The W’ solution

W’ to the rescue!

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2nd LHCb open semitauonic workshop
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Outline

The facts

Anomalous R(D) and R(D*)

The W' solution

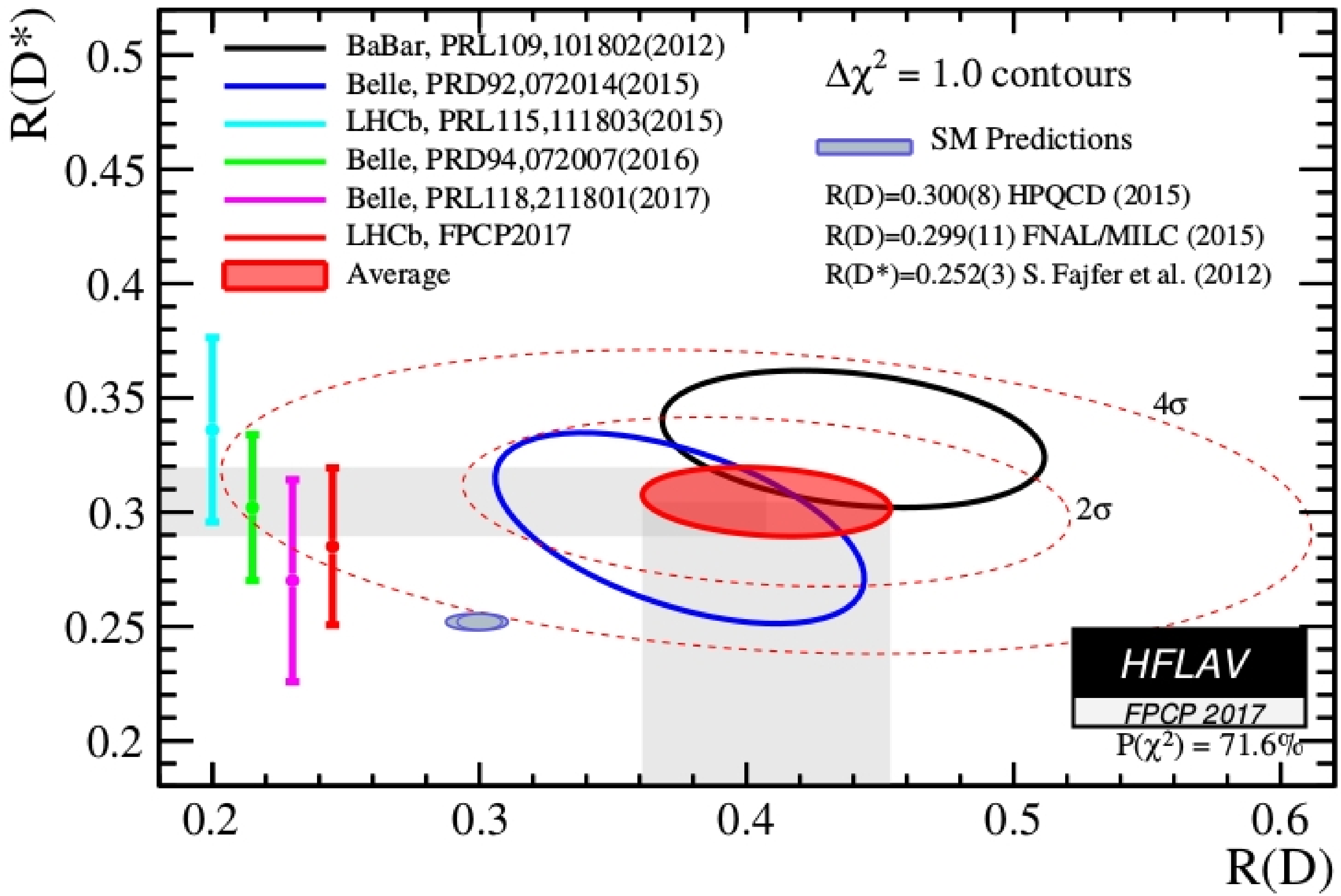
Motivations for extended gauge sectors

An example model

Boucenna, Celis, Fuentes-Martin, AV, Virto
[1604.03088, 1608.01349]

The facts

The $b \to c$ anomalies



The $b \to c$ anomalies

New LHCb results

Talk by Marianna Fontana: September 13th

LHCb-PAPER-2017-035

$$R\,(J/\psi) = \frac{\mathrm{BR}(B_c^+ \to J/\psi\,\tau^+\nu)}{\mathrm{BR}(B_c^+ \to J/\psi\,\mu^+\nu)}$$

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

$\sim 2\sigma$ deviation

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

[1709.08644, 1710.04127]

$$\begin{cases} R\,(J/\psi)_{\mathrm{exp}} = 0.71 \pm 0.17 \pm 0.18 \\ R\,(J/\psi)_{\mathrm{SM}} \sim 0.29 \end{cases}$$

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

Important messages for model buiders

The W’ solution

W’ to the rescue!

Why the W’ solution?

Theoretical reasons

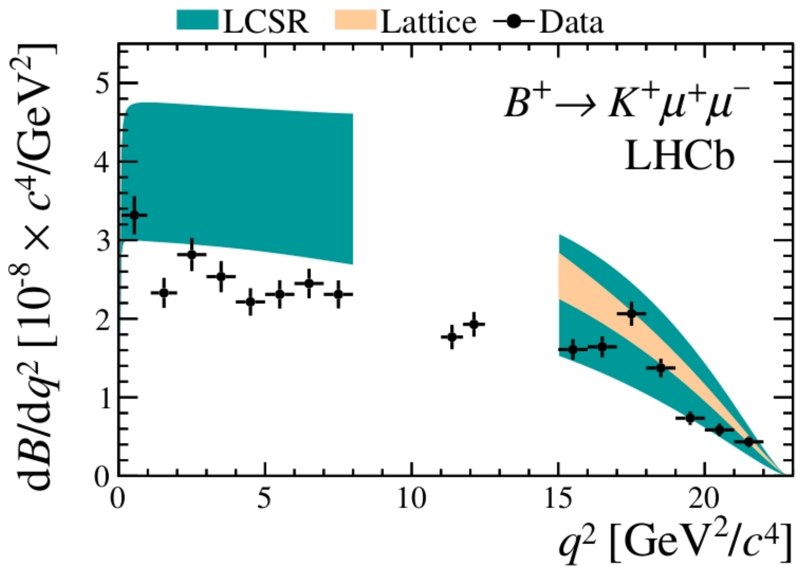
Extended gauge sectors can help understanding the nature of EW symmetry breaking: Left-Right, 331, ...

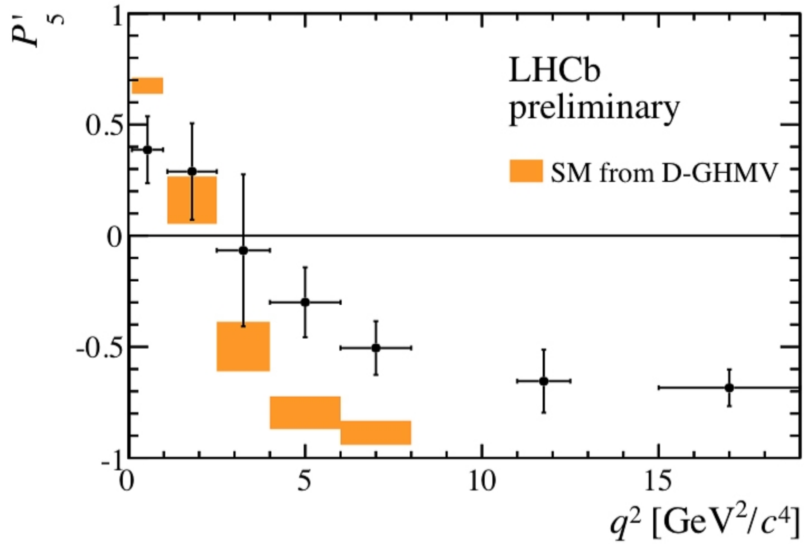
Experimental reasons

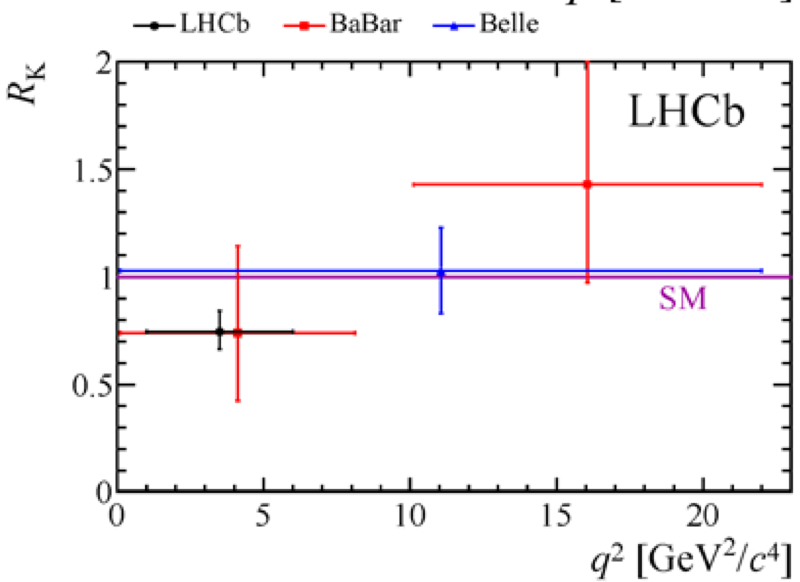
A W’ with couplings to fermions similar to those of the SM W would scale up the decay rates but leave other observables unaffected: exactly as observed!

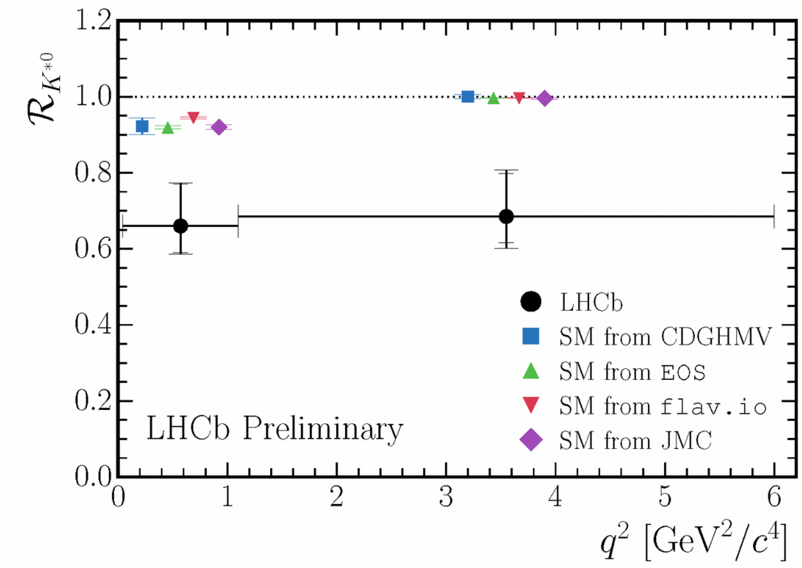
A W’ **always** comes with a Z’. Perhaps this boson can address other anomalies in B-meson decays?

The $b \to s$ anomalies

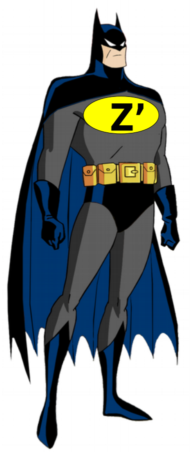








Killing two birds with one stone



R_{K,K^*} ⇐ **A common NP framework** ⇒ $R(D^{(*)})$

Chuck Norris fact of the day

Chuck Norris can kill two stones with one bird

Warning

Of course, the <u>W' candidate</u> has to respect a long list of experimental constraints...

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

Direct LHC searches: <u>tension</u> with $R(D^{(*)})$

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

Precision EW data

...

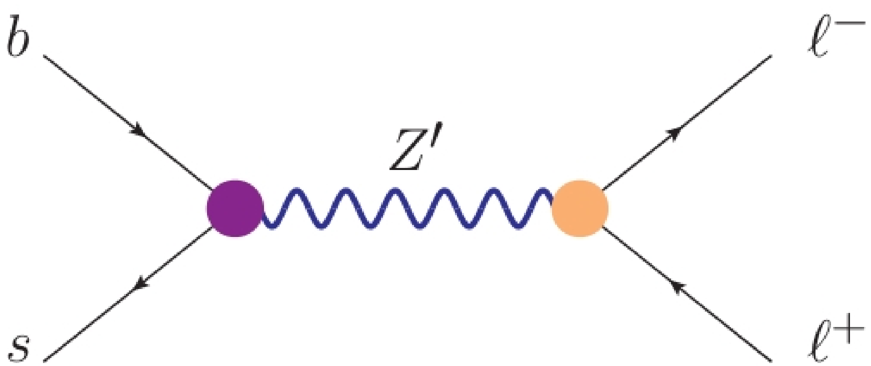
... and it may well be that it does not work after all!

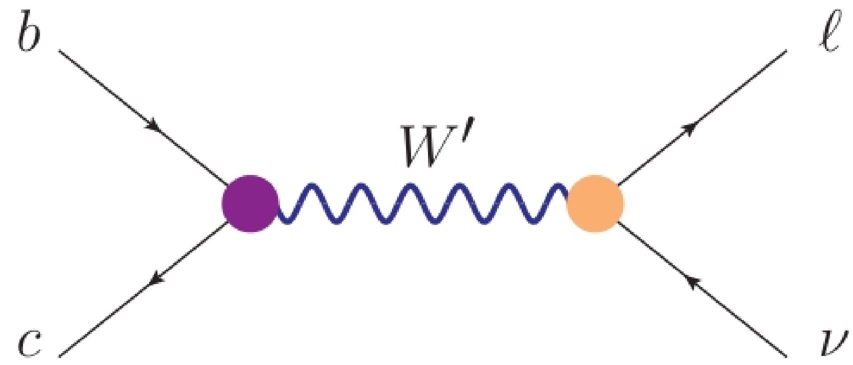
An example model

Boucenna, Celis, Fuentes-Martin, AV, Virto

PLB 760 (2016) 214-219 [arXiv:1604.03088]
JHEP 1612 (2016) 059 [arXiv:1608.01349]

Simplest Z'-W' explanation of the anomalies





Flavor violating couplings to quarks

Non-universal couplings to leptons

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 → s and $R(D^{(*)})$ apparent universal scaling

It looks *easy*, right?

The model

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

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

$$\boxed{SU(2)_L \otimes U(1)_Y}$$

$\langle \phi \rangle, \langle \phi' \rangle \sim v$ $\quad\big\downarrow\quad$ $M_Z, M_W \sim \mathcal{O}(v)$

$$\boxed{U(1)_{\text{em}}}$$

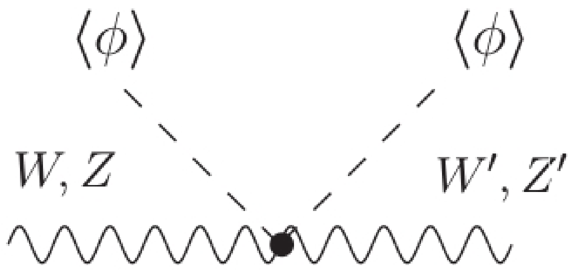
Particle content

- 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 $SU(2)_1$

SM-VL mixing

$$\mathcal{L}_{\text{mix}} = \lambda^\dagger \bar{F}_R \, \Phi \, f_L$$

The issue of gauge mixing



$$\sim \zeta \, \frac{M_{Z,W}^2}{M_{Z'}^2} \sim 10^{-2} \, \zeta \left(\frac{1 \, \mathrm{TeV}}{M_{Z'}} \right)^2$$

For unsuppressed ζ, gauge mixing effects are potentially of the <u>same size</u> as Z', W' tree-level exchange (for certain observables)

Z', W' tree-level: $\sim \dfrac{1}{M_{W'}^2}$ Z, W tree-level + GM: $\sim \dfrac{1}{M_W^2} \dfrac{v^2}{u^2} \sim \dfrac{1}{M_{W'}^2}$

- ➔ Potential to spoil the desired <u>couplings</u>
  (Anomalous couplings to electrons, corrections to $C_9^{NP} = - C_{10}^{NP}$, ...)
- ➔ Constrained by LEP at the per-mil level (Z- and W-pole observables)

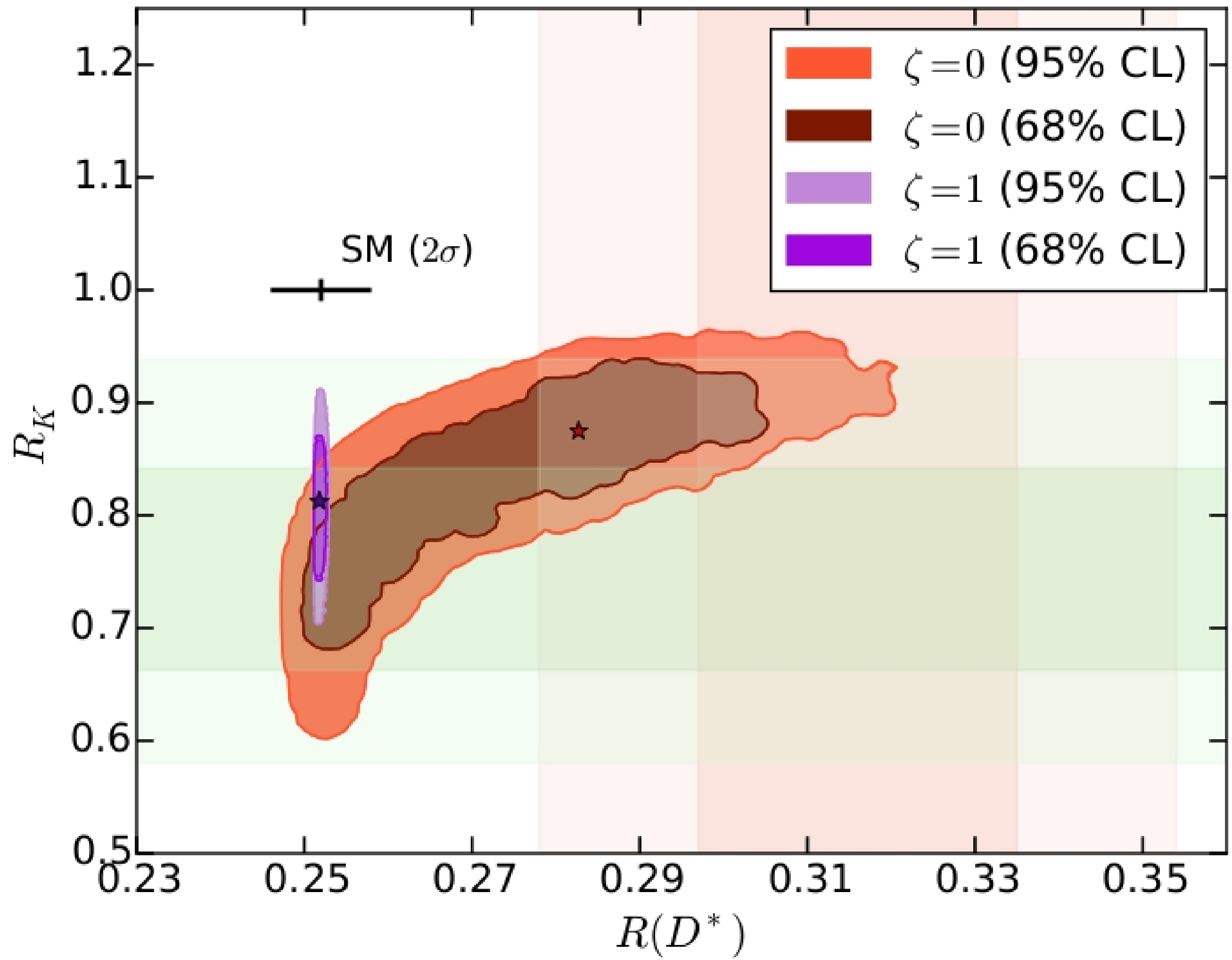
Solution: A second Higgs doublet $\phi' = (2,1)_{1/2}$ $\Longrightarrow$ ζ free parameter

Our global fit

Many more details in
Boucenna, Celis, Fuentes-Martin, AV, Virto [arXiv:1608.01349]

- Bounds from Z and W pole observables [Efrati et al, 2015]
- Tests of lepton universality violation in tree-level charged current processes: $\ell \to \ell' \nu \bar{\nu}, \pi/K \to \ell\nu, \tau \to \pi/K\nu, K^+ \to \pi\ell\nu,$ $D \to K\ell\nu, D_s \to \ell\nu, B \to D^{(*)}\ell\nu$ and $B \to X_c \ell\nu$
- |ΔF| = 1,2 transitions in the b → s sector receiving NP contributions at tree-level
- Bounds from the lepton flavor violating decays $\tau \to 3\,\mu$ and $Z \to \tau\mu$
- CKM inputs from a fit by the CKMfitter group with only tree-level processes

Gauging the anomalies away



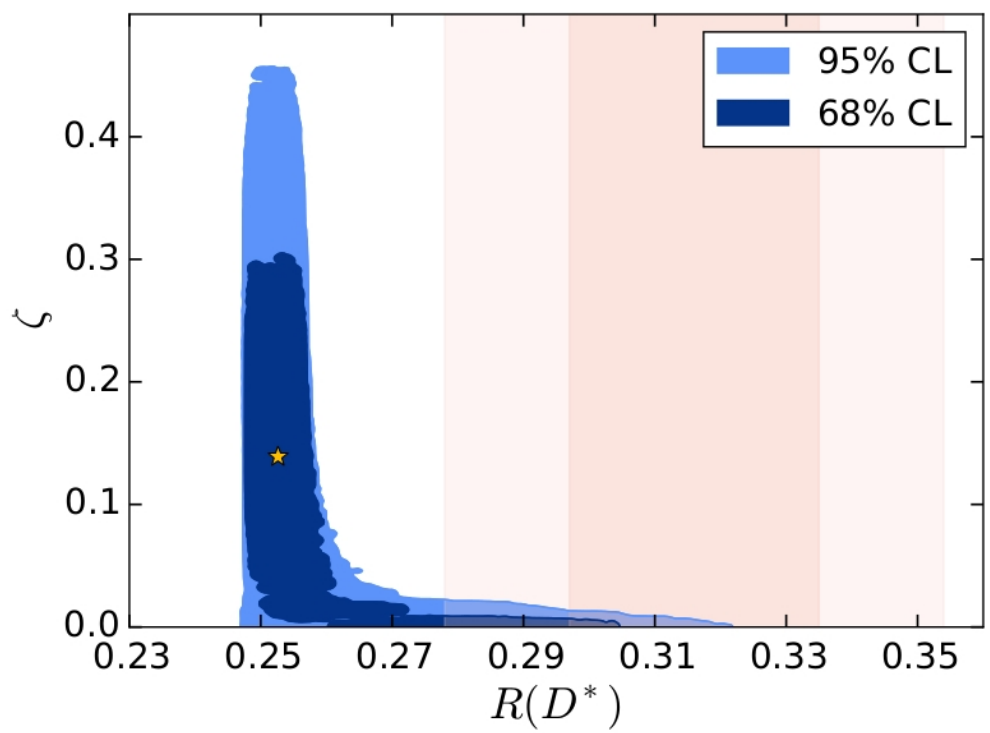
Global fit

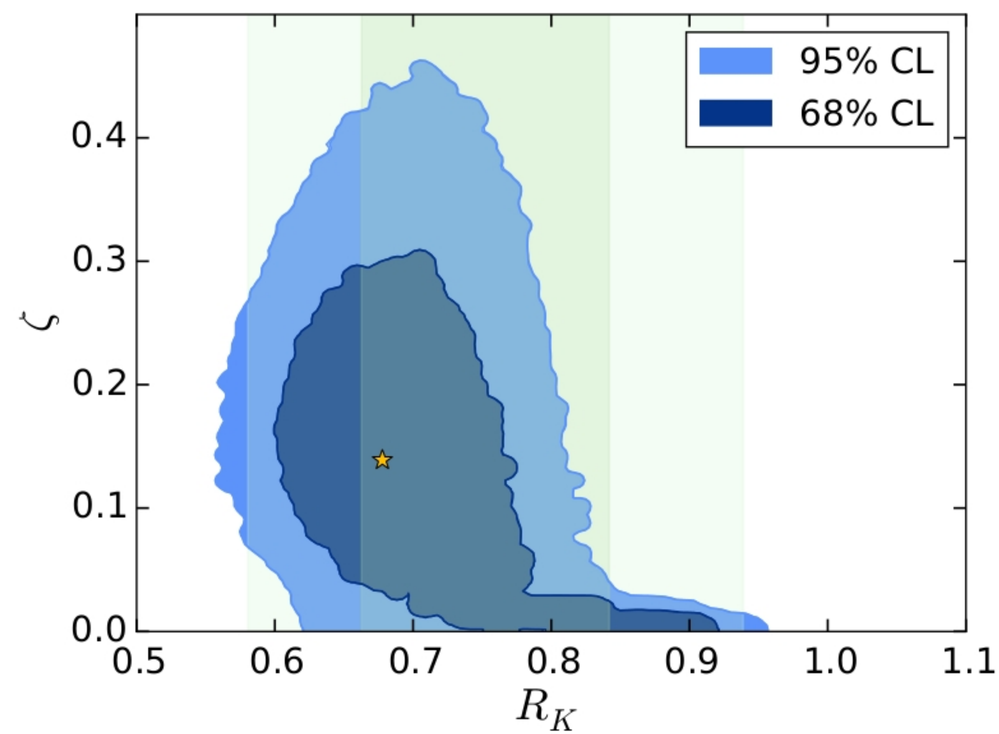
- EW precision data
- Flavor data

The model gives a good fit to 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 → c observables

NP contributions have <u>the same Dirac structure</u> as the SM ones

$$\Longrightarrow \quad \frac{R(D)_{\rm exp}}{R(D)_{\rm SM}} = \frac{R(D^*)_{\rm exp}}{R(D^*)_{\rm SM}} = \ldots$$

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

$\Longrightarrow$ 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_Φ are strongly correlated

$$\Longrightarrow \quad R_{K^*} \sim R_K < 1$$

(for example)

FOUND

Predictions

(3) Lepton flavor violation

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

$\Longrightarrow$ $\mathrm{BR}(\tau \to 3\,\mu)$ 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 2nd and 3rd generation quarks

$\Longrightarrow$ The usual limits (1st generation couplings) do not apply

$\Longrightarrow$ Nevertheless: the LHC is sensitive

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

[tension in almost all models for b → c anomalies]

Summary

Summary

The R(D) and R(D*) anomalies constitute an intriguing set of hints for New Physics

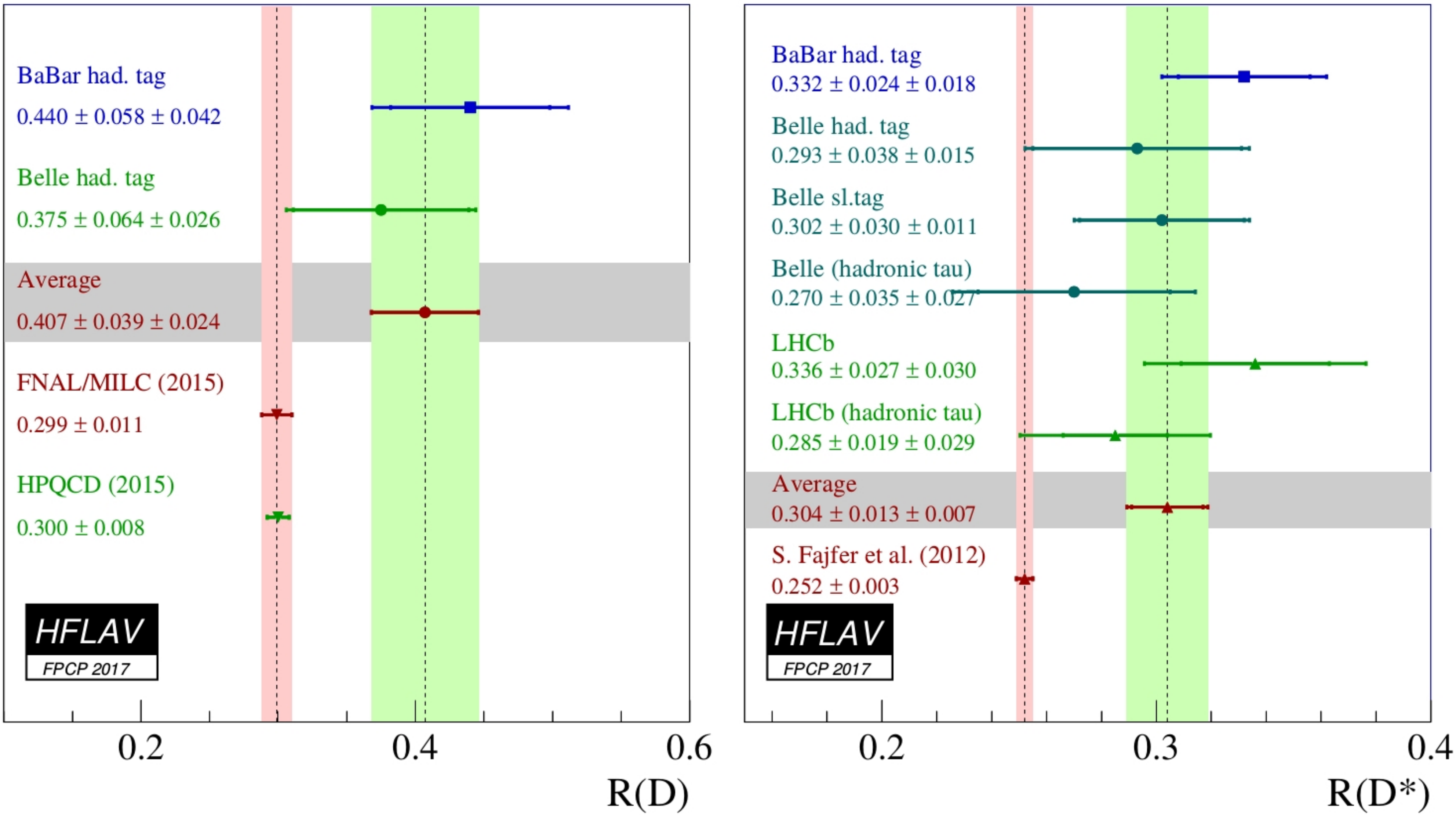
A heavy W’ boson is a theoretically well-motivated candidate to address these anomalies... and it automatically explains some of the experimental features!

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

Summary

Backup slides

The $b \to c$ anomalies



Model classification

Breaking pattern

L-BP :

$$\boxed{\begin{array}{c} SU(2)_L \otimes SU(2)_H \otimes U(1)_H \\ \downarrow \\ SU(2)_L \otimes U(1)_Y \end{array}}$$

Y-BP :

$$\boxed{\begin{array}{c} SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y \\ \downarrow \\ SU(2)_L \otimes U(1)_Y \end{array}}$$

Source of non-universality

g-NU : Non-universal gauge couplings

y-NU : Through non-universal mixings with other fermions

	L-BP	**Y-BP**
g-NU	✘ No left-handed currents	✘ Perturbativity
y-NU	✘ No GIM	✓

The model

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	generations	$SU(3)_C$	$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
ϕ	1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Φ	1	$\mathbf{1}$	$\mathbf{2}$	$\bar{\mathbf{2}}$	0
ϕ'	1	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$1/2$
q_L	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$1/6$
u_R	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$
d_R	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$
ℓ_L	3	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
e_R	3	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$Q_{L,R}$	n_{VL}	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$1/6$
$L_{L,R}$	n_{VL}	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$-1/2$

The model

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Fermion representations

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

$$Q_{L,R} = \begin{pmatrix} U \\ D \end{pmatrix}_{L,R} = (\mathbf{3},\mathbf{2},\mathbf{1})_{\frac{1}{6}} \qquad \mathrm{L}_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} = (\mathbf{1},\mathbf{2},\mathbf{1})_{-\frac{1}{2}}$$

Scalar representations

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \qquad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi^0 & \Phi^+ \\ -\Phi^- & \bar{\Phi}^0 \end{pmatrix} \qquad \phi' = \begin{pmatrix} \varphi'^+ \\ \varphi'^0 \end{pmatrix}$$

self-dual bidoublet : $\Phi = \widetilde{\Phi} = \sigma_2 \Phi^* \sigma_2$

$$\bar{\Phi}^0 = (\Phi^0)^* \qquad \Phi^- = \left(\Phi^+\right)^*$$

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_{VL} x n_{VL} matrices

λ_q , λ_l : 3 x n_{VL} matrices

VL-SM Yukawa terms

$$-\mathcal{L}_\Phi = \overline{Q_R}\, \lambda_q^\dagger\, \Phi\, q_L + \overline{L_R}\, \lambda_\ell^\dagger\, \Phi\, \ell_L + \text{h.c.}$$

$$-\mathcal{L}_{\phi'} = \overline{Q_L}\, \widetilde{y}^d\, \phi'\, d_R + \overline{Q_L}\, \widetilde{y}^u\, \tilde{\phi}'\, u_R + \overline{L_L}\, \widetilde{y}^e\, \phi'\, e_R + \text{h.c.}$$

The model

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Scalar potential and symmetry breaking

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

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

$$\boxed{\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_Y \xrightarrow{u} \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \xrightarrow{v} \mathrm{U}(1)_{\mathrm{em}}}$$

$$u \sim \mathrm{TeV} \gg v \simeq 246\,\mathrm{GeV}$$

Doublets VEVs

$$v_\phi = v \,\sin\beta$$
$$v_{\phi'} = v \,\cos\beta$$
$$v^2 = v_\phi^2 + v_{\phi'}^2$$

$$\boxed{Q = \left(T_3^1 + T_3^2\right) + Y = T_3^L + Y}$$

The model

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Particle spectrum I: Scalars

$\{\phi, \Phi, \phi'\}$ 12 d.o.f. $\Longrightarrow$ W, Z, W', Z' long. components 6 d.o.f. + 3 CP-even + 1 CP-odd + 1 Charged 2 d.o.f.

[constrained 2HDM + CP-even singlet scenario]

Particle spectrum II: Fermions

$$\mathcal{F}^I_{L,R} \equiv (f^i_{L,R}, F^k_{L,R})$$

$$i = 1, 2, 3$$

$$k = 1, \dots, n_{\rm VL}$$

$$I = 1, \dots, 3 + n_{\rm VL}$$

$$\mathcal{M}_{\mathcal{F}} = \begin{pmatrix} \frac{1}{\sqrt{2}} y_f v_\phi & \frac{1}{2} \lambda_f u \\ \frac{1}{\sqrt{2}} \widetilde{y}_f v_{\phi'} & M_F \end{pmatrix}$$

SM-VL mixing induced by λ_f

The model

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Particle spectrum III: Gauge bosons

Neutral gauge bosons

$$\mathcal{V}^0 = \left(W_3^1, W_3^2, B\right)$$

$$\mathcal{M}^2_{\mathcal{V}^0} = \frac{1}{4} \begin{pmatrix} g_1^2 \left(v_{\phi'}^2 + u^2\right) & -g_1 g_2 u^2 & -g_1 g' v_{\phi'}^2 \\ -g_1 g_2 u^2 & g_2^2 \left(v_\phi^2 + u^2\right) & -g_2 g' v_\phi^2 \\ -g_1 g' v_{\phi'}^2 & -g_2 g' v_\phi^2 & g'^2 \left(v_\phi^2 + v_{\phi'}^2\right) \end{pmatrix}$$

$$\left.\begin{array}{l} \text{controlled by } \zeta = s_\beta^2 - \dfrac{g_1^2}{g_2^2} c_\beta^2 \\ \text{vanishes for } \tan\beta = g_1/g_2 \end{array}\right\}$$

gauge mixing

$$\widehat{\mathcal{V}}^0 = \left(Z_h, Z_l, A\right)$$

$$\mathcal{M}^2_{\mathcal{V}^0} = \frac{1}{4} \begin{pmatrix} \left(g_1^2 + g_2^2\right) u^2 + \frac{g^2 g_2^2}{g_1^2} v^2 \left(s_\beta^2 + \frac{g_1^4}{g_2^4} c_\beta^2\right) & -g\, n_2 \frac{g_2}{g_1} v^2 \left(s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2\right) & 0 \\ -g\, n_2 \frac{g_2}{g_1} v^2 \left(s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2\right) & \left(g^2 + g'^2\right) v^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Z' Z

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Particle spectrum III: Gauge bosons

Charged gauge bosons

$$\mathcal{V}^+ = \left(W_{12}^1, W_{12}^2\right)$$

$$W_{12}^r = \frac{1}{\sqrt{2}}\left(W_1^r - i W_2^r\right)$$

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

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

vanishes for $\tan\beta = g_1/g_2$

gauge mixing

$$\widehat{\mathcal{V}}^+ = \left(W_h, W_l\right)$$

W' W

$$\mathcal{M}_{\mathcal{V}^+}^2 = \frac{1}{4}\begin{pmatrix} \left(g_1^2 + g_2^2\right)u^2 + \frac{g^2 g_2^2}{g_1^2} v^2\left(s_\beta^2 + \frac{g_1^4}{g_2^4} c_\beta^2\right) & -g^2 \frac{g_2}{g_1} v^2\left(s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2\right) \\ -g^2 \frac{g_2}{g_1} v^2\left(s_\beta^2 - \frac{g_1^2}{g_2^2} c_\beta^2\right) & g^2 v^2 \end{pmatrix}$$

The model

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Z' and W' couplings to light fermions

$$\hat{g} \equiv g \, \frac{g_2}{g_1}$$

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

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

$$\boxed{n_{\rm VL} = 2}$$

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

universal

non-universal due to SM-VL mixing

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

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

$u\widetilde{M}$: physical VL mass

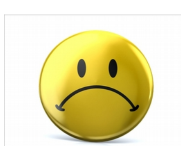
Z' and W' couplings to fermions

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

$$\boxed{n_{\rm VL} = 1}$$

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

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



Does not work!

$$\boxed{n_{\rm VL} = 2}$$

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

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

It works!

Our global fit

Many more details in
Boucenna, Celis, Fuentes-Martin, AV, Virto [arXiv:1608.01349]

Free parameters: $\{M_{Z'}, g_2, \underbrace{\Delta_s, \Delta_b, \Delta_\mu, \Delta_\tau}_{\lambda_{\ell,q}}, \zeta\} \quad + \quad \{\lambda, A, \bar{\rho}, \bar{\eta}\}$

$\simeq M_{W'}$ $\quad g_1 \quad$ $\lambda_{\ell,q}$ $\quad$ gauge mixing $\quad$ CKM matrix

Global χ^2 function

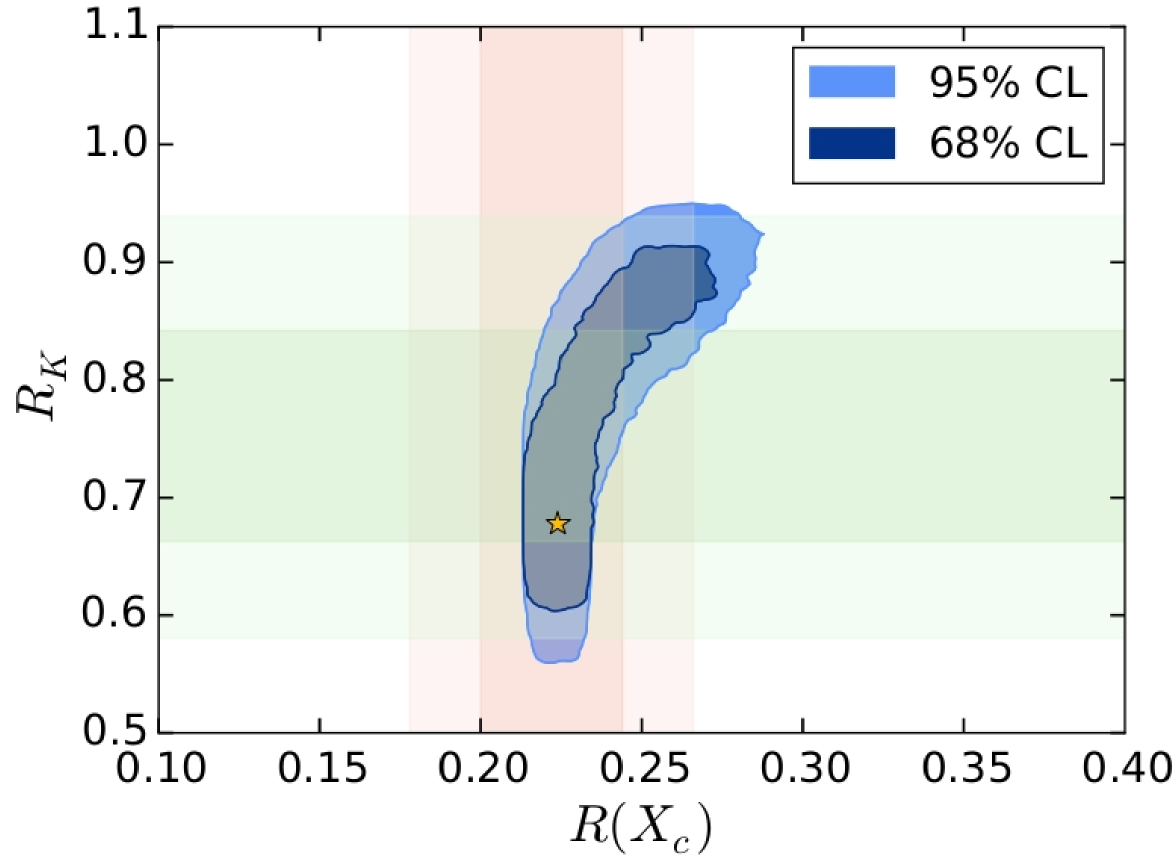
<u>Best-fit point</u>:

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

$$\chi^2_{\mathrm{min}} = 54.8 \xrightarrow{\text{to be compared with}} \chi^2_{\mathrm{SM}} = 93.7$$

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

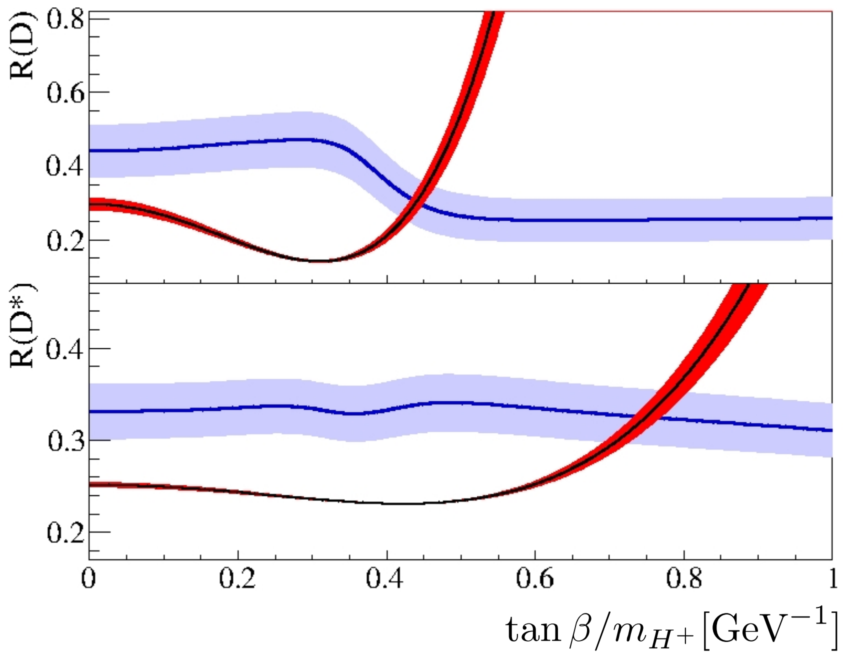


Explaining the R(D*) best-fit would induce a slight tension with the $R(X_c)$ experimental measurement

Charged Higgs and R(D$^{(*)}$)

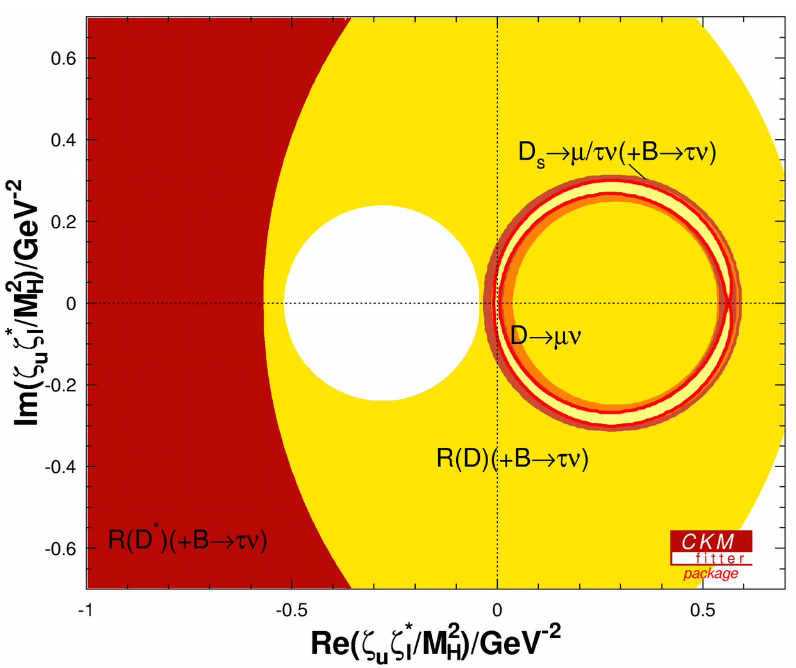
Natural candidate for the b → c anomalies: a charged Higgs
But the “standard” 2HDMs do not work [Celis et al, 2012]

Type II 2HDM



[BaBar collaboration, 2012]

Aligned 2HDM



[Celis et al, 2012]

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