_{\mathcal{V}_0} = \frac{1}{4} \begin{pmatrix}
  g_1^2 \left( v^2_{\phi'} + u^2 \right) & -g_1 g_2 u^2 & -g_1 g' v^2_{\phi'} \\
  -g_1 g_2 u^2 & g_2^2 \left( v^2_{\phi} + u^2 \right) & -g_2 g' v^2_{\phi} \\
  -g_1 g' v^2_{\phi'} & -g_2 g' v^2_{\phi} & g'^2 \left( v^2_{\phi} + v^2_{\phi'} \right)
\end{pmatrix}
\]

controlled by \( \zeta = s^2_\beta - \frac{g_1^2}{g_2^2} c^2_\beta \)

vanishes for \( \tan \beta = g_1 / g_2 \)

gauge mixing
The model

Particle spectrum III: Gauge bosons

Charged gauge bosons

\[ \mathcal{V}^+ = (W^1_{12}, W^2_{12}) \]
\[ W^r_{12} = \frac{1}{\sqrt{2}} (W^r_1 - iW^r_2) \]

\[ \mathcal{M}_{\mathcal{V}^+}^2 = \frac{1}{4} \begin{pmatrix} g_1^2 (v_{\phi'}^2 + u^2) & -g_1 g_2 u^2 \\ -g_1 g_2 u^2 & g_2^2 (v_{\phi}^2 + u^2) \end{pmatrix} \]

controlled by \( \zeta = s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2 \)

vanishes for \( \tan \beta = g_1/g_2 \)

\[ \hat{\mathcal{V}}^+ = (W_h, W_l) \]

\[ \mathcal{M}_{\hat{\mathcal{V}}^+}^2 = \frac{1}{4} \begin{pmatrix} (g_1^2 + g_2^2) u^2 + \frac{g_1^2 g_2^2}{g_1^2} v^2 (s_\beta^2 + \frac{g_1^4}{g_2^2} c_\beta^2) & -g_2^2 g_1 v^2 (s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2) \\ -g_2^2 g_1 v^2 (s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2) & g^2 v^2 \end{pmatrix} \]
The model

Z' and W' couplings to light fermions

\[ \mathcal{L}_{NC} \supset \frac{\hat{g}}{2} Z_h^\mu \left[ \overline{d_L} \gamma_\mu \Delta^q d_L + \overline{e_L} \gamma_\mu \Delta^\ell e_L \right] \]

\[ \mathcal{L}_{CC} \supset -\frac{\hat{g}}{\sqrt{2}} W_h^\mu \left[ \overline{u_L} \gamma_\mu V_{CKM} \Delta^q d_L + \overline{\nu_L} \gamma_\mu \Delta^\ell e_L \right] + \text{h.c.} \]

\[ \hat{g} \equiv g \frac{g_2}{g_1} \]

\[ n_{VL} = 2 \]

\[ \Delta^q,\ell = \mathbb{I} - \frac{g_1^2 + g_2^2}{4g_2^2} \lambda_{q,\ell} \tilde{M}^{-2} \lambda_{q,\ell}^\dagger \]

universal \hspace{1cm} \text{non-universal due to SM-VL mixing}

\[ \lambda_{q,\ell} = \frac{2g_2}{\sqrt{g_1^2 + g_2^2}} \begin{pmatrix} \tilde{M}_{Q_1,L_1} & 0 \\ 0 & \tilde{M}_{Q_2,L_2} \Delta_{s,\mu} \\ 0 & \tilde{M}_{Q_2,L_2} \Delta_{b,\tau} \end{pmatrix} \]

\[ \Delta^q,\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 - (\Delta_{s,\mu})^2 & \Delta_{s,\mu} \Delta_{b,\tau} \\ 0 & \Delta_{s,\mu} \Delta_{b,\tau} & 1 - (\Delta_{b,\tau})^2 \end{pmatrix} \]

\[ u\tilde{M} : \text{physical VL mass} \]
The model

**Z’ and W’ couplings to fermions**

\[
\Delta_{q,\ell} = \mathbb{I} - \frac{g_1^2 + g_2^2}{4g_2^2} \lambda_{q,\ell} \tilde{M}^{-2} \lambda_{q,\ell}^\dagger
\]

\[
\lambda_{q,\ell} = \frac{2g_2}{\sqrt{g_1^2 + g_2^2}} \tilde{M}_{Q,L} \begin{pmatrix} \Delta_{d,e} \\ \Delta_{s,\mu} \\ \Delta_{b,\tau} \end{pmatrix}
\]

\[
\Delta_{q,\ell} = \begin{pmatrix}
1 - (\Delta_{d,e})^2 & \Delta_{d,e} \Delta_{s,\mu} & \Delta_{d,e} \Delta_{b,\tau} \\
\Delta_{d,e} \Delta_{s,\mu} & 1 - (\Delta_{s,\mu})^2 & \Delta_{s,\mu} \Delta_{b,\tau} \\
\Delta_{d,e} \Delta_{b,\tau} & \Delta_{s,\mu} \Delta_{b,\tau} & 1 - (\Delta_{b,\tau})^2
\end{pmatrix}
\]

\[
\lambda_{q,\ell} = \frac{2g_2}{\sqrt{g_1^2 + g_2^2}} \begin{pmatrix}
\tilde{M}_{Q_1,L_1} & 0 & 0 \\
0 & \tilde{M}_{Q_2,L_2} & \Delta_{s,\mu} \\
0 & 0 & \tilde{M}_{Q_2,L_2} \Delta_{b,\tau}
\end{pmatrix}
\]

**n_{VL} = 1**

Does not work!

**n_{VL} = 2**

It works!
Our global fit


Free parameters: \[ \{ M_{Z'}, g_2, \Delta_s, \Delta_b, \Delta_\mu, \Delta_\tau, \zeta \} + \{ \lambda, A, \rho, \eta \} \]

Global \( \chi^2 \) function

Best-fit point:

\[ \{ M_{Z'}, [\text{GeV}], g_2, \Delta_s, \Delta_b, |\Delta_\mu|, |\Delta_\tau|, \zeta \} = \{1436, 1.04, -1.14, 0.016, 0.39, 0.075, 0.14\} \]

\[ \chi^2_{\text{min}} = 54.8 \quad \text{to be compared with} \quad \chi^2_{\text{SM}} = 93.7 \]

In the parameter space region where \( R_K \) and \( R(D^{(*)}) \) are accommodated within 2σ, the \( Z' \) and \( W' \) bosons couple predominantly to the third fermion generation.
Other observables

Explaining the $R(D^*)$ best-fit would induce a slight tension with the $R(X_c)$ experimental measurement.
Charged Higgs and $R(D^{(*)})$

- **Natural candidate** for the $b \to c$ anomalies: a charged Higgs
- But the “standard” 2HDMs do not work [Celis et al, 2012]

**Type II 2HDM**

![Graph showing $R(D)$ and $R(D^*)$ vs. $\tan \beta / m_{H^+}$](image1)

- [BaBar collaboration, 2012]

**Aligned 2HDM**

![Graph showing $\text{Re}(\zeta, \zeta')/M_3$ and $\text{Im}(\zeta, \zeta')/M_3$](image2)

- [Celis et al, 2012]

**However**: a general Type III 2HDM can do the job [Crivellin et al, 2012]