New Physics in B-meson decays

A flavorful study in scarlet

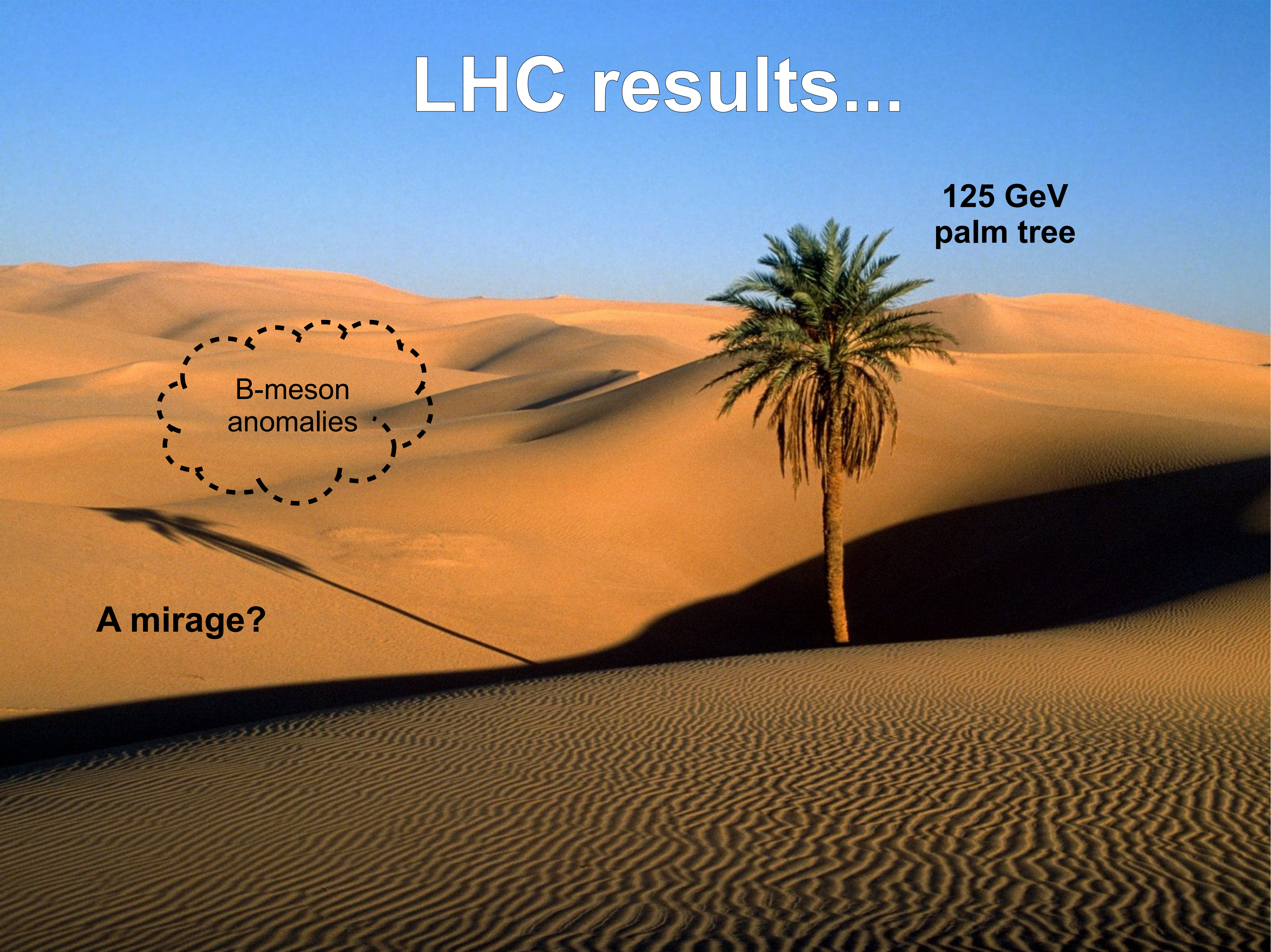
Avelino Vicente
IFIC – CSIC / U. Valencia

Laboratori Nazionali di Frascati
Theory Group seminar

Before the LHC started operating we all hoped for great discoveries...

LHC expectations

LHC results...


LHC results...
125 GeV
palm tree
B-meson
anomalies
A mirage?

Outline

The facts

Anomalies in B-meson decays

The suspects

New physics explanations of the anomalies

My favorite suspect

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

The facts

The $b \to s$ anomalies

[LHCb, 2013]
1305.2168, 1308.1707, 1403.8044

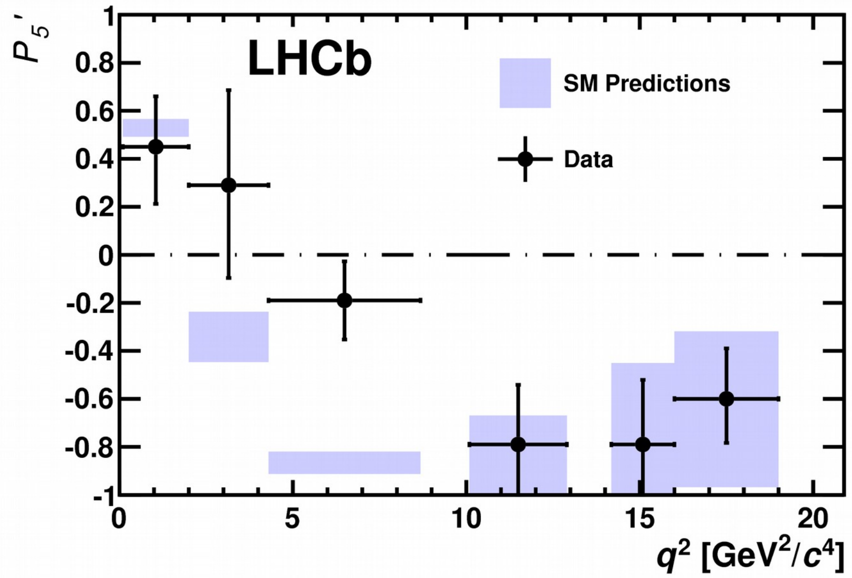
Episode 1

2013 : First anomalies found by LHCb

- Data collected: 1 fb^{-1} $(3 \text{ fb}^{-1}$ in some observables$)$
- Decrease (w.r.t. the SM) in several branching ratios
- Several anomalies in angular observables

Popular example: P_5' in
$B \to K^* \mu^+ \mu^-$

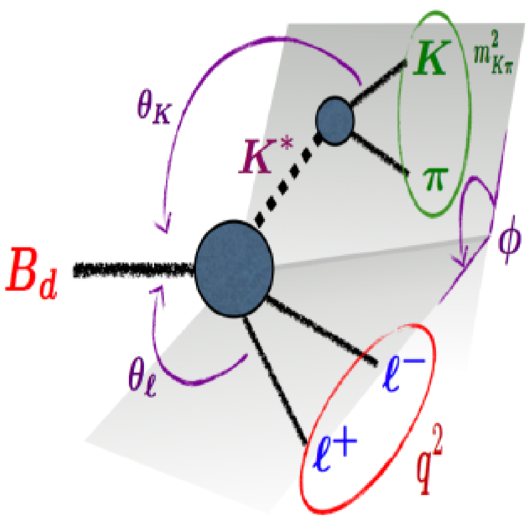
arXiv:1308.1707



The $b \to s$ anomalies

$B \to K^* (\to K\pi)\, \mu^+\mu^-$ differential angular distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



[Figure borrowed from Javier Virto]

J_i : functions of q^2, C_i, FF

Optimized observables
[Descotes-Genon et al, 2012, 2013]

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

The $b \to s$ anomalies

[LHCb, 2014]
arXiv:1406.6482

Episode 2

2014 : Lepton universality violation

Obtained with 3 fb^{-1}

$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$ [Hiller, Kruger, 2004]

2.6σ away from the SM

The $b \to s$ anomalies

[LHCb, 2015]
C. Langenbruch, Moriond 2015
March 20th

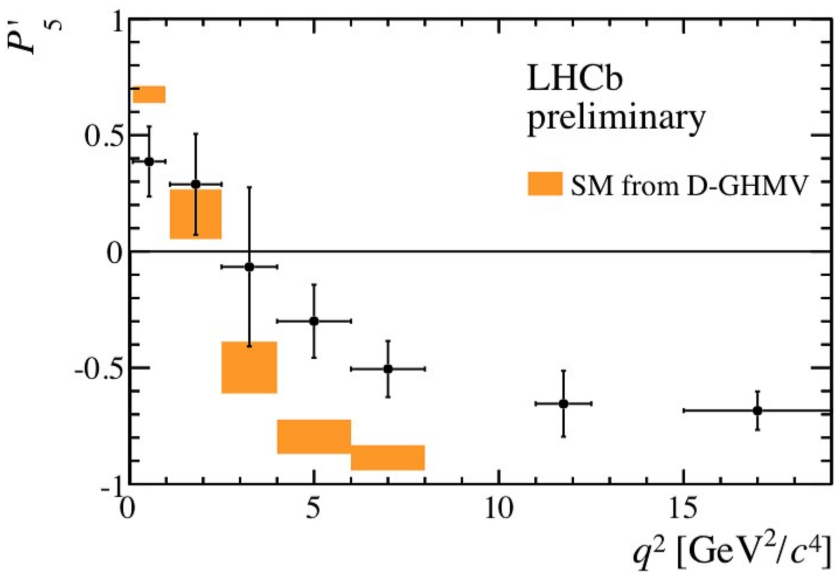
Episode 3

2015 : LHCb confirms first anomalies

All observables updated to 3 fb^{-1}

[Complete LHC Run I dataset]

Errors shrunk...
... anomalies persist



Interpreting the anomalies

$$\boxed{\boldsymbol{b \to s}}$$

Effective hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \text{h.c.}$$

C_i : Wilson coefficients

$\mathcal{O}_i$: Operators

$$\mathcal{O}_9 = (\bar{s} \gamma_\mu P_L b) \, \left(\bar{\ell} \gamma^\mu \ell \right) \qquad \mathcal{O}_9' = (\bar{s} \gamma_\mu P_R b) \, \left(\bar{\ell} \gamma^\mu \ell \right)$$

$$\mathcal{O}_{10} = (\bar{s} \gamma_\mu P_L b) \, \left(\bar{\ell} \gamma^\mu \gamma_5 \ell \right) \qquad \mathcal{O}_{10}' = (\bar{s} \gamma_\mu P_R b) \, \left(\bar{\ell} \gamma^\mu \gamma_5 \ell \right)$$

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

[analogous for primed operators]

...including also $b \to s\, e^+ e^-$

David Straub's talk Moriond 2015

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.02]$	$[-0.10, 0.01]$	1.52	1.1
C_7'	0.00	$[-0.05, 0.06]$	$[-0.11, 0.11]$	0.05	0.8
C_9^{NP}	-1.12	$[-1.34, -0.88]$	$[-1.55, -0.63]$	4.33	10.6
C_9'	-0.04	$[-0.26, 0.18]$	$[-0.49, 0.40]$	0.18	0.8
C_{10}^{NP}	0.65	$[0.40, 0.91]$	$[0.17, 1.19]$	2.75	2.5
C_{10}'	-0.01	$[-0.19, 0.16]$	$[-0.36, 0.33]$	0.09	0.8
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.20	$[-0.41, 0.05]$	$[-0.60, 0.33]$	0.82	0.8
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.57	$[-0.73, -0.41]$	$[-0.90, -0.27]$	3.88	6.8
$C_9' = C_{10}'$	-0.08	$[-0.33, 0.17]$	$[-0.58, 0.41]$	0.32	0.8
$C_9' = -C_{10}'$	-0.00	$[-0.11, 0.10]$	$[-0.22, 0.20]$	0.03	0.8

$\chi^2_{\text{SM}} = 125.8$ for 91 measurements ($p = 0.92$ %)

Coefficient	Best fit	1σ	3σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value (%)
$\mathcal{C}_7^{\mathrm{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1	17.0
$\mathcal{C}_9^{\mathrm{NP}}$	-1.14	$[-1.34, -0.93]$	$[-1.71, -0.47]$	**4.9**	74.0
$\mathcal{C}_{10}^{\mathrm{NP}}$	0.64	$[0.42, 0.87]$	$[0.00, 1.38]$	3.0	33.0
$\mathcal{C}_{7'}^{\mathrm{NP}}$	0.02	$[0.00, 0.04]$	$[-0.04, 0.09]$	1.0	17.0
$\mathcal{C}_{9'}^{\mathrm{NP}}$	0.15	$[-0.08, 0.39]$	$[-0.54, 0.85]$	0.7	16.0
$\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.10	$[-0.27, 0.06]$	$[-0.61, 0.40]$	0.6	16.0
$\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{10}^{\mathrm{NP}}$	-0.18	$[-0.37, 0.02]$	$[-0.70, 0.53]$	0.9	16.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$	-0.66	$[-0.81, -0.50]$	$[-1.15, -0.21]$	**4.6**	66.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}}$	-0.05	$[-0.29, 0.19]$	$[-0.77, 0.66]$	0.2	15.0
$\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	0.07	$[-0.03, 0.18]$	$[-0.24, 0.39]$	0.7	16.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.43]$	**4.9**	73.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.65	$[-0.83, -0.49]$	$[-0.19, -0.19]$	4.4	62.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{9'}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.21	$[-0.30, -0.12]$	$[-0.50, 0.05]$	2.4	26.0

Table from Descotes-Genon et al, 1510.04239

The $b \to s$ anomalies

Slide from June 2015
Already outdated

$b \to s$ anomalies

Model building

Composite Higgs

Buras, Girrbach-Noe, Niehoff, Stangl, Straub

Z' boson

Altmannshofer, Aristizabal Sierra, Buras, Celis, Crivellin, D' Ambrosio, Fuentes-Martín, Gauld, Girrbach-Noe, Goertz, Gori, Haisch, Heeck, Jung, Niehoff, Pospelov, Serôdio, Staub, Straub, Vicente, Yavin

Other

Calibbi, Crivellin, Greljo, Isidori, Marzocca, Ota

Leptoquarks

Alonso, Becirevic, Biswas, Chowdhuri, de Medeiros Varzielas, Fajfer, Grinstein, Gripaios, Han, Hiller, Kosnik, Lee, Martin Camalich, Mohanta, Nardecchia, Renner, Sahoo, Schmaltz

Global fits

Alonso, Altmannshofer, Beaujean, Bobeth, Descotes-Genon, Egede, Ghosh, Grinstein, Hiller, Hurth, Mahmoudi, Martin Camalich, Matias, Nardecchia, Neshatpour, Patel, Petridis, Renner, Schmaltz, Straub, van Dyk, Virto

Implications - LFV -

Bhattacharya, Boucenna, Civellin, Datta, de Medeiros Varzielas, Glashow, Gripaios, Guadagnoli, Hiller, Hofer, Kane, Lee, London, Matias, Mohanta, Nardecchia, Nierste, Pokorski, Renner, Rosiek, Sahoo, Shivashankara, Tandean, Valle, Vicente

SM uncertainties

Altmannshofer, Bharucha, Descotes-Genon, Ghosh, Hiller, Hofer, Horgan, Hurth, Jaeger, Liu, Lyon, Martin Camalich, Matias, Meinel, Straub, Virto, Wingate, Zwicky

The $b \to c$ anomalies

$$\boxed{\mathcal{R}(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)},}$$

$$\begin{aligned}
\mathcal{R}(D^*)_{\mathrm{BABAR}} &= 0.332 \pm 0.024 \pm 0.018\,, \\
\mathcal{R}(D^*)_{\mathrm{BELLE}} &= 0.293 \pm 0.038 \pm 0.015\,, \\
\mathcal{R}(D^*)_{\mathrm{LHCb}} &= 0.336 \pm 0.027 \pm 0.030\,.
\end{aligned}$$

BaBar
+
Belle
+
LHCb

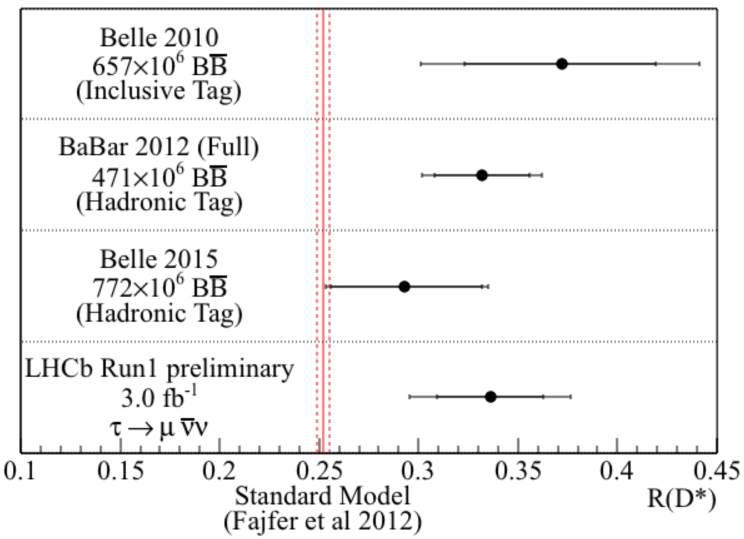
$$\mathcal{R}(D^*)_{\mathrm{SM}} = 0.252 \pm 0.003\,, \qquad \mathcal{R}(D^*)_{\mathrm{exp}} = 0.321 \pm 0.021\,.$$

$$\begin{aligned}
\mathcal{R}(D)_{\mathrm{BABAR}} &= 0.440 \pm 0.058 \pm 0.042\,, \\
\mathcal{R}(D)_{\mathrm{BELLE}} &= 0.375 \pm 0.064 \pm 0.026\,,
\end{aligned}$$

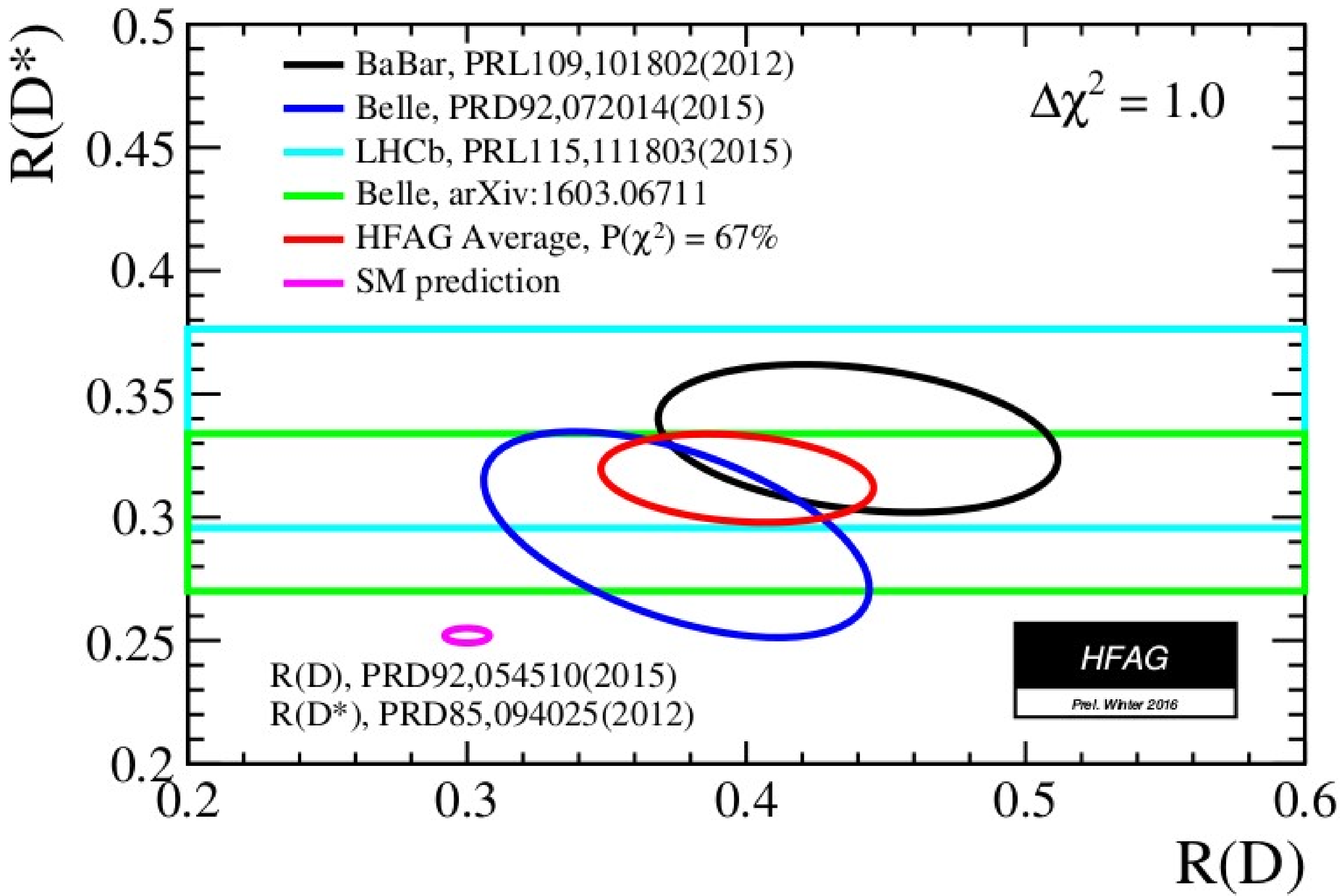
$$\mathcal{R}(D)_{\mathrm{SM}} = 0.297 \pm 0.017\,, \qquad \mathcal{R}(D)_{\mathrm{exp}} = 0.388 \pm 0.047\,.$$

Another hint of lepton universality violation?

Deviation from the SM at the <u>4 σ level</u>



The $b \to c$ anomalies



Remarks about the anomalies

The $b \to s$ anomalies in angular distributions and branching ratios can be faked by hadronic effects

A matter of hot debate

However, ratios such as R_K and $R(D^{(*)})$ are theoretically clean and cannot be explained with hadronic physics

Hadronic effects are lepton universal!

The C_9^μ coefficient seems to play a key role in the $b \to s$ anomalies

Preference for left-handed quark neutral currents

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

This is guaranteed by a left-handed charged current

The suspects

New Physics explanations

R_K $\Rightarrow$ **Neutral current**

Z' boson, leptoquarks, compositeness, RPV loops

$R(D^{(*)})$ $\Rightarrow$ **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

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

A model with a dark sector

[Aristizabal Sierra, Staub, AV, 2015]

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

Vector-like = "joker"
for model builders

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 dark sector

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

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

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

Vector-like (Dirac) masses

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

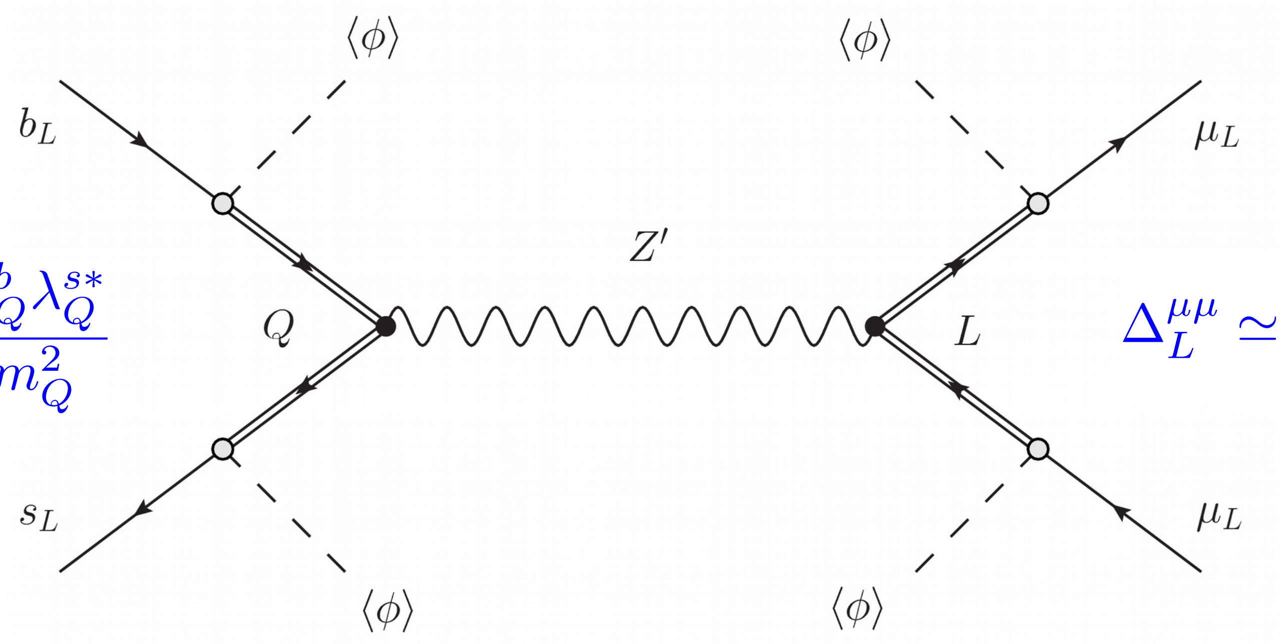
VL – SM mixing

Solving the $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]

Similar to Altmannshofer et al, Crivellin et al, 2014

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



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

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

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

Direct Z' couplings also possible

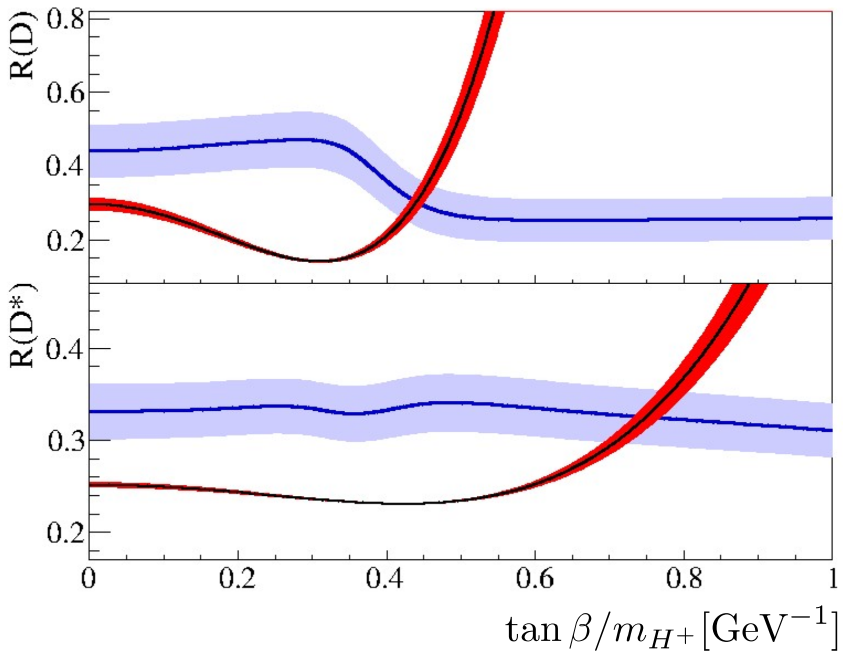
Altmannshofer et al, 2014, Crivellin et al, 2014, 2015 [$L_\mu - L_\tau$], Celis et al, 2015 [BGL], ...

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

<u>Natural candidate</u> for the $b \to c$ anomalies: a charged Higgs

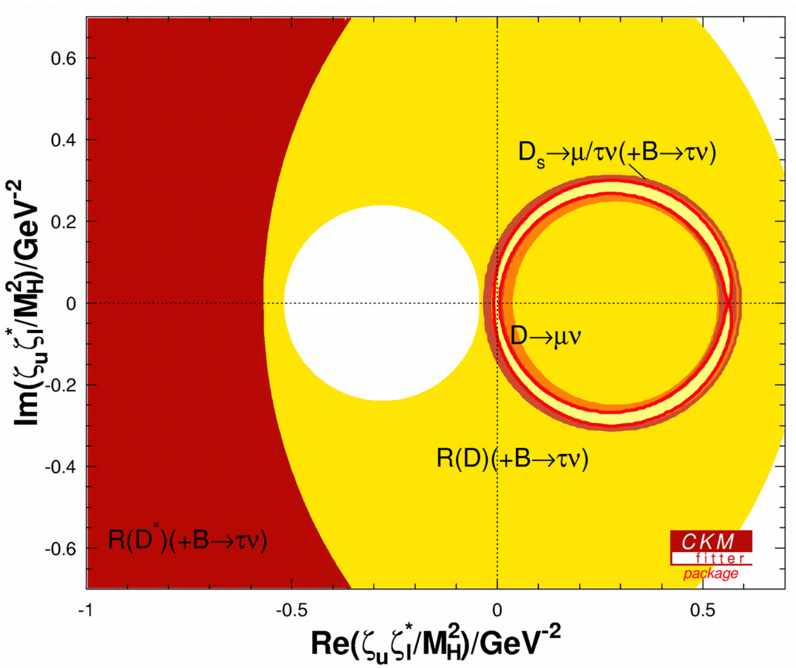
But the "standard" 2HDMs do not work [Celis et al, 2012]

Type II 2HDM



[BaBar collaboration, 2012]

Aligned 2HDM



[Celis et al, 2012]

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

Killing two birds with one stone

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

$R(D^{(*)})$ ⇐ **A common NP framework** ⇒ R_K

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

Leptoquarks

Simultaneous explanation of R_K and R(D*) puzzles:
leptoquarks?

One leptoquark to rule them all [1511.01900]

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

Candidates in the literature

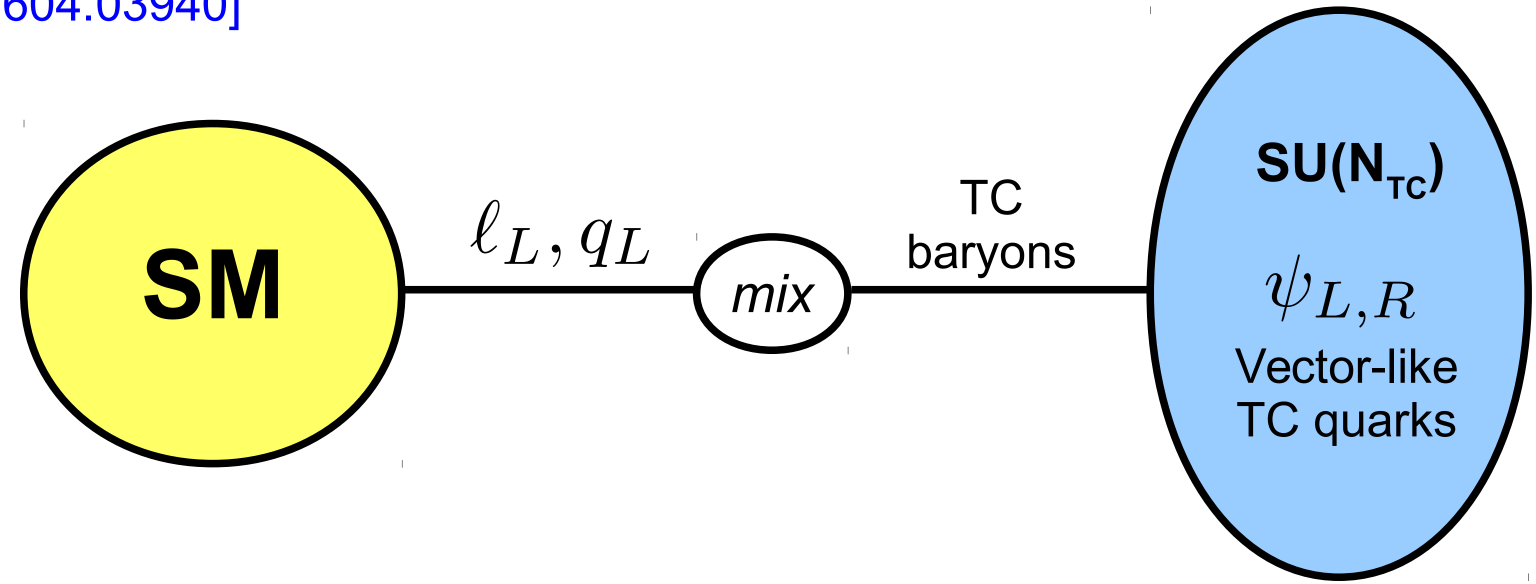
V_μ = (3,1,-2/3)	Φ = (3,1,-1/3)	V_μ = (3,3,2/3)
Alonso, Grinstein, Martin-Camalich [1505.05164]	Bauer, Neubert [1511.01900, 1512.06828]	Fajfer, Kosnik [1511.06024]
Barbieri, Isidori, Pattori, Senia [1512.01560]	Das, Hati, Kumar, Mahajan [1605.06313]	

Same as in RPV SUSY
Deshpande, He [1608.04817]

See also Deppisch, Kulkarni, Päs, Schumacher [1603.07672] for a possible connection to neutrino masses

Strongly-coupled NP

Buttazzo, Greljo, Isidori, Marzocca
[1604.03940]



Lowest-lying
vector meson resonances

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

R_K and $R(D^{(*)})$

I prefer something
more... *elementary*

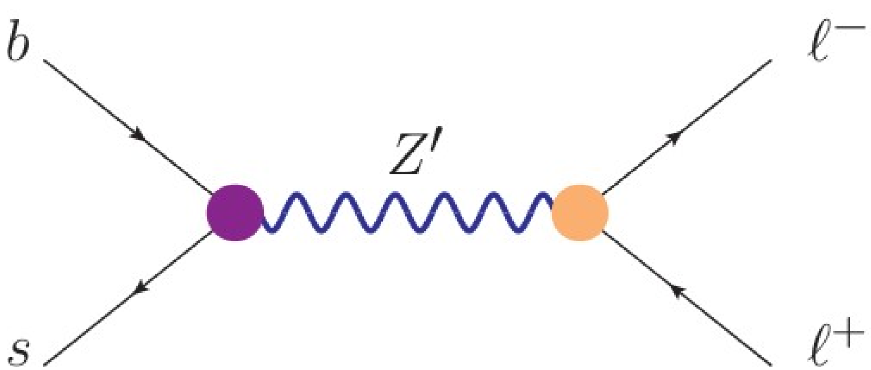
My favorite suspect

1604.03088
1608.01349

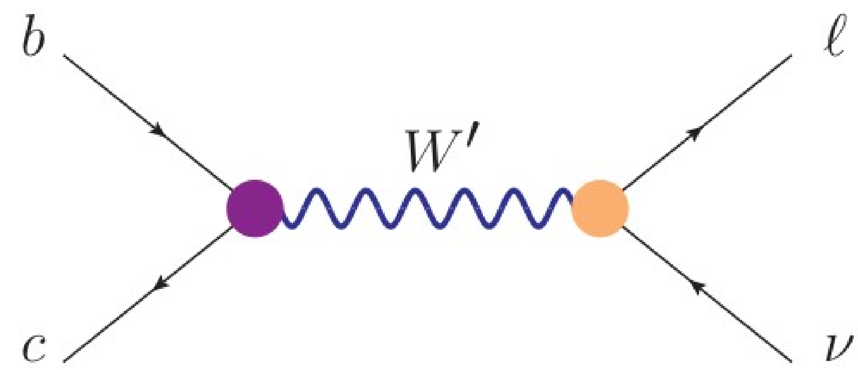
My favorite suspect

- Towards a gauge model
- The model I
- The model II
- Numerical results

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)

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

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

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

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

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

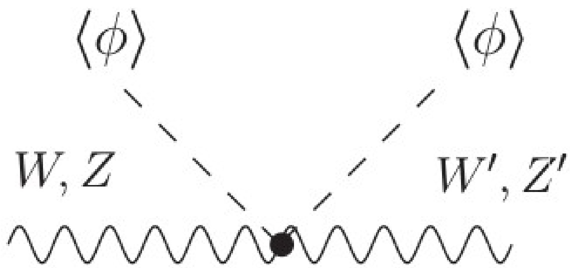
Particle content

- 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 same size 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 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 $\phi' = (2,1)_{1/2}$ ⇨ ζ free parameter

The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

	generations	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_1$	$\mathrm{SU}(2)_2$	$\mathrm{U}(1)_Y$
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 (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

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 (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

$\{\phi, \Phi, \phi'\}$ 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

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

$$i = 1, 2, 3$$

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

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

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

SM-VL mixing induced by λ_f

The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

Particle spectrum III: Gauge bosons

Neutral gauge bosons

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

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

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

$$Z_h \to Z' \qquad Z_l \to Z$$

The model (II)

PARENTAL ADVISORY EXPLICIT CONTENT

Particle spectrum III: Gauge bosons

Charged gauge bosons

$$\mathcal{V}^+ = \left(W_{12}^1, W_{12}^2\right) \qquad \mathcal{M}^2_{\mathcal{V}^+} = \frac{1}{4}\begin{pmatrix} g_1^2\left(v_{\phi'}^2 + u^2\right) & -g_1 g_2 u^2 \\ -g_1 g_2 u^2 & g_2^2\left(v_\phi^2 + u^2\right) \end{pmatrix}$$

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

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

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

$W' \quad W$

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)

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]

- 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

Our global fit

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

Free parameters: $\{\underbrace{M_{Z'}}_{\simeq M_{W'}}, \underbrace{g_2}_{g_1}, \underbrace{\Delta_s, \Delta_b, \Delta_\mu, \Delta_\tau}_{\lambda_{\ell,q}}, \underbrace{\zeta}_{\text{gauge mixing}}\} \quad + \quad \underbrace{\{\lambda, A, \bar{\rho}, \bar{\eta}\}}_{\text{CKM matrix}}$

Global χ^2 function

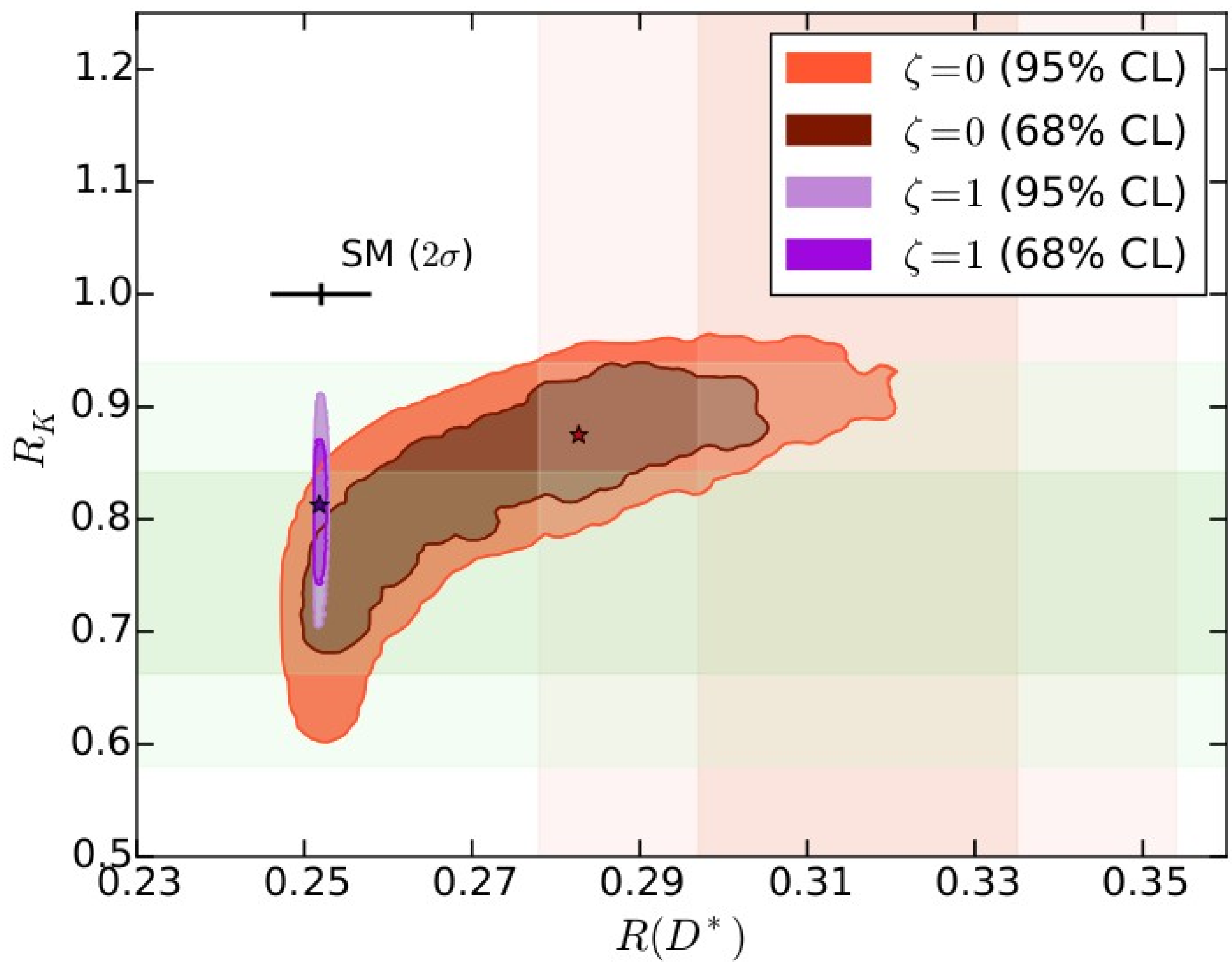
Best-fit point:

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

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

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

Gauging the anomalies away



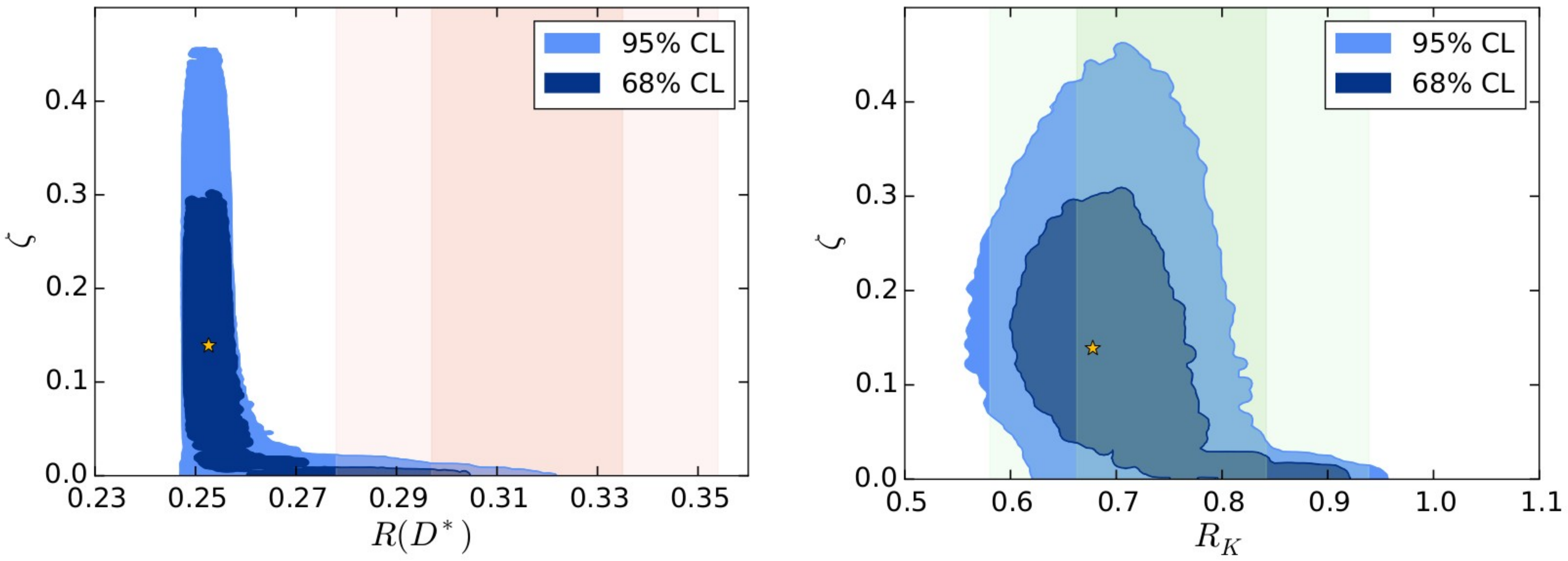
Global fit

- 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 $b \to c$ 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_Φ are strongly correlated

$$\Longrightarrow \quad R_{K^*} \sim R_K < 1 \qquad \text{(for example)}$$

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). Heavier Z' bosons become broad and require dedicated searches

Summary

Summary

The anomalies in B-meson decays constitute an intriguing set of hints for NP

Possible NP explanations include charged Higgses, Z' bosons, leptoquarks and some other possibilities, but finding a common explanation is not trivial

A simple SU(2) gauge extension of the SM can do the job!

Summary

The anomalies in B-meson decays constitute an intriguing set of hints for NP

Possible NP explanations include charged Higgses, Z' bosons, leptoquarks and some other possibilities, but finding a common explanation is not trivial

A simple SU(2) gauge extension of the SM can do the job!

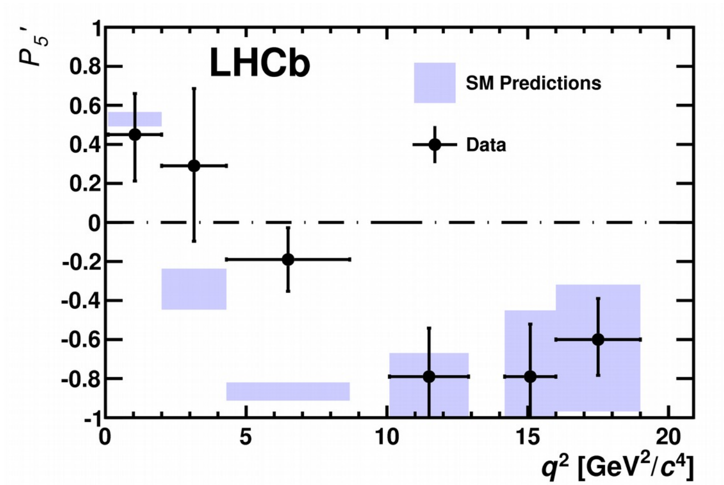
Thank you!

Backup slides

The $b \to s$ anomalies

Episode 1

2013 : First anomalies found by LHCb



Episode 2

2014 : Lepton universality violation

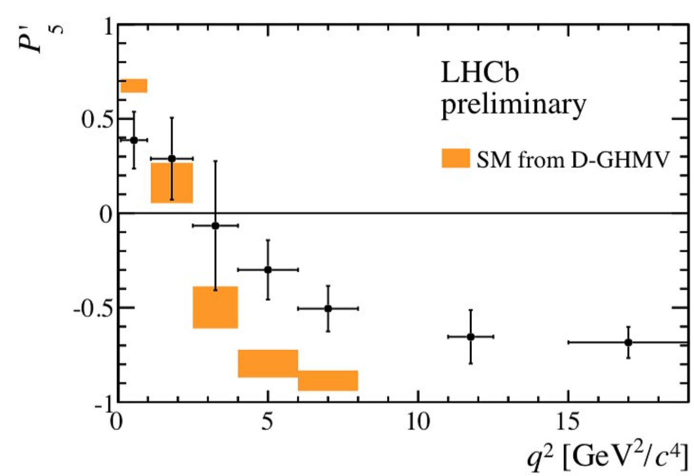
$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$ [Hiller, Kruger, 2004]

2.6σ away from the SM

Episode 3

2015 : LHCb confirms first anomalies



$$\boxed{B_s \to \mu^+\mu^-}$$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\;(\bar{\mu}\gamma^\alpha P_L \mu) \qquad \Rightarrow \qquad \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$$

Contributes to
$\mathcal{O}_9$ and $\mathcal{O}_{10}$

[CMS and LHCb, 2013]

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (2.9 \pm 0.7) \times 10^{-9}$$

[Bobeth et al, 2013]

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$$-0.25 < C_{10}^{\mu,\mathrm{NP}}/C_{10}^{\mu,\mathrm{SM}} < 0.03$$ (at 1σ)

The model is compatible at 2σ

$$\boxed{B_s - \bar{B}_s \text{ mixing}}$$

[Altmannshofer et al, 2014]

Allowing for a 10% deviation from the SM expectation in the mixing amplitude

$$\frac{m_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244\,\mathrm{TeV}$$

FlavorKit

[Porod, Staub, AV, 2014]

A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

Lepton flavor	**Quark flavor**
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

Not limited to a single model: use it for the model of your choice

Easily extendable

Many observables ready to be computed in your favourite model!

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

Some comments on DM

However:

Higgs portal also possible

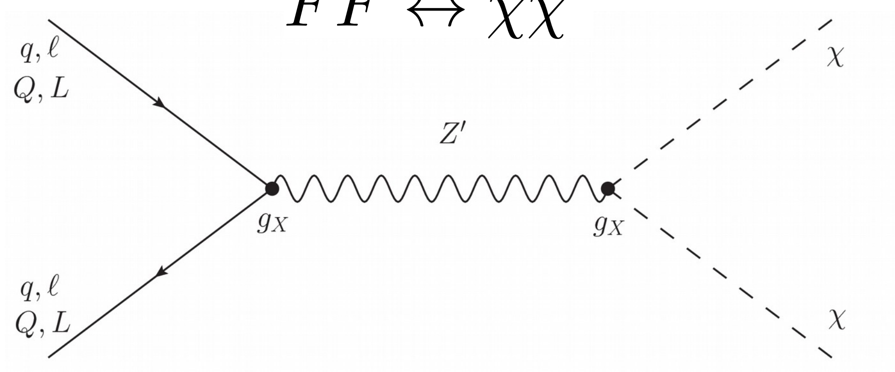
<u>Assumption:</u>

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

Z' portal

Interplay between flavor and DM

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



$$\sigma(s) \sim \left|\Delta^{f_i f_j}\right|^2 g_X^2 \frac{1}{s} \frac{m_{Z'}^4}{\left(m_{Z'}^2 - s\right)^2 - m_{Z'}^2 \Gamma_{Z'}^2} F_{\text{kin}}$$

<u>Favorable conditions</u>

$$m_\chi > m_{Q,L}$$

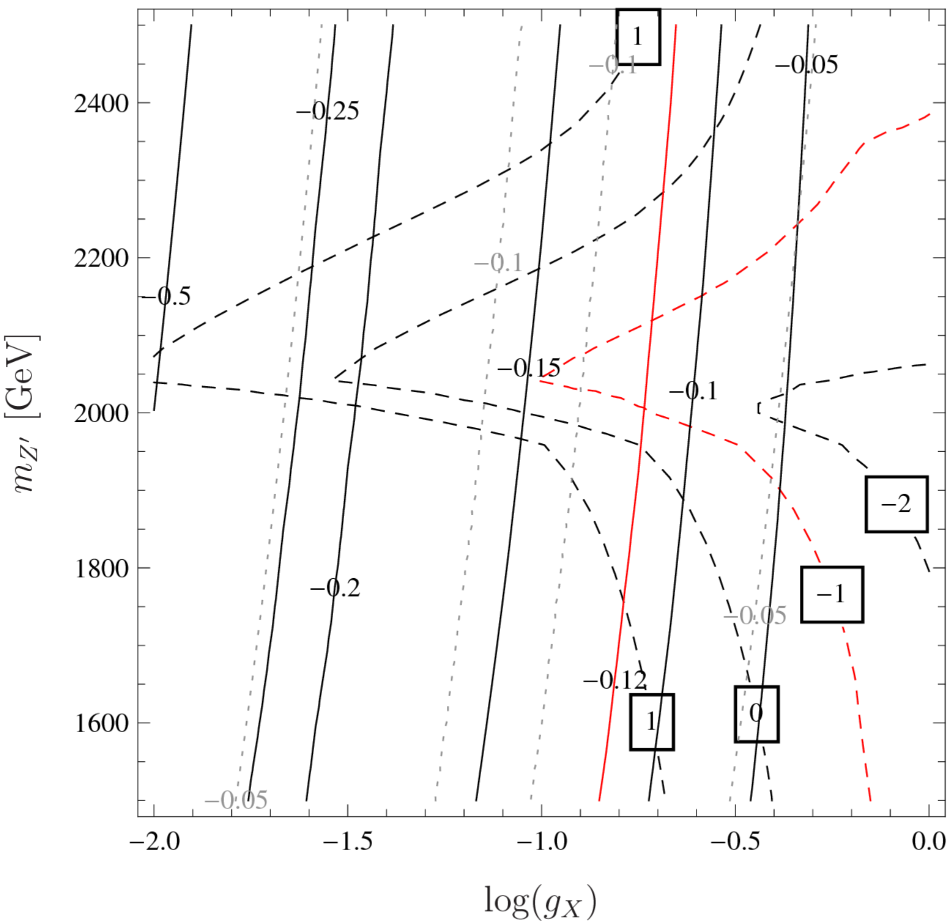
$$m_{Z'} > m_\chi$$

$$m_\chi \simeq \frac{m_{Z'}}{2}$$

(resonance)

Dark matter and LHCb anomalies

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



[DM RD Computed with **micrOMEGAs**]

Parameters:

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

$$\lambda_L^\mu = 0.5$$

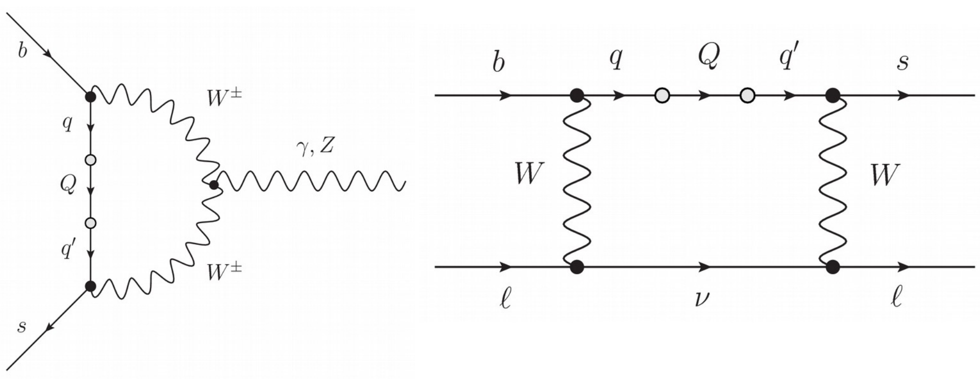
$$m_Q = m_L = 1 \text{ TeV}$$

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

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

Loop corrections

At 1-loop, the vector-like quarks contribute to all operators



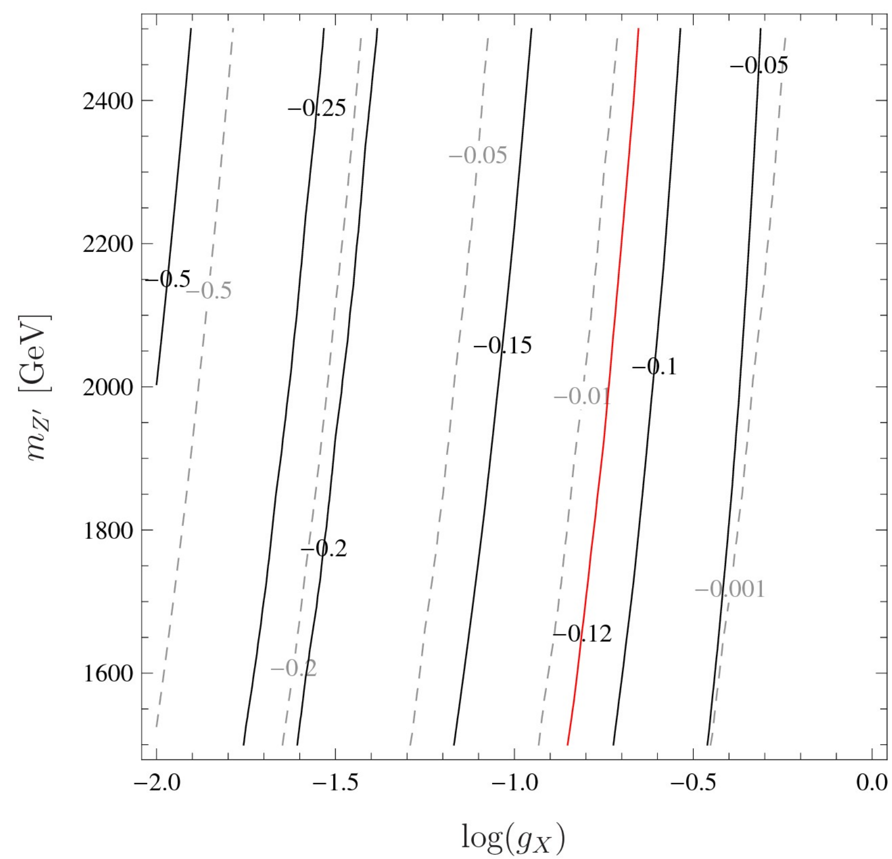
- Non-negligible corrections to C_9
- Unwanted contributions to other Wilson coefficients

However: "Valid" region is safe

$$C_7^{\rm NP}/C_7^{\rm SM} < 1\%$$

[Computed with **FlavorKit**]

$C_9^{\rm NP}/C_9^{\rm SM}$ (full) $C_7^{\rm NP}/C_7^{\rm SM}$ (dotted gray)



LFV in B meson decays

What about LFV?

[Glashow et al, 2014]

Lepton universality violation generically implies lepton flavor violation

Gauge basis

Mass basis

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

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

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

Are the LHCb anomalies related to neutrino oscillations?

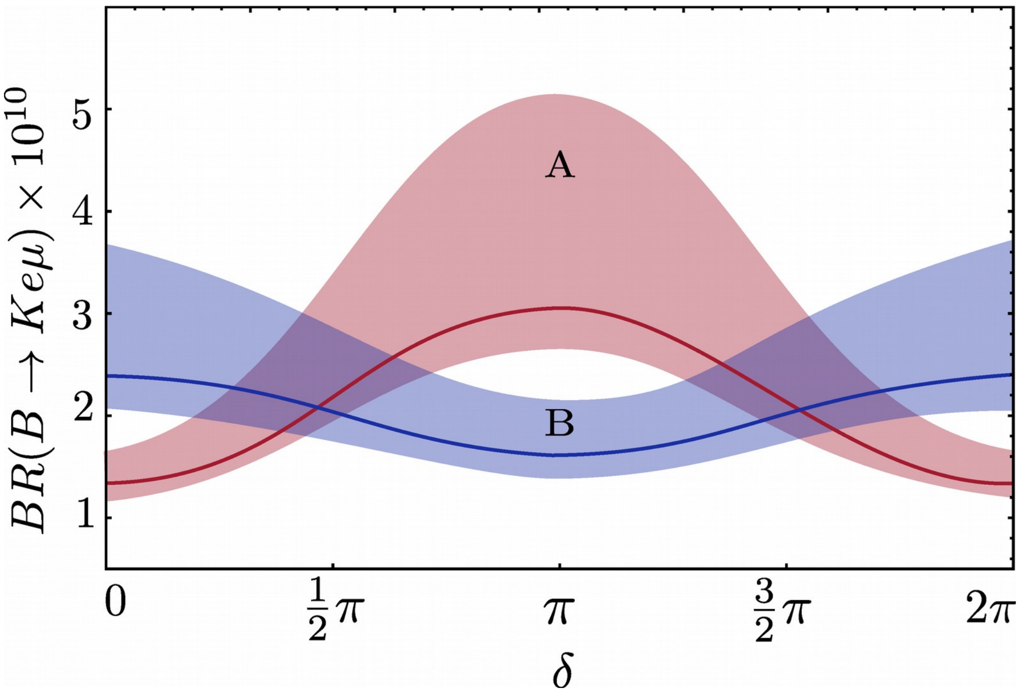
Working hypothesis: What if $U_\ell = K^\dagger$? [Boucenna, Valle, AV, 2015]

Neutrino oscillations

Neutrinos ⟷ B-physics

LHCb sensitivity

$\sim 10^{-10}$



Lines: BF
Bands: 1σ

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 :

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

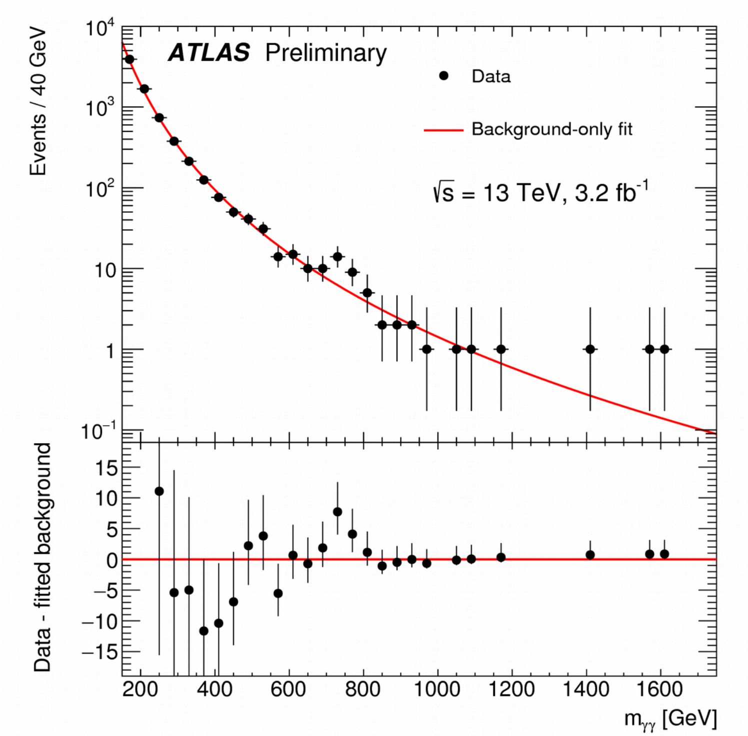
Source of non-universality

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 diphoton excess

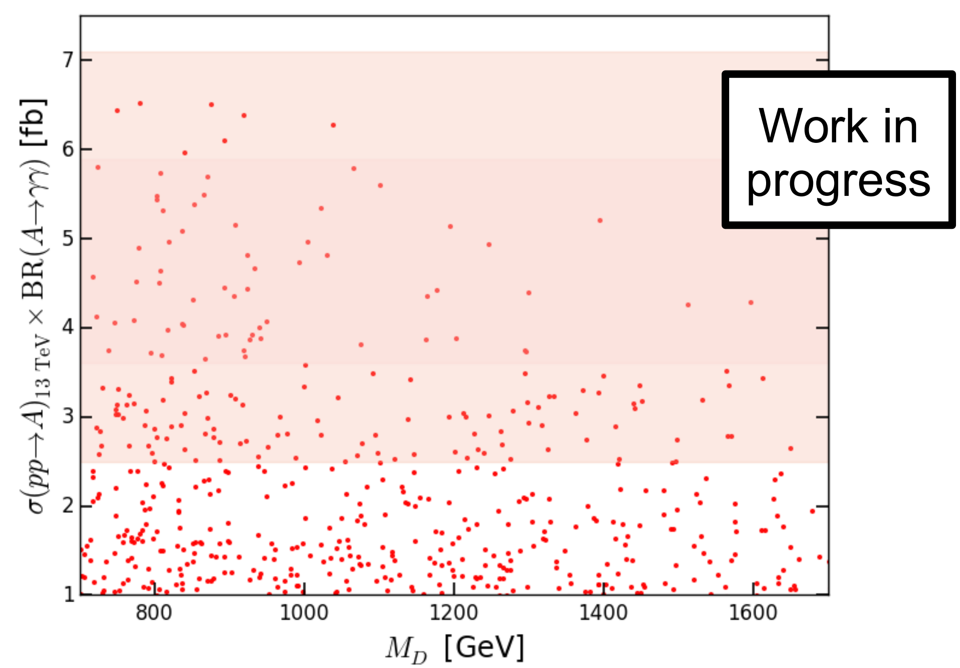


Can this model explain the LHC diphoton excess as well?

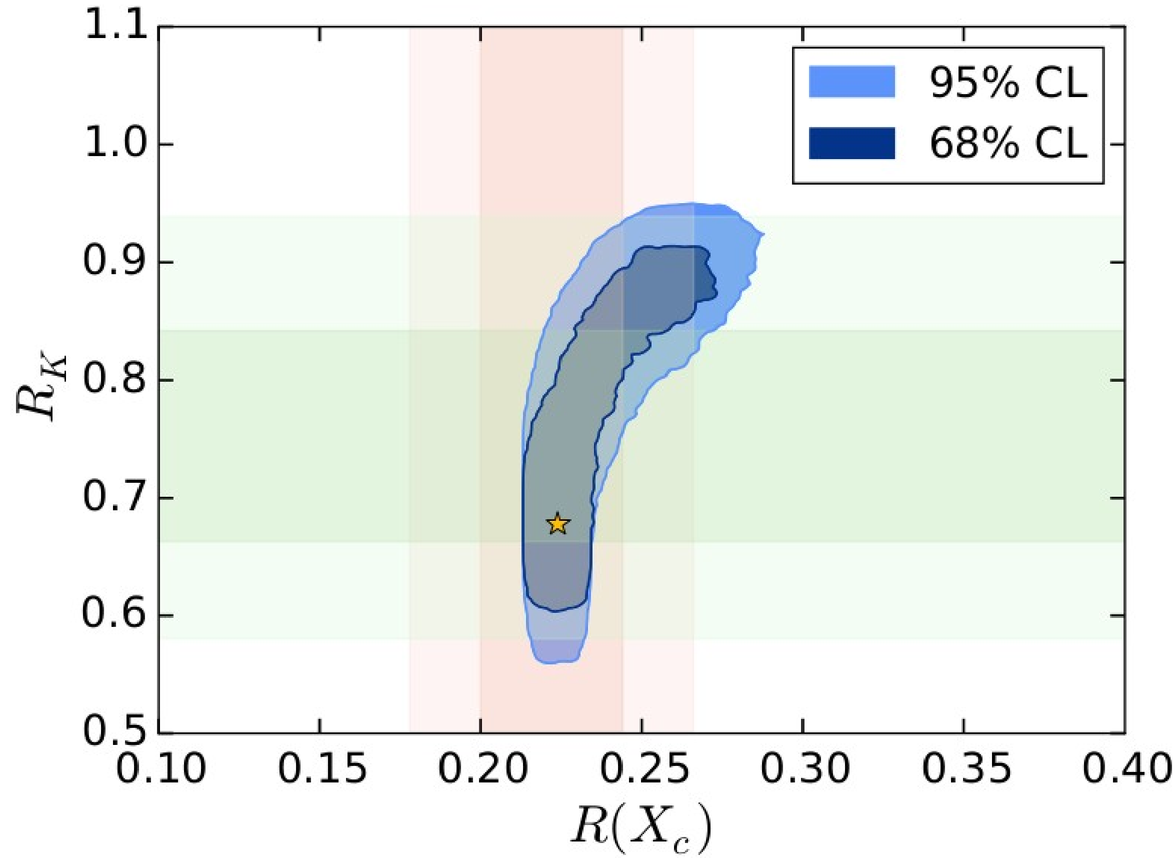
$\Phi \supset A$ (CP-odd state)

C_{Agg} and $C_{A\gamma\gamma}$ induced by loops of VL quarks and leptons

required for flavor!



Other observables



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