# An introduction to the B-anomalies

## - Lecture 3 -
## *Model-dependent interpretation*

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# Summary of this lecture

**1) Models, models and models**

**2) $b \to s$ anomalies and dark matter**

**3) A gauge explanation of the B-anomalies**

# Models, models and models


# New Physics explanations

$R_{K,K^*}$ ⇒ **Neutral current**

Z' boson, leptoquarks,
compositeness, RPV loops

$R(D^{(*)})$ ⇒ **Charged current**

Charged Higgs, leptoquarks,
compositeness, W' boson, RPV sfermions

**+ EFTs, of course**

# Z’ : what do we need?

## Z' model building

**Easiest (but not unique) solution to the b-s anomalies**

List of “ingredients”:

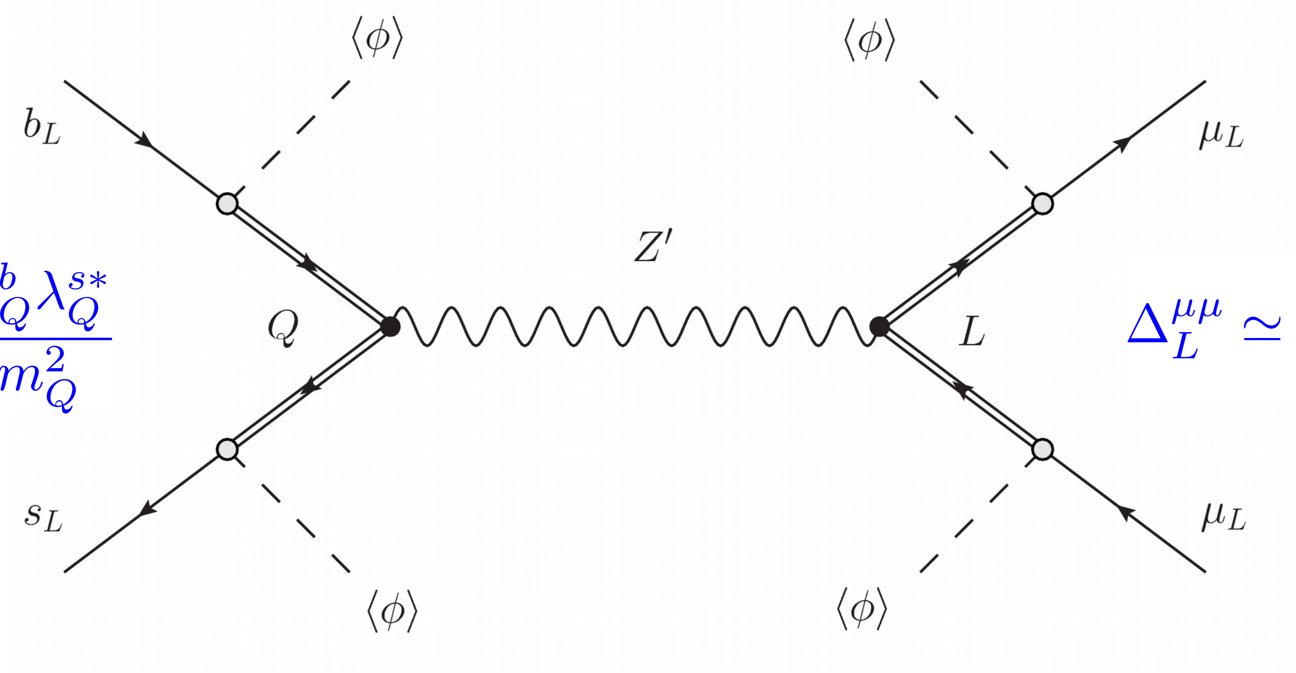
- A Z' boson that contributes to $\mathcal{O}_9$ (and optionally to $\mathcal{O}_{10}$)
- The Z' must have flavor violating couplings to quarks
- The Z' must have non-universal couplings to leptons
- Optional (but highly desirable!): interplay with some other physics ⟶ **Dark Matter**

*More about this later!*

# Solving the $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]

$$\Delta_L^{bs} \simeq g_X v_\phi^2 \frac{\lambda_Q^b \lambda_Q^{s*}}{m_Q^2}$$




$$\Delta_L^{\mu\mu} \simeq \frac{2\, g_X |\lambda_L^\mu|^2 v_\phi^2}{2 m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}$$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\ (\bar{\mu}\gamma^\alpha P_L \mu)$$

$$C_9^{\rm NP} = -C_{10}^{\rm NP}$$

*Alternatives with direct Z' couplings*

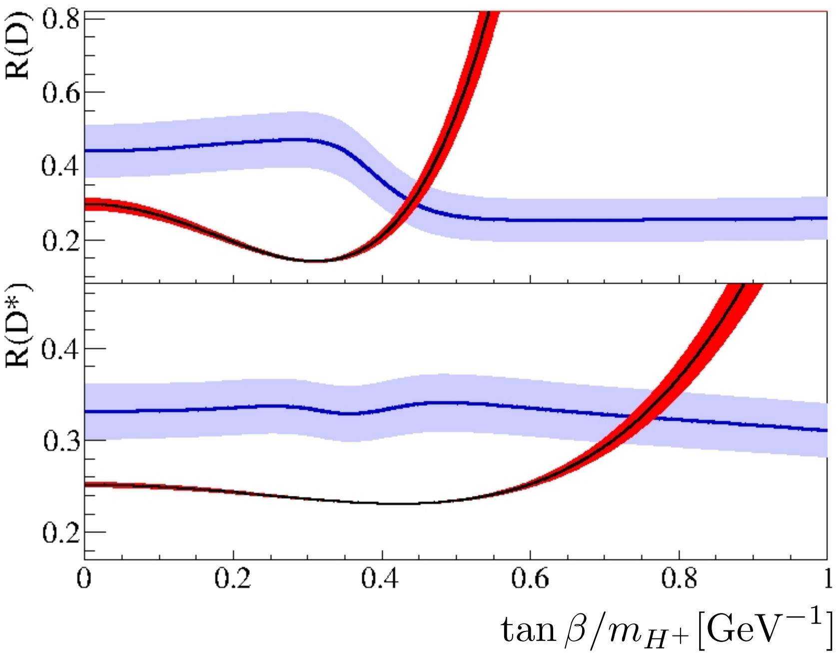
Altmannshofer et al, 2014, Crivellin et al, 2014, 2015 [$L_\mu - L_\tau$], Celis et al, 2015 [BGL], ...

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

Natural candidate for the $b \to c$ anomalies: a charged Higgs

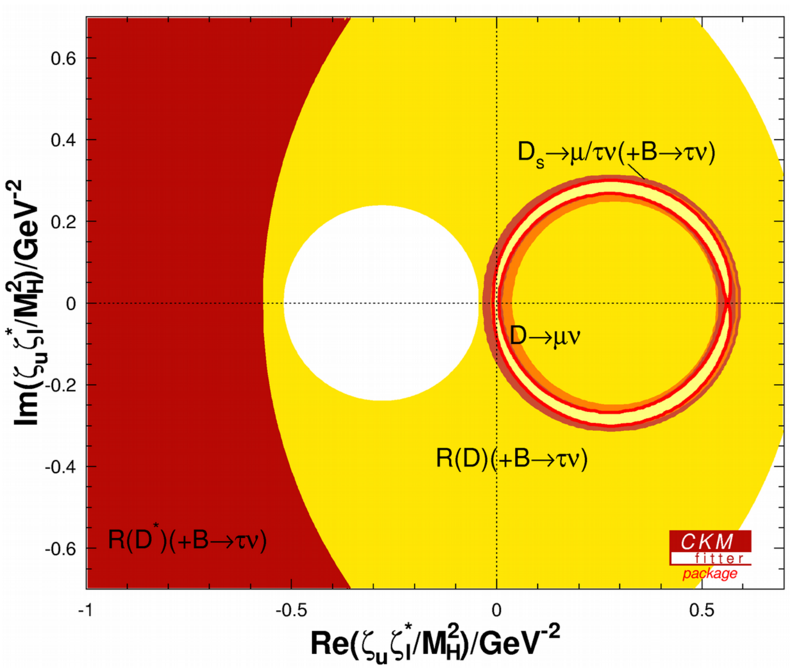
But the “standard” 2HDMs do not work [Celis et al, 2012]

**Type II 2HDM**




[BaBar collaboration, 2012]

**Aligned 2HDM**



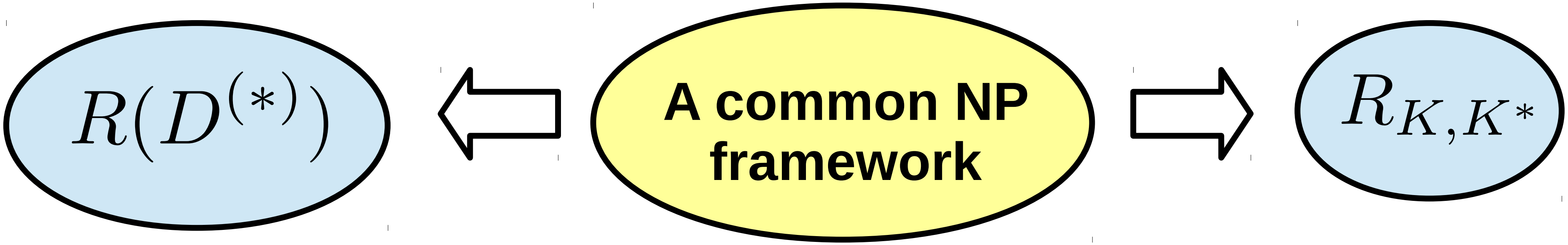

[Celis et al, 2012]

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

Although currently disfavored!

# Killing two birds with one stone

What if the two anomalies are hinting at the same New Physics?




EFTs:
[Bhattacharya et al, 2014, Alonso et al, Calibbi et al, Greljo et al, 2015]

**Chuck Norris fact of the day**

*Chuck Norris can kill two stones with one bird*

Lectures by Nejc Košnik

See also talk by Marta Moscati at FPCP 2018

Simultaneous explanation of both puzzles:
leptoquarks?

$$\mathcal{L} \sim \lambda_{d\ell}\, \bar{d}\, \ell\, \phi + \lambda_{u\nu}\, \bar{u}\, \nu\, \phi$$

**One leptoquark to rule them all [1511.01900]**

**Candidates in the literature**

Very incomplete and outdated list!

$V_\mu$ = (3,1,-2/3)

Alonso, Grinstein, Martin-Camalich [1505.05164]

Barbieri, Isidori, Pattori, Senia [1512.01560]

$\Phi$ = (3,1,-1/3)

Bauer, Neubert [1511.01900, 1512.06828]

Das, Hati, Kumar, Mahajan [1605.06313]

$V_\mu$ = (3,3,2/3)

Fajfer, Košnik [1511.06024]

**Same as in RPV SUSY**

Deshpande, He [1608.04817]

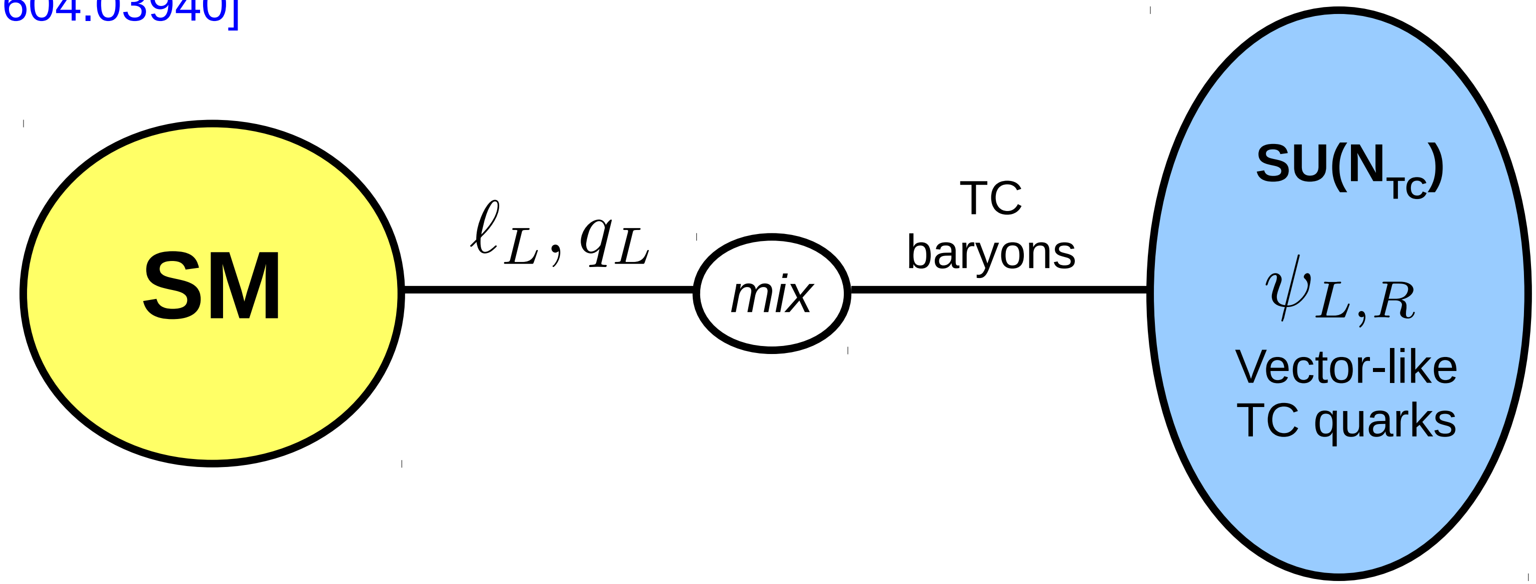
Possible connection to neutrino masses:

Deppisch, Kulkarni, Päs, Schumacher [1603.07672]

Hati, Kumar, Orloff, Teixeira [1806.10146]

# Strongly-coupled NP

Buttazzo, Greljo, Isidori, Marzocca
[1604.03940]




I prefer something
more... *elementary*

**Lowest-lying**
**vector meson resonances**

$$\rho^{\pm}, \rho^0, \omega, \ldots$$

⇩

$R_{K,K^*}$ and $R(D^{(*)})$

# Warning

Of course, all these candidates have 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: tension with $R(D^{(*)})$

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

Precision EW data

...

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


# $b \to s$ anomalies and Dark Matter

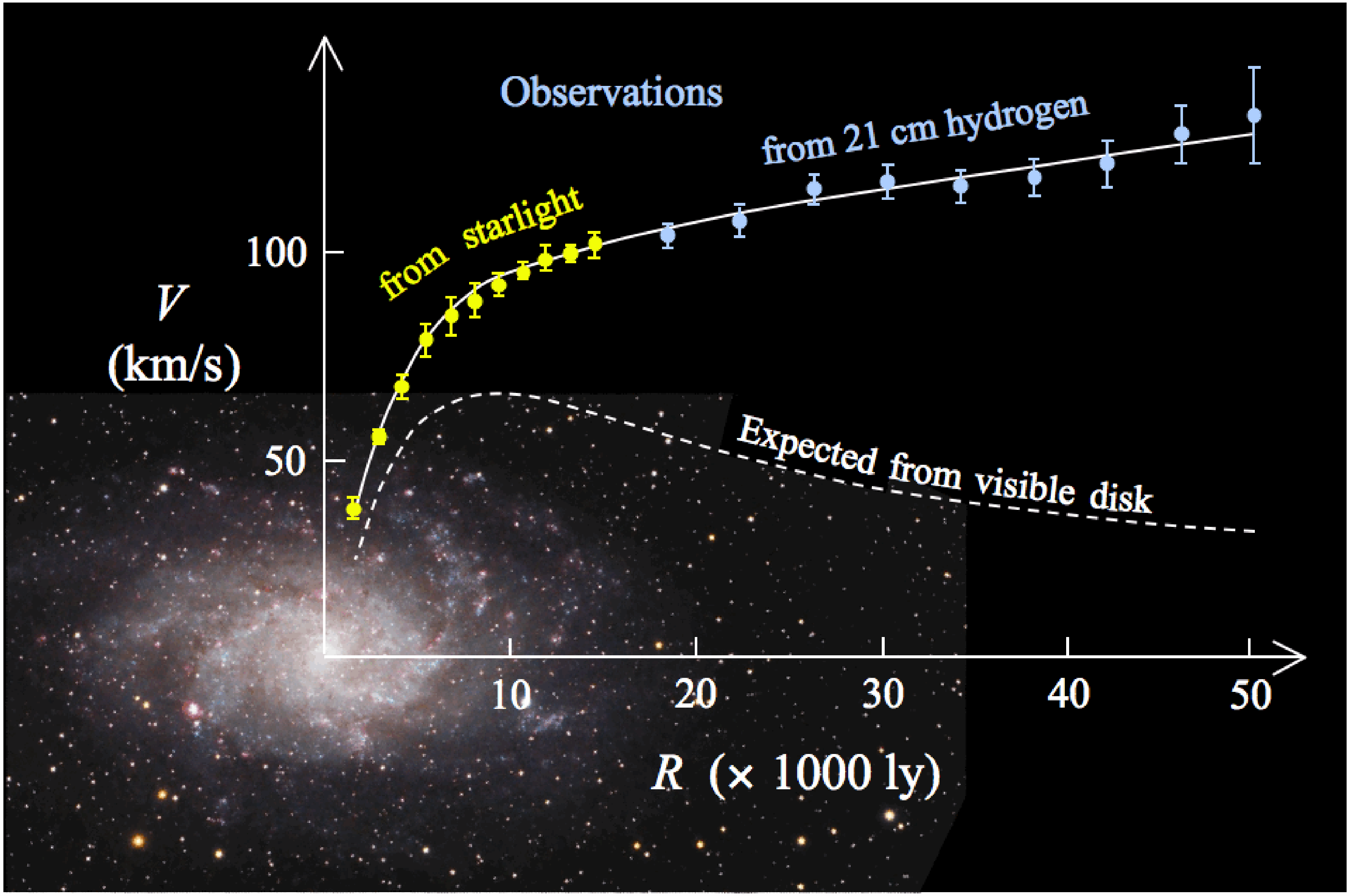
# Evidences for Dark Matter

Evidences for **Dark Matter** come from many different sources:

- Galactic rotation curves
- Clusters dynamics
- Gravitational lensing
- Cosmic microwave background
- Large scale structure simulations
- Bullet cluster
- ...

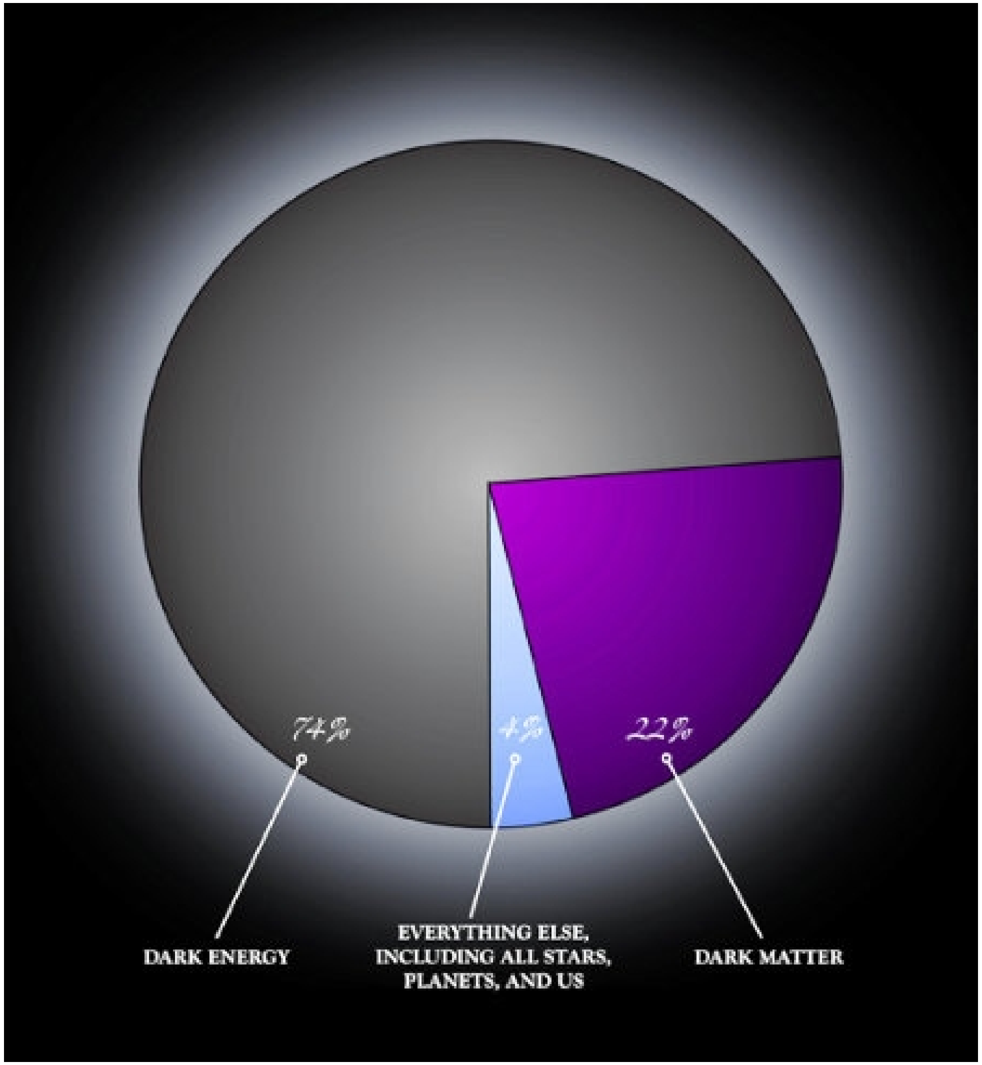
So we are pretty
sure it does exist!

# Evidences for Dark Matter



# Evidences for Dark Matter

Composition of the universe:




Remember:
DE is not the same as DM

# DM for particle physicists

Hypothesis: **DM** is made of particles → Not the only possibility, but the most popular

Requirements for the **DM particle**:

- **Electrically neutral:** Since DM is dark, it should not interact with photons, at least at tree-level. Otherwise they would scatter light becoming visible.
- **Colorless:** If DM particles were strongly interacting, like quarks, they would form bound states. This is strongly constrained by different cosmological searches.
- **Stable or long-lived:** We need the DM particles to be stable or long-lived (with a life-time of the order of the age of the universe) or otherwise they would have disappared with the evolution of the universe.

**Neutrinos** do not work (they destroy structures) $\Rightarrow$ Beyond the SM

# Killing two birds with one stone (II)

What if the explanation to these anomalies also solves other physics problems?

$b \to s$ ⇐ **A common NP framework** ⇒ **DM**

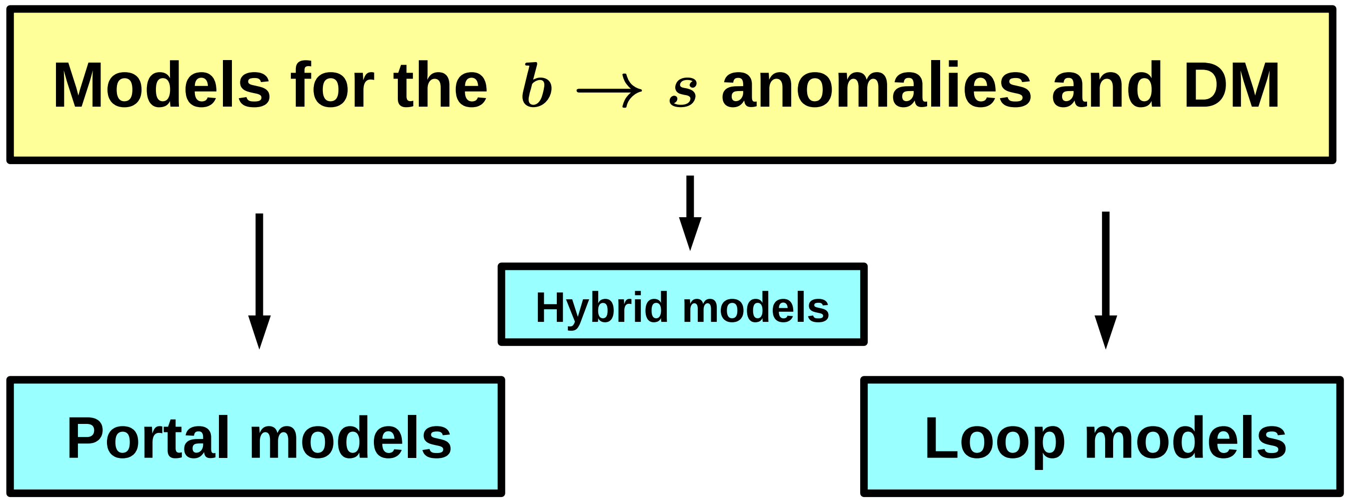
**Chuck Norris fact of the day**

You better learn it this time! →

*Chuck Norris can kill two stones with one bird*

# Linking $b \to s$ and DM

[AV, 2018]




The mediator responsible for the NP contributions to $b \to s$ transitions also mediates the DM production in the early Universe

**Example:**

Aristizabal-Sierra, Staub, AV
[ 1503.06077 ]

The required NP contributions to $b \to s$ transitions are induced with loops containing the DM particle

**Example:**

Kawamura, Okawa, Omura
[ 1706.04344 ]

# A model with a Z' portal

[Aristizabal Sierra, Staub, AV, 2015]


Vector-like = "joker"
for model builders

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

## Vector-like fermions

Link to SM fermions

$$Q = \left(\mathbf{3}, \mathbf{2}, \frac{1}{6}, 2\right) \qquad L = \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2\right)$$

## Scalars

$$\phi = (\mathbf{1}, \mathbf{1}, 0, 2) \qquad \chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

$U(1)_X$ breaking

Dark matter candidate

# A model with a Z' portal

[Aristizabal Sierra, Staub, AV, 2015]


Vector-like = "joker"
for model builders

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

$$\mathcal{L}_m = m_Q \overline{Q} Q + m_L \overline{L} L$$

Vector-like (Dirac) masses

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R} \phi q_L + \lambda_L \overline{L_R} \phi \ell_L + \text{h.c.}$$

VL – SM mixing

# Solving the $b \to s$ anomalies

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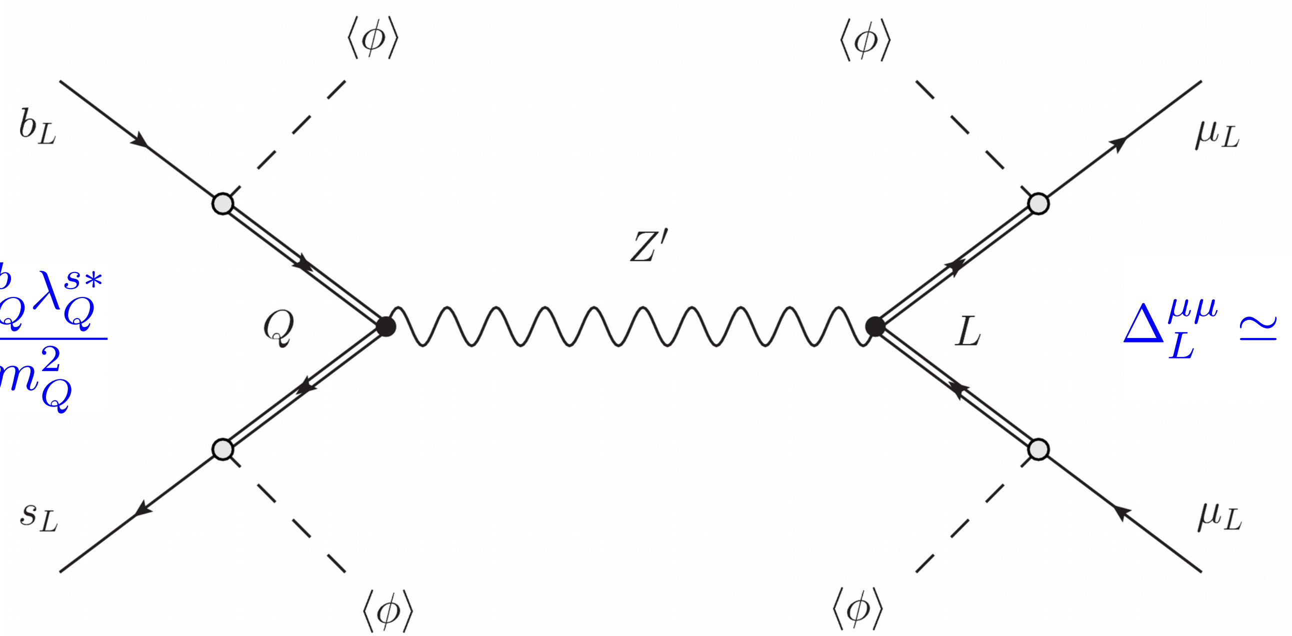


$$\Delta_L^{\mu\mu} \simeq \frac{2\, g_X |\lambda_L^\mu|^2 v_\phi^2}{2 m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}$$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\,(\bar{\mu}\gamma^\alpha P_L \mu)$$

$$C_9^{\rm NP} = -C_{10}^{\rm NP}$$

*Alternatives with direct Z' couplings*

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# Dark Matter

**DM stability**

$$U(1)_X \quad \to \quad \mathbb{Z}_2$$

[Krauss, Wilczek, 1989]
[Petersen et al, 2009]
[Aristizabal Sierra, Dhen, Fong, AV, 2014]

$$\chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

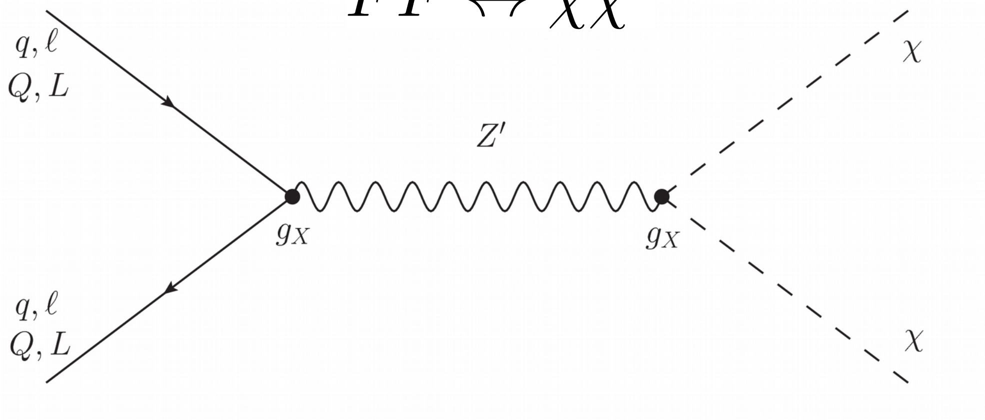
Odd under $\mathbb{Z}_2$

Automatically stable

The dynamics behind the $b \to s$ anomalies stabilizes the DM and provides a production mechanism

**DM production**

$$\bar{F}F \leftrightarrow \chi\chi^*$$




**Z' portal**

Interplay between Flavor and DM

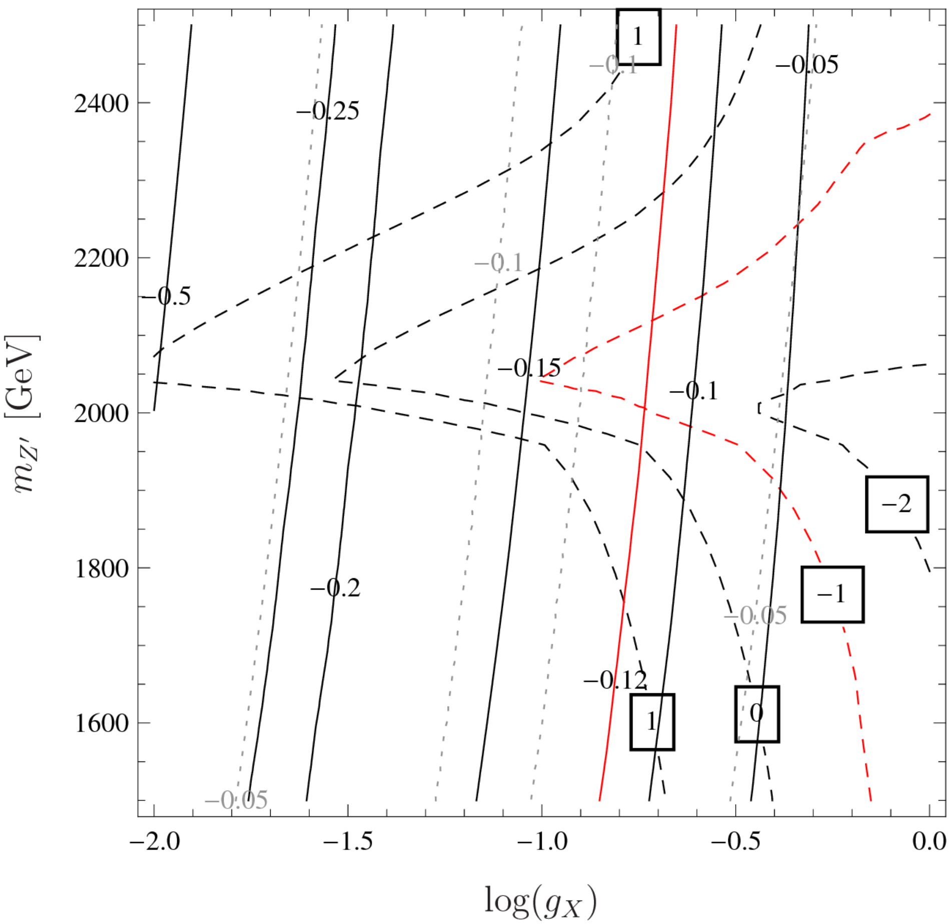
**However:**
Higgs portal also possible

Assumption:

$$\lambda_{H\chi} \ll 1$$

# DM and $b \to s$ anomalies

$C_9^{\rm NP}/C_9^{\rm SM}$ (full) $\quad \log\left(\Omega_{\rm DM} h^2\right)$ (dashed) $\quad C_9^{\rm NP}/C_9^{\rm SM}$ (tree) (dotted gray)




[ DM RD Computed with **microMEGAs** ]

**Parameters:**

$$\lambda_Q^b = \lambda_Q^s = 0.025$$

$$\lambda_L^\mu = 0.5$$

$$m_Q = m_L = 1 \text{ TeV}$$

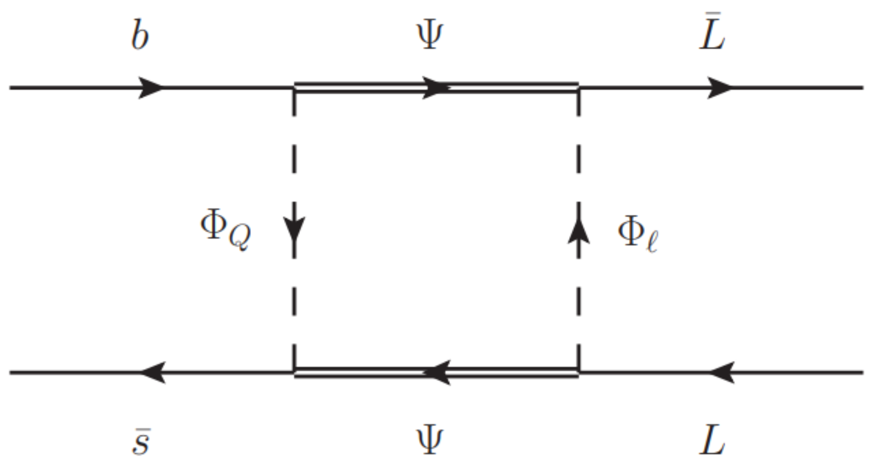
$$m_\chi^2 = 1 \text{ TeV}^2$$

- Compatible with flavor constraints (small quark mixings)
- Resonance required to get the correct DM relic density
- Large loop effects for low $g_X$

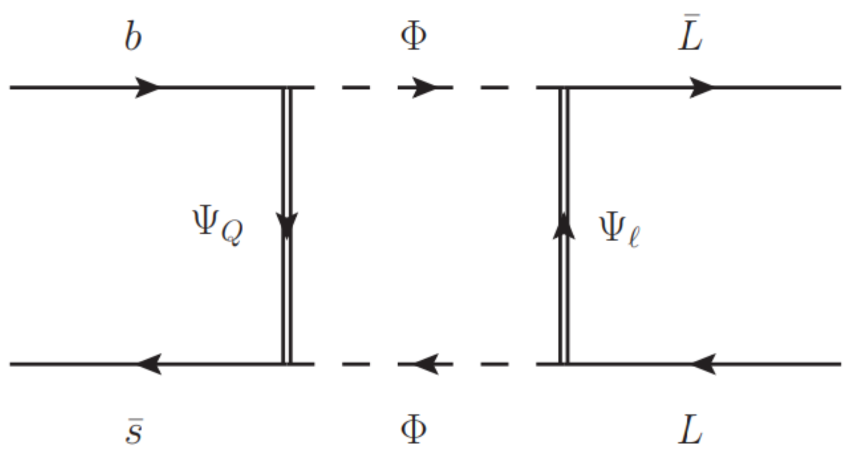
# Loops and $b \to s$ anomalies

[Gripaios et al, 2015]
[Arnan et al, 2016]

**Class (a)**




**Class (b)**




Figures from Arnan et al [ 1608.07832 ]

Model classification

All possible quantum numbers → Some multiplets include colorless neutral states **(DM candidates)**

Different contributions to $B_s$-mixing

# An example loop model

[Kawamura, Okawa, Omura, 2017]

Global ← DM stability

DM → X

VL fermions → { $Q_{L,R}$, $L_{L,R}$ }

| Field | Spin | $SU(3)_c \times SU(2)_L \times U(1)_Y$ | $U(1)_X$ |
|---|---|---|---|
| $X$ | $0$ | $(\mathbf{1}, \mathbf{1}, 0)$ | $-1$ |
| $Q_{L,R}$ | $\frac{1}{2}$ | $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | $1$ |
| $L_{L,R}$ | $\frac{1}{2}$ | $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ | $1$ |

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R}\, X\, q_L + \lambda_L \overline{L_R}\, X\, \ell_L + \text{h.c.}$$

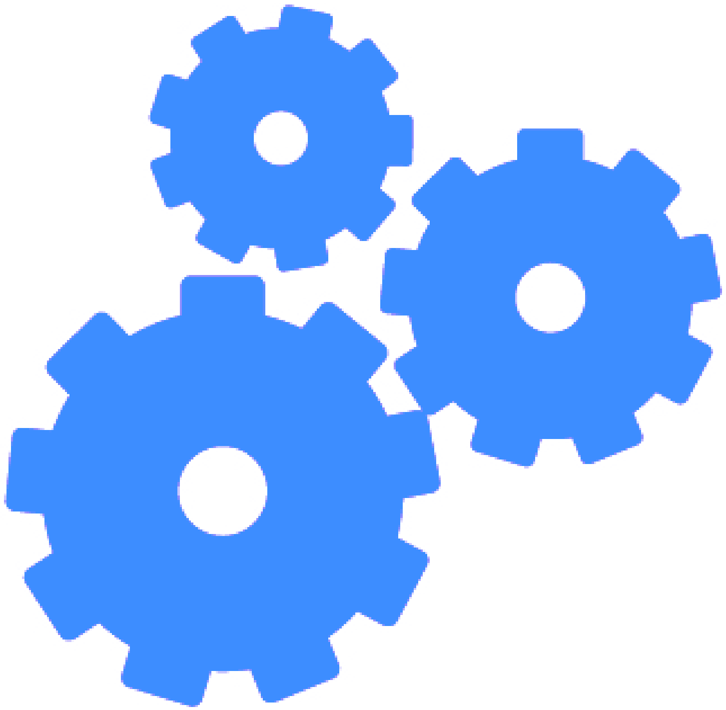
$$\langle X \rangle = 0 \quad \Rightarrow$$

No VL – SM mixing
But new Yukawa interactions

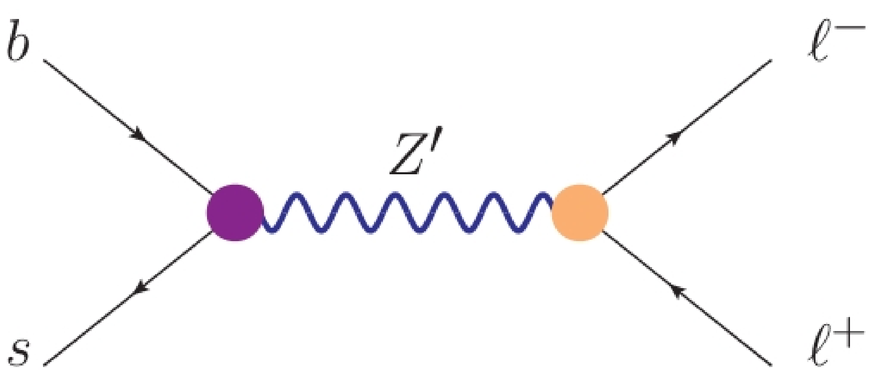
Unbroken
$U(1)_X$ symmetry

→ Loop explanation to the $b \to s$ anomalies

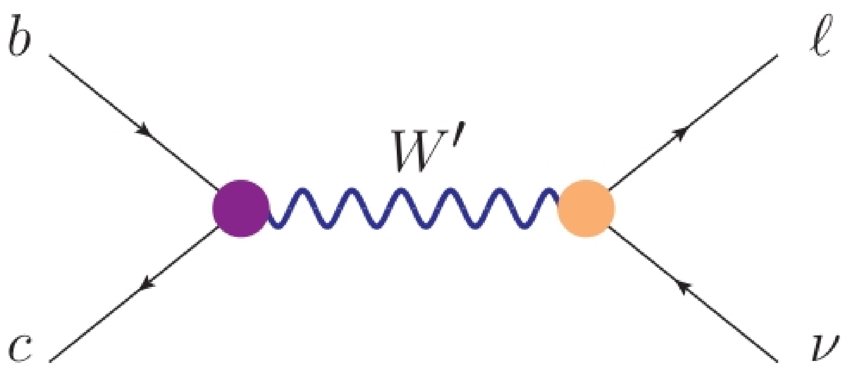
# A gauge explanation of the B-anomalies



# Towards a gauge 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 $b \to s$ and $R(D^{(*)})$ apparent universal scaling
- An "*effective dynamical*" model in this direction [Greljo et al, 2015]

# The model (I)

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

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

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

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

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

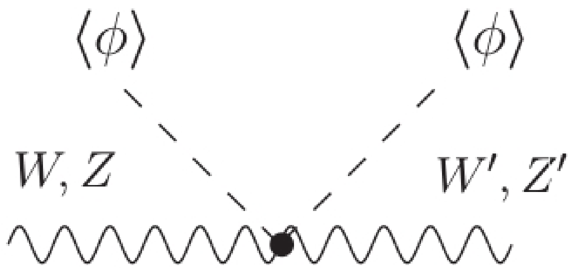
**Particle content**

- 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




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

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

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

- ➔ Potential to spoil the desired couplings (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 $\phi' = (2,1)_{1/2}$ $\Longrightarrow$ $\zeta$ free parameter

# The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

## 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 (II)

PARENTAL ADVISORY EXPLICIT CONTENT

**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

$\lambda_q, \lambda_\ell$ : 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 (II)

PARENTAL ADVISORY EXPLICIT CONTENT

## 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 (II)

PARENTAL ADVISORY EXPLICIT CONTENT

## Particle spectrum I: Scalars

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

[ constrained 2HDM + CP-even singlet scenario ]

## Particle spectrum II: Fermions

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

$$i = 1, 2, 3$$

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

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

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

SM-VL mixing induced by $\lambda_f$

PARENTAL ADVISORY EXPLICIT CONTENT

## Particle spectrum III: Gauge bosons

### Neutral gauge bosons

$$\mathcal{V}^0 = \left(W_3^1, W_3^2, B\right) \qquad \mathcal{M}^2_{\mathcal{V}^0} = \frac{1}{4}\begin{pmatrix} g_1^2\left(v_{\phi'}^2 + u^2\right) & -g_1 g_2 u^2 & -g_1 g' v_{\phi'}^2 \\ -g_1 g_2 u^2 & g_2^2\left(v_\phi^2 + u^2\right) & -g_2 g' v_\phi^2 \\ -g_1 g' v_{\phi'}^2 & -g_2 g' v_\phi^2 & g'^2\left(v_\phi^2 + v_{\phi'}^2\right) \end{pmatrix}$$

↓

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

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

$Z_h \to Z'$, $Z_l \to Z$

PARENTAL ADVISORY EXPLICIT CONTENT

## 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

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

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

$W'$ $W$

PARENTAL ADVISORY EXPLICIT CONTENT

## 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 ($\mathbb{I}$) — non-universal due to SM-VL mixing ($\lambda_{q,\ell} \widetilde{M}^{-2} \lambda_{q,\ell}^\dagger$)

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

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

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

# 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 $B \to X_c \ell\nu$
- $|\Delta F| = 1, 2$ transitions in the $b \to s$ 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

# Our global fit

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

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

$M_{Z'} \to \simeq M_{W'}$, $g_2 \to g_1$, $\Delta_s, \Delta_b, \Delta_\mu, \Delta_\tau \to \lambda_{\ell,q}$, $\zeta \to$ gauge mixing, $\{\lambda, A, \bar{\rho}, \bar{\eta}\} \to$ CKM matrix

Global $\chi^2$ function

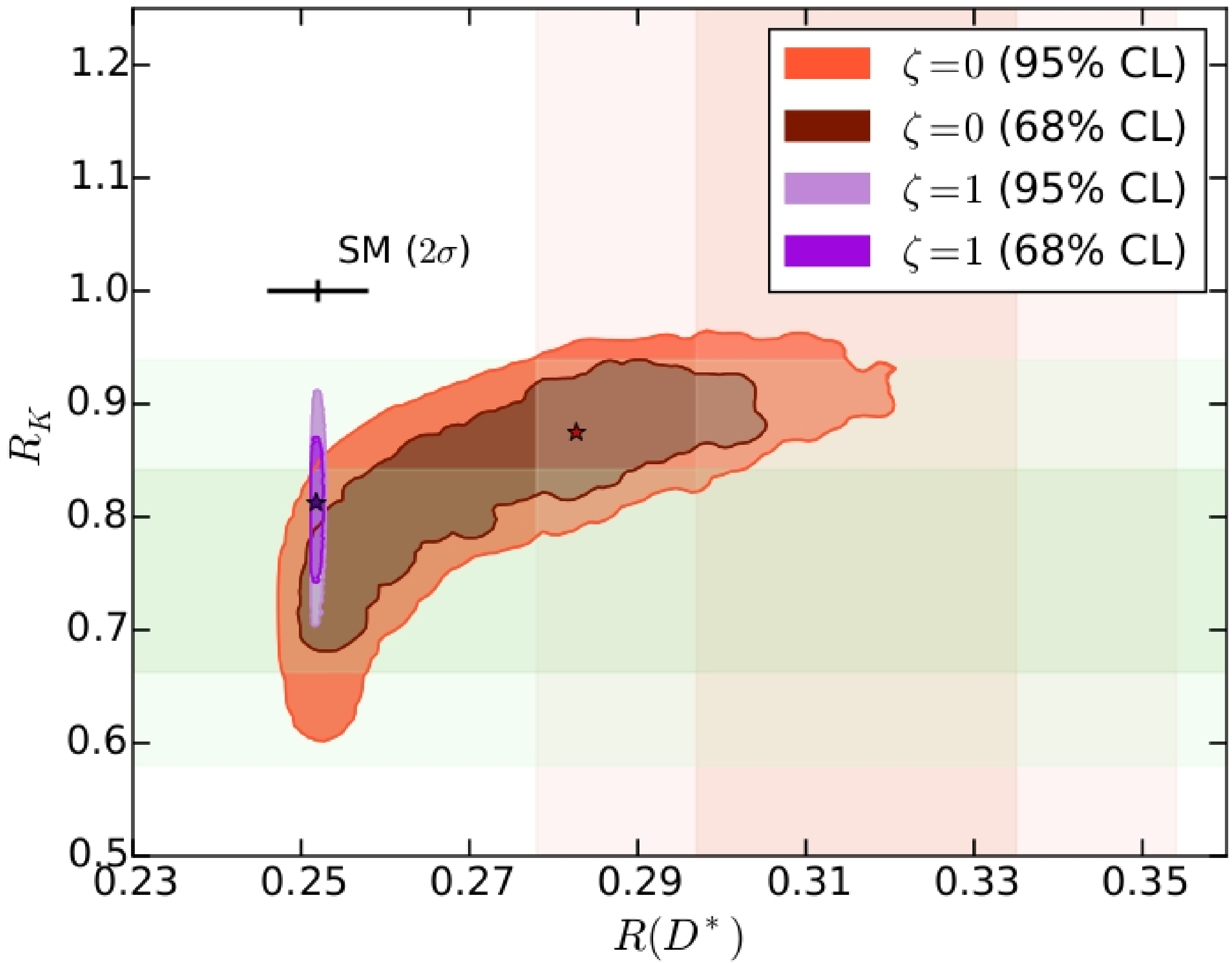
Best-fit point:

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

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

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

# Gauging the anomalies away



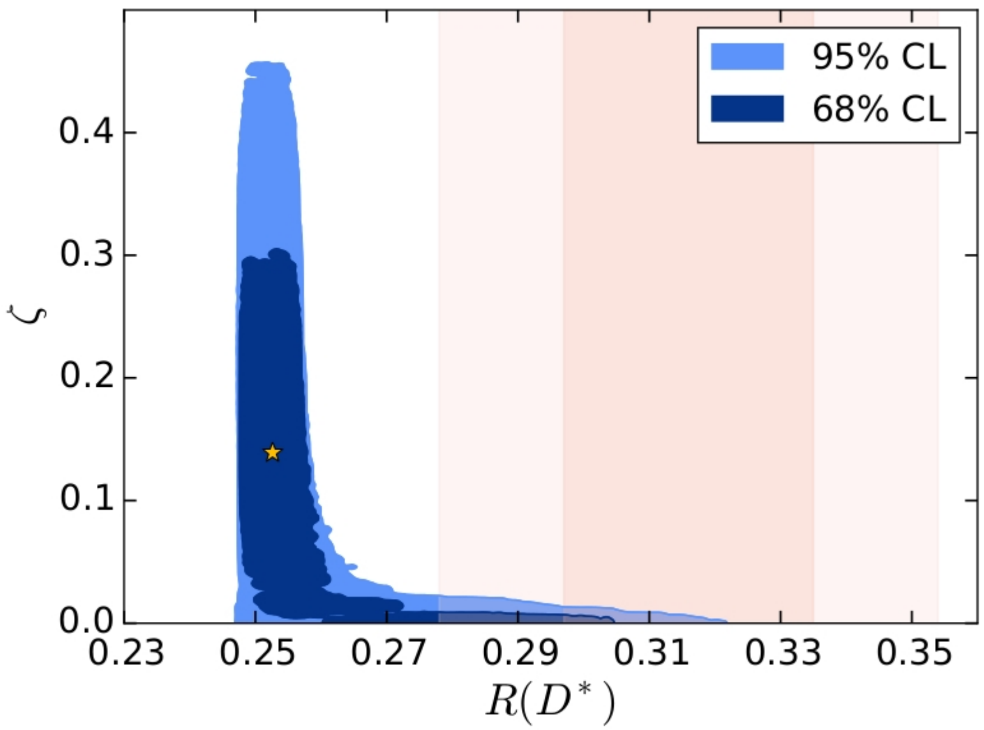

Global fit

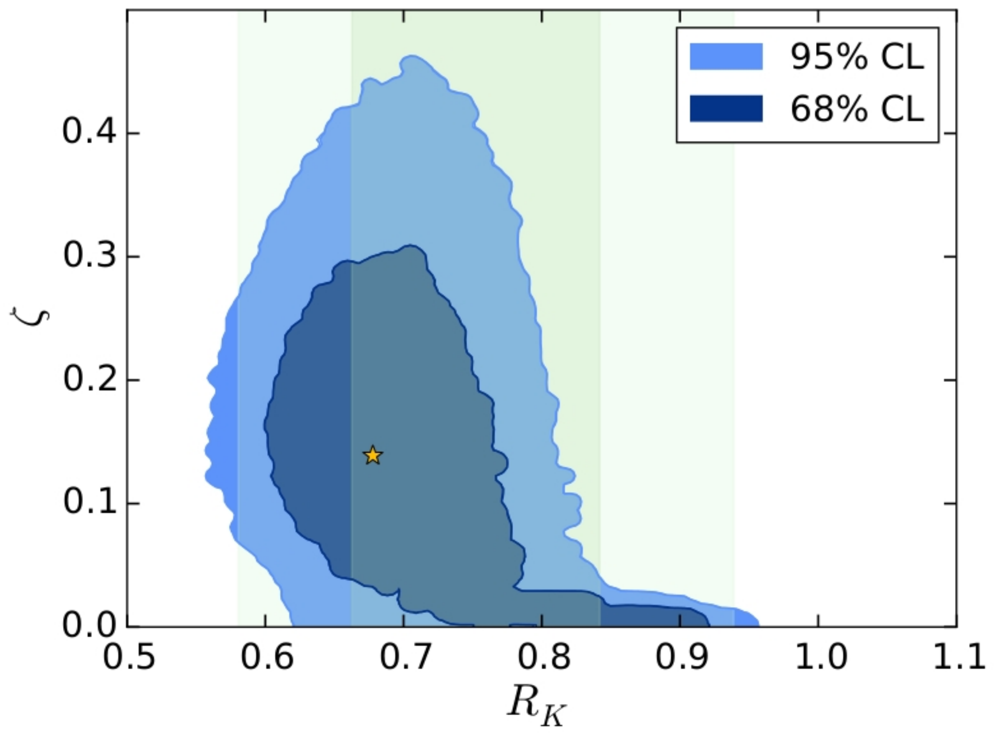
- EW precision data
- Flavor data

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 the same Dirac structure as the SM ones

$$\Longrightarrow \quad \frac{R(D)}{R(D^*)} = \left[\frac{R(D)}{R(D^*)}\right]_{\rm SM}$$

$\Longrightarrow$ 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 $R_\Phi$ 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 $2^{nd}$ and $3^{rd}$ generation quarks

$\Longrightarrow$ The usual limits ($1^{st}$ 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 $M_{Z'}$ ~ 1 TeV unless the Z' is broad [Greljo et al, 1609.07138, 1704.09015]

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

# Summary of the lecture

# Summary of the lecture

**The explanation to the B-anomalies may well open a gate to a whole new sector**

Connection to Dark Matter

**Many models...**

Individual explanations: Z’, leptoquarks, charged Higgs, loops, ...

Combined explanations: W’+Z’, leptoquarks, strongly coupled

**We definitely need more data**

# Summary of the lecture

**The explanation to the B-anomalies may well open a gate to a whole new sector**

Connection to Dark Matter

**Many models...**

Individual explanations: Z', leptoquarks, charged Higgs, loops, ...

Combined explanations: W'+Z', leptoquarks, strongly coupled

**We definitely need more data**

**I hope you enjoyed and will contribute to this field of research!**

# Backup

# LFV in B meson decays

**What about LFV?**

[Glashow et al, 2014]

*Lepton universality violation generically implies lepton flavor violation*

Gauge basis

Mass basis

$$\mathcal{O} = \widetilde{C}^Q \left( \bar{q}' \gamma_\alpha P_L q' \right) \widetilde{C}^L \left( \bar{\ell}' \gamma^\alpha P_L \ell' \right) \longrightarrow \mathcal{O} = C^Q \left( \bar{q} \gamma_\alpha P_L q \right) C^L \left( \bar{\ell} \gamma^\alpha P_L \ell \right)$$

$$C^L = U_\ell^\dagger \, \widetilde{C}^L \, U_\ell$$

However: we must have a flavor theory in order to make predictions

# Are the LHCb anomalies related to neutrino oscillations?

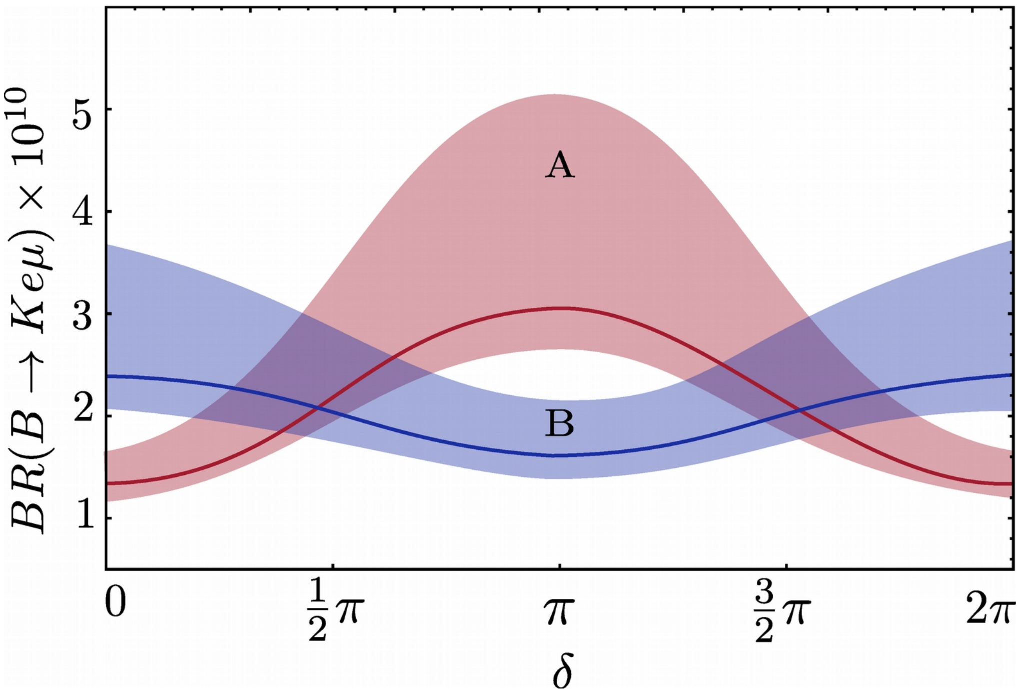
Working hypothesis: What if $U_\ell = K^\dagger$?

[Boucenna, Valle, AV, 2015]

Neutrino oscillations

**Neutrinos ⟷ B-physics**

LHCb
sensitivity
$\sim 10^{-10}$




Lines: BF
Bands: $1\sigma$

[de Medeiros Varzielas, Hiller, 2015]

## Flavor symmetries!

| symmetry | flavons | $\Delta$ assignment |
|---|---|---|
| $SU(3)_F \times U(1)_F$ | $\langle \phi_{23} \rangle = (0, b, -b)$ | $\{\Delta\} = -2$ |
| $A_4 \times Z_3$ | $\langle \phi_l \rangle = (u, 0, 0)$ | $1, \{\Delta\} = 2$ |
| $A_4 \times Z_3$ | $\langle \phi_l \rangle = (u, 0, 0)$ | $1”, \{\Delta\} = 2$ |
| $1^x, \{\Delta\} = 0$ | | |
| $A_4 \times Z_4$ | $\langle \phi_l \rangle = (0, u, 0), \xi''$ | $1’, \{\Delta\} = 2$ |
| $A_4 \times Z_4$ | $\langle \phi_l \rangle = (0, u, 0), \xi''$ | $1”, \{\Delta\} = 2$ |
| $A_4 \times Z_4$ | $\langle \phi_l \rangle = (0, u, 0)$ | $1’ , \{\Delta\} = 2$ |

$$\lambda = \begin{pmatrix} 0 & \lambda_{d\mu} & 0 \\ 0 & \lambda_{s\mu} & 0 \\ 0 & \lambda_{b\mu} & 0 \end{pmatrix}$$

[ Table from de Medeiros Varzielas, Hiller, arXiv:1503.01084 ]

The rates for the different channels are predicted by the symmetry!

# 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

**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 (II)

| | generations | $\mathrm{SU}(3)_C$ | $\mathrm{SU}(2)_1$ | $\mathrm{SU}(2)_2$ | $\mathrm{U}(1)_Y$ |
|---|---|---|---|---|---|
| $\phi$ | 1 | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $1/2$ |
| $\Phi$ | 1 | $\mathbf{1}$ | $\mathbf{2}$ | $\bar{\mathbf{2}}$ | $0$ |
| $\phi'$ | 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 | $\mathbf{3}$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1/3$ |
| $\ell_L$ | 3 | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $-1/2$ |
| $e_R$ | 3 | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1$ |
| $Q_{L,R}$ | $n_{\mathrm{VL}}$ | $\mathbf{3}$ | $\mathbf{2}$ | $\mathbf{1}$ | $1/6$ |
| $L_{L,R}$ | $n_{\mathrm{VL}}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ | $-1/2$ |

# The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

## Z' and W' couplings to fermions

$$\mathcal{L}_{\rm NC} \supset \frac{\hat{g}}{2} Z_h^\mu \left[ \overline{\mathcal{D}_L} \, \gamma_\mu \, O_L^Q \, \mathcal{D}_L + \overline{\mathcal{E}_L} \, \gamma_\mu \, O_L^L \, \mathcal{E}_L \right]$$

$$\mathcal{L}_{\rm CC} \supset -\frac{\hat{g}}{\sqrt{2}} W_h^\mu \left[ \overline{\mathcal{U}_L} \, \gamma_\mu \, V O_L^Q \, \mathcal{D}_L + \overline{\mathcal{N}_L} \, \gamma_\mu \, O_L^L \, \mathcal{E}_L \right] + \text{h.c.}$$

$$\hat{g} \equiv g \, \frac{g_2}{g_1} \qquad V = \begin{pmatrix} V_{\rm CKM} & 0 \\ 0 & 1 \end{pmatrix} \qquad O_L^{Q,L} \equiv \begin{pmatrix} \Delta^{q,\ell} & \Sigma \\ \Sigma^\dagger & \Omega^{Q,L} \end{pmatrix}$$

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

Note: $u\widetilde{M}$ is the physical VL mass

universal

non-universal due to SM-VL mixing

# The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

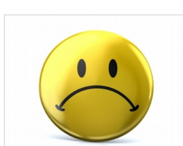
## Z' and W' couplings to fermions

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

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

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

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



Does not work!

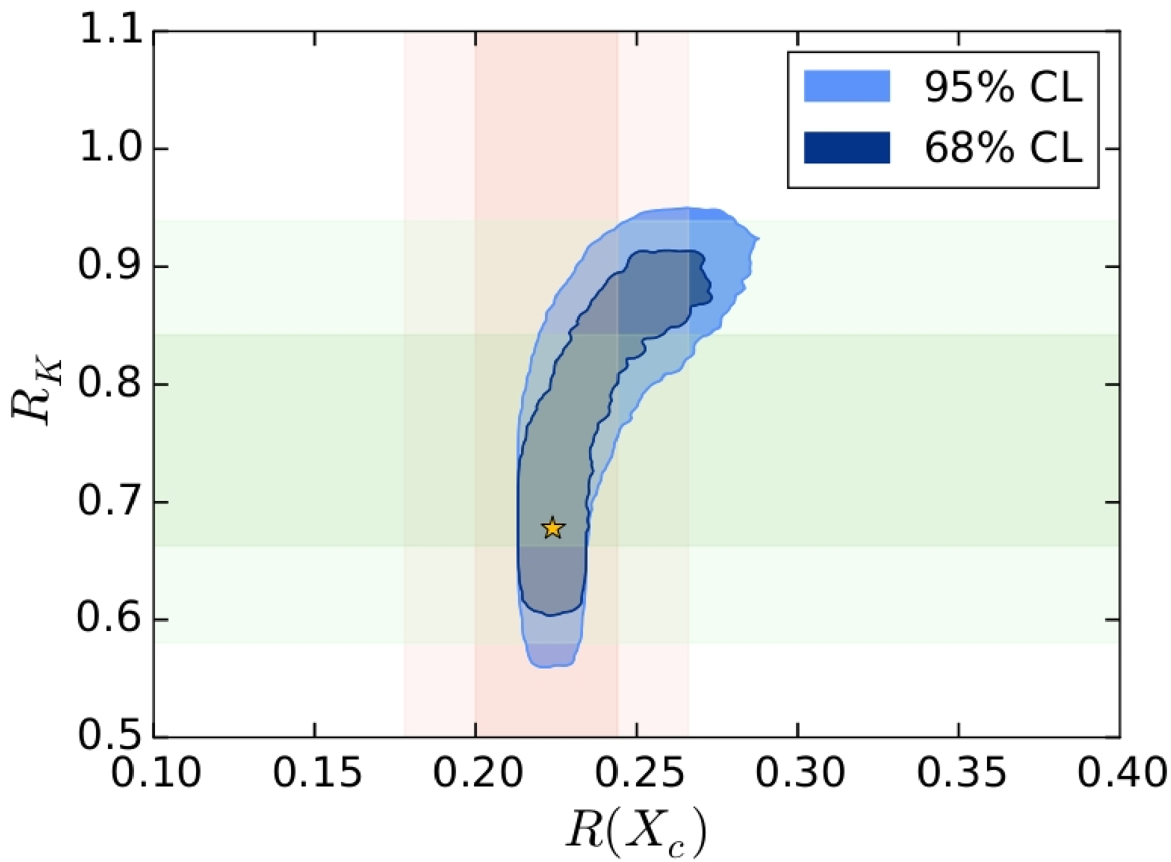
$$\boxed{n_{\rm VL} = 2}$$

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

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

It works!

# Other observables




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